APPENDIX L

EXCAVATED ROCK PLACEMENT ASSESSMENT SUMMARY

ANNEXURE A – CSIRO COMPREHENSIVE GEOCHEMISTRY EXAMINATION AND
ANNEXURE B – ENVIRONMENTAL RISK CATEGORISATION OF ROCK MATERIALS

REPORT

Snowy 2.0 Excavated Rock Placement

Excavated Rock Placement Assessment Summary

Client: Snowy Hydro Limited

Reference: PA2138 ERP Assessment Summary
Status: Final/P02.01
Date: 11 September 2019

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Enhancing Society Together

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Internal use only

MANAGEMENT SYSTEM CERTIFICATION
DNV·GL
ISO 9001 = ISO 14001
OHSAS 18001

Disclaimer

Table of Contents

Table of Tables

Table of Figures

Annexures

Acronym	Definition
ADCP	Acoustic Doppler Current Profiler
AEMO	Australian Energy Market Operator
AHD	Australian Height Datum
AMSA	Australian Maritime Safety Authority
ANC	Acid Neutralising Capacity
ARI	Average Recurrence Interval
APET	Areal potential evapotranspiration data
AWM	AW Maritime Pty Ltd
BOM	Bureau of Meteorology
CFD	Computational Fluid Dynamics
CFL	Courant-Friedrichs-Lewy
COLREGs	Convention on the International Regulations for Preventing Collision at Sea 1972
COPC	Contaminants of Potential Concern
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSSI	Critical State Significant Infrastructure
CTD	Conductivity, Temperature, Depth (Pressure)
D&B	Drill and Blast
DoEE	Commonwealth Department of Environment and Energy
DEM	Digital Elevation Model
DFL	Design Flood Level
DGV	Default Guideline Value
DIDO	Drive In Drive Out
DPIE	Department of Planning, Industry and Environment (NSW)
ECVT	(Emergency) Egress, Cable and Ventilation Tunnel
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EP&A	Environmental Planning & Assessment Act 1979
EPBC	Environment Protection and Biodiversity Conservation Act 1999
ERP	Excavated Rock Placement
FGJV	Future Generation Joint Venture
FIFO	Fly In Fly Out
FM	Flexible Mesh
FSL	Full Supply Level

Acronym	Definition
FU	Functional Unit
GIS	Geographic Information System
HD	Mike 3 Flow ‘Hydrodynamic’ Model
ISQG	Interim Sediment Quality Guidelines
KNP	Kosciuszko National Park
L/S	Liquid to Solid Ratio
LGA	Local Government Area
LOA	Length Overall
m	Metres
MAT	Main Access Tunnel
MOL	Minimum Operating Level
MPA	Maximum Potential Acidity
MT	Mud Transport
MVA	Mega Volt Amp
MW	Megawatt
MWh	Megawatt hours
NAGD	National Assessment Guidelines for Dredging
NEM	National Electricity Market
NIA	Navigation Impact Assessment
NOA	Naturally Occurring Asbestos
NPWS	National Parks and Wildlife Service (NSW)
NSW	New South Wales
NTU	Nephelometric Turbidity Unit
PSD	Particle Size Distribution
QA	Quality Assurance
RHDHV	Royal HaskoningDHV
RMS	NSW Roads and Maritime Service
SEARs	Secretary’s Environmental Assessment Requirements
SEPP	State Environmental Planning Policy
SRD	State and Regional Development
SSI	State Significant Infrastructure
T2	Tumut 2 Power Station
T3	Tumut 3 Power Station

Acronym	Definition
TBM	Tunnel Boring Machine
TN	True North
TSS	Total Suspended Sediments
WED	Wake Enhancement Device
XRF	X-ray Fluorescence

1 Introduction

1.1 The Project

Snowy Hydro Limited (Snowy Hydro) proposes to develop Snowy 2.0, a large-scale pumped hydro-electric storage and generation project which would increase hydro-electric capacity within the existing Snowy Mountains Hydro-electric Scheme (Snowy Scheme).. Snowy 2.0 is the largest committed renewable energy project in Australia and is critical to underpinning system security and reliability as Australia transitions to a decarbonised economy. . Snowy 2.0 will link the existing Tantangara and Talbingo reservoirs within the Snowy Scheme through a series of underground tunnels and a new hydro-electric power station will be built underground.

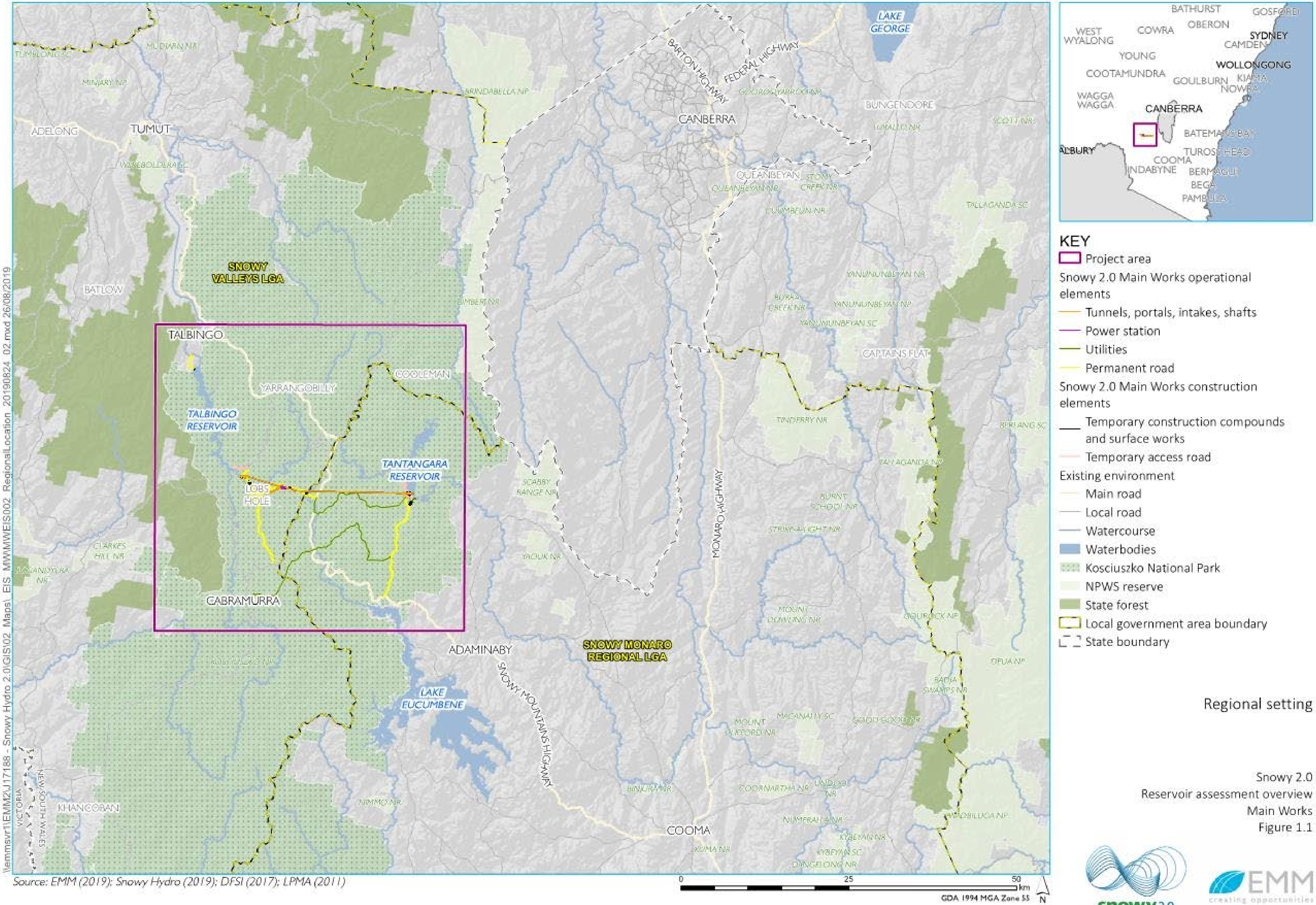
Snowy 2.0 has been declared to be State significant infrastructure (SSI) and critical State significant infrastructure (CSSI) by the former NSW Minister for Planning under Part 5 of the NSW *Environmental Planning and Assessment Act 1979* (EP&A Act) and is defined as CSSI in clause 9 of Schedule 5 of the *State Environmental Planning Policy (State and Regional Development) 2011* (SRD SEPP). CSSI is infrastructure that is deemed by the NSW Minister to be essential for the State for economic, environmental or social reasons. An application for CSSI must be accompanied by an environmental impact statement (EIS).
Separate applications are being submitted by Snowy Hydro for different stages of Snowy 2.0 under Part 5, Division 5.2 of the EP&A Act. This includes the preceding first stage of Snowy 2.0, Exploratory Works for Snowy 2.0 (the Exploratory Works) and the stage subject of this current application, Snowy 2.0 Main Works (the Main Works). In addition, an application under Part 5, Division 5.2 of the EP&A Act is also being submitted by Snowy Hydro for a segment factory that will make tunnel segments for both the Exploratory Works and Main Works stages of Snowy 2.0.

The first stage of Snowy 2.0, the Exploratory Works, includes an exploratory tunnel and portal and other exploratory and construction activities primarily in the Lobs Hole area of the Kosciuszko National Park (KNP). The Exploratory Works were approved by the former NSW Minister for Planning on 7 February 2019 as a separate project application to DPIE (SSI 9208).

This **Excavated Rock Placement (ERP) Assessment Summary** Report assessment has been prepared to accompany an application and supporting EIS for the **Snowy 2.0 Main Works**. As the title suggests, this stage of the project covers the major construction elements of Snowy 2.0, including permanent infrastructure (such as the underground power station, power waterways, access tunnels, chambers and shafts), temporary construction infrastructure (such as construction adits, construction compounds and accommodation), management and storage of excavated rock material and establishing supporting infrastructure (such as road upgrades and extensions, water and sewage treatment infrastructure, and the provision of construction power). Snowy 2.0 Main Works also includes the operation of Snowy 2.0.

This stage of the Snowy 2.0 project covers the major construction elements, including permanent infrastructure (such as the underground power station, power waterways, access tunnels, chambers and shafts), temporary construction infrastructure (such as construction adits, construction compounds and accommodation), management and storage of excavated rock material and establishing supporting infrastructure (such as road upgrades and extensions, water and sewage treatment infrastructure, and the provision of construction power). Snowy 2.0 Main Works also include the operation of Snowy 2.0.

Snowy 2.0 Main Works are shown in **Figure 1-1** and **Figure 1-2**. If approved, the Snowy 2.0 Main Works would commence before completion of Exploratory Works.



Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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Regional setting

Snowy 2.0
Reservoir assessment overview
Main Works
Figure 1.1

The Snowy 2.0 Main Works do not include the transmission works proposed by TransGrid (TransGrid 2018) that provide connection between the cableyard and the NEM. These transmission works will provide the ability for Snowy 2.0 (and other generators) to efficiently and reliably transmit additional renewable energy to major load centres during periods of peak demand, as well as enable a supply of renewable energy to pump water from Talbingo Reservoir to Tantangara Reservoir during periods of low demand. While the upgrade works to the wider transmission network and connection between the cableyard and the network form part of the CSSI declaration for Snowy 2.0 and Transmission Project, they do not form part of this application and will be subject to separate application and approval processes, managed by TransGrid. This project is known as the HumeLink and is part of AEMO's Integrated System Plan.

With respect to the provisions of the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), on 30 October 2018 Snowy Hydro referred the Snowy 2.0 Main Works to the Commonwealth Department of the Environment and Energy (DoEE) and, on a precautionary basis, nominated that Snowy 2.0 Main Works has potential to have a significant impact on MNES and the environment generally.

On 5 December 2018, Snowy 2.0 Main Works were deemed a controlled action by the Assistant Secretary of the DoEE. It was also determined that potential impacts of the project will be assessed by accredited assessment under Part 5, Division 5.2 of the EP&A Act. This accredited process will enable the NSW Department of Planning, Industry and Environment (DPIE) to manage the assessment of Snowy 2.0 Main Works, including the issuing of the assessment requirements for the EIS. Once the assessment has been completed, the Commonwealth Minister for the Environment will make a determination under the EPBC Act.

1.2 Project Location

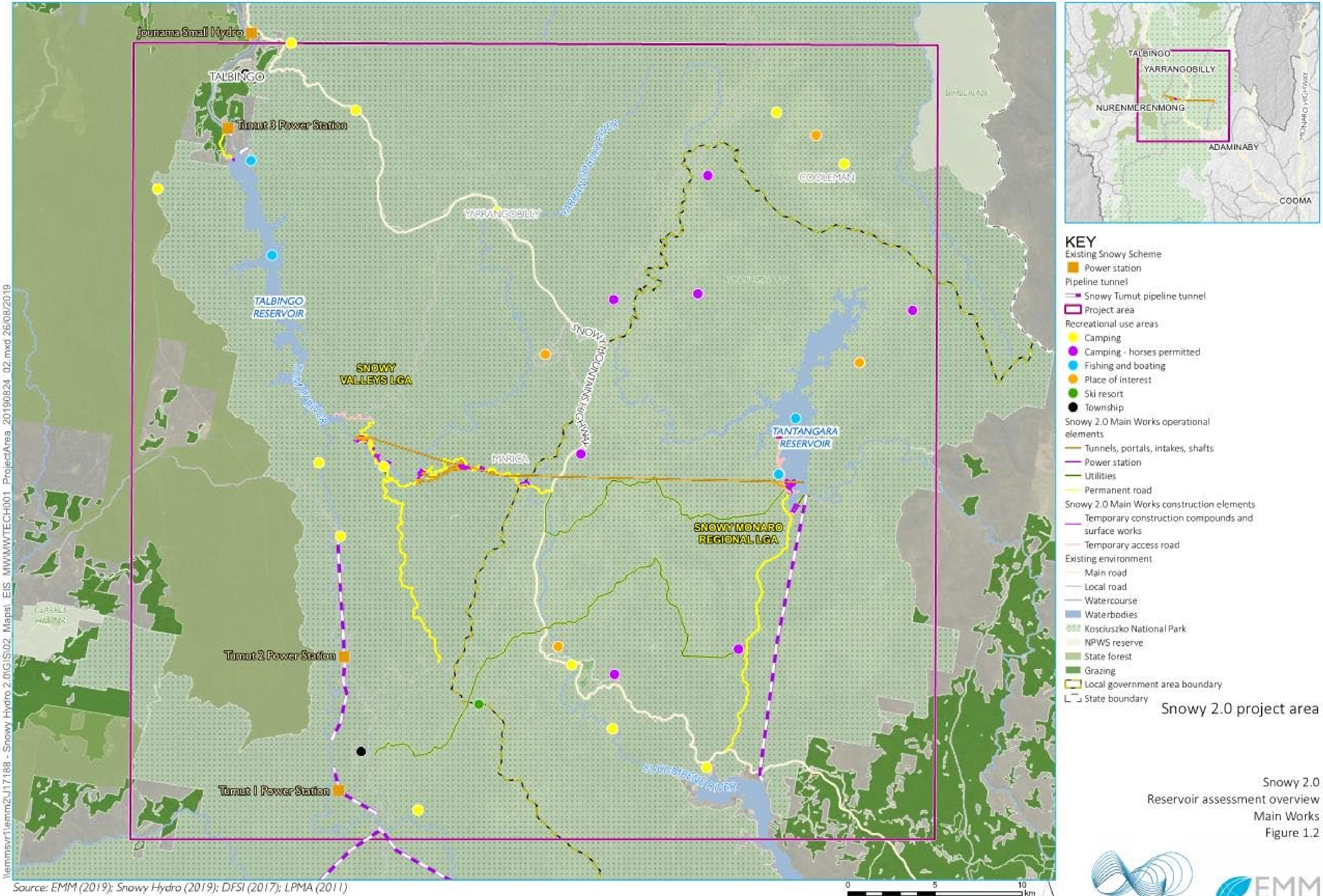
Snowy 2.0 Main Works are within the Australian Alps, in southern NSW, about mid-way between Canberra and Albury. Snowy 2.0 Main Works is within both the Snowy Valleys and Snowy Monaro Regional local government areas (LGA).

The nearest large towns to Snowy 2.0 Main Works are Cooma and Tumut. Cooma is located about 50 kilometres (km) south east of the project area (or 70 km by road from Providence Portal at the southern edge of the project area), and Tumut is located about 35 km north west of the project areas (or 45 km by road from Tumut 3 (T3) power station at the northern edge of the project area). Other townships near the project area include Talbingo, Cabramurra, Adaminaby and Tumbarumba. Talbingo and Cabramurra were built for the original Snowy Scheme workers and their families, while Adaminaby was relocated in 1957 to make way for the establishment of Lake Eucumbene.

The location of the Snowy 2.0 Main Works with respect to the region is shown in **Figure 1-1**.

The pumped hydro-electric scheme elements of Snowy 2.0 Main Works are mostly underground between the southern ends of Talbingo and Tantangara reservoirs, a straight-line distance of 27 km. Surface works will also occur at locations on and between the two reservoirs. Key locations for surface works include:

- **Tantangara Reservoir** – at a full supply level (FSL) of about 1 229 metres (m) to Australian Height Datum (AHD), Tantangara Reservoir will be the upper reservoir for Snowy 2.0 and include the headrace tunnel and intake structure. The site will also be used for a temporary construction compound, accommodation camp and other temporary ancillary activities.
- **Marica** – this site will be used primarily for construction including construction of vertical shafts to the underground power station (ventilation shaft) and headrace tunnel (surge shaft), and a temporary accommodation camp.



Snowy 2.0 project area

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

Snowy 2.0
Reservoir assessment overview
Main Works
Figure 1.2

- **Lobs Hole** – the site will be used primarily for construction but will also become the main entrance to the power station during operation. Lobs Hole will provide access to the Exploratory Works tunnel, which will be refitted to become the main access tunnel (MAT), as well as the location of the emergency egress, cable and ventilation tunnel (ECVT), portal, associated services and accommodation camp, and

- **Talbingo Reservoir** – at a FSL of about 546 m AHD, Talbingo Reservoir will be the lower reservoir for Snowy 2.0 and will include the tailrace tunnel and water intake structure. The site will also be used for temporary construction compounds and other temporary ancillary activities.

Works will also be required within the two reservoirs for the placement of excavated rock and surplus cut material. Supporting infrastructure will include establishing or upgrading access tracks and roads and electricity connections to construction sites.

Most of the proposed pumped hydro-electric and temporary construction elements and most of the supporting infrastructure for Snowy 2.0 Main Works are located within the boundaries of KNP. Some of the supporting infrastructure and construction sites and activities (including sections of road upgrade, power and communications infrastructure) extends beyond the national park boundaries. These sections of infrastructure are primarily located to the east and south of Tantangara Reservoir. One temporary construction site is located beyond the national park along the Snowy Mountains Highway about 3 km east of Providence Portal (referred to as Rock Forest).

The project is described in more detail in **Section 2**.

1.2.1 Project Area

The project area for Snowy 2.0 Main Works has been identified and includes all the elements of the project, including all construction and operational elements. The project area is shown on **Figure 1-2**. Key features of the project area are:

- the water bodies of Tantangara and Talbingo Reservoirs, covering areas of 19.4 square kilometres (km^2) and 21.2 km^2 respectively. The reservoirs provide the water to be utilised in Snowy 2.0

- major watercourses including the Yarrangobilly, Eucumbene and Murrumbidgee rivers and some of their tributaries, and

- KNP, which covers the majority of the project area. Within the project area, KNP is characterised by two key zones: upper slopes and inverted treelines in the west of the project area (referred to as the ‘ravine’) and associated subalpine treeless flats and valleys in the east of the project area (referred to as the ‘plateau’); and farm land southeast of KNP at Rock Forest.

The project area is interspersed with built infrastructure including recreational sites and facilities, main roads as well as unsealed access tracks, hiking trails, farm land, electricity infrastructure, and infrastructure associated with the Snowy Scheme.

1.2.2 Excavated Rock Placement Study Area

The study area for the ERP studies has focussed on both reservoirs in their entirety. Hydrodynamic models have been developed for both reservoirs.

1.3 Proponent

Snowy Hydro Limited is the proponent for the Snowy 2.0 Main Works. Snowy Hydro is an integrated energy business – generating energy, providing price risk management products for wholesale customers and delivering energy to homes and businesses. Snowy Hydro is the fourth largest energy retailer in the NEM and is Australia's leading provider of peak, renewable energy.

1.4 Purpose of Report

This **Excavated Rock Placement Assessment Summary** supports the EIS for the Snowy 2.0 Main Works. It documents all of the work and studies undertaken to date by, or on behalf of Royal HaskoningDHV (RHDHV), and provides, where relevant, the key findings and recommendations from previously completed reports and studies. This is a summary document and, as such, the reader is referred to the reports that this document summarises for the full detail and content.

1.4.1 Assessment Guidelines and Requirements

The ERP assessment has been prepared in accordance with the Secretary's Environmental Assessment Requirements (SEARs) for Snowy 2.0 Main Works, issued on 31 July 2019, as well as relevant government assessment requirements, guidelines and policies, and in consultation with the relevant government agencies. The SEARs must be addressed in the EIS.

Table 1-1 lists the matters relevant to the ERP assessment.

Table 1-1 Relevant matters raised in SEARs

Requirement
• an assessment of the impacts of the project on the quantity and quality of the region's surface and ground water resources, including Yarrangobilly River, Wallaces Creek, and the Tantangara and Talbingo Reservoirs;
• a strategy to manage the emplacement of excavated rock in the Tantangara and Talbingo Reservoirs and enhance any new landforms created;

To inform preparation of the SEARs, the DPIE invited relevant government agencies to advise on matters to be addressed in the EIS. These matters were taken into account by the Secretary for DPIE when preparing the SEARs

1.5 Related Projects

There are three other projects related to Snowy 2.0 Main Works, they are:

- Snowy 2.0 Exploratory Works (SSI-9208) – a Snowy Hydro project with Minister's approval
- Snowy 2.0 Transmission Connect Project (SSI-9717) – a project proposed by TransGrid, and
- Snowy 2.0 – Segment Factory (SSI-10034) – a project proposed by Snowy Hydro.

While these projects form part of the CSSI declaration for Snowy 2.0 and Transmission Project, they do not form part of Snowy Hydro's application for Snowy 2.0 Main Works. These related projects are subject to separate application and approval processes. However, cumulative impacts have been considered in this report where relevant.

1.6 Relevant Reports

This summary report has been prepared with direct reference to a number of technical reports that were prepared as part of the Snowy 2.0 ERP. These reports are as follows:

- P1 Comprehensive Geochemistry Examination (CSIRO, 2018) (**Annexure A** of this report)
- P2 Environmental Risk Categorisation of Rock Materials (CSIRO, 2019) (**Annexure B**)
- P3 Environmental Characterisations of Excavated Rock Interactions with and Potential Impacts on Reservoir Waters and Sediments (CSIRO, 2019) (**Annexure C**)
- P4 Ecotoxicology Assessment of Excavated Rock Leachates in Water and Excavated Rock-Sediment Mixtures (CSIRO, 2019) (**Annexure D**)
- Dissolved Aluminium Assessment for Talbingo Reservoir (CSIRO, 2019) (**Annexure E**)
- Vibrocore Investigation Talbingo Reservoir (RHDHV, 2018) (**EIS Appendix J Annexure A**)
- Sediment Sampling Investigation Operational Scenario Assessment Talbingo and Tantangara Reservoirs (RHDHV, 2019) (**EIS Appendix J Annexure A**)
- Settlement Characteristics of Fine Crushed Rock – Laboratory Assessment Factual Report (RHDHV, 2019) (**Annexure F**)
- Snowy 2.0 Reservoir Modelling – Construction (RHDHV, 2019) (**Annexure G**)
- Snowy 2.0 Reservoir Modelling – Operations (RHDHV, 2019) (**Annexure H**)
- Navigation Impact Assessment of the Talbingo and Tantangara Reservoirs (RHDHV, 2019) **EIS Appendix W**)

1.7 Structure of Report

This report assumes the reader has an understanding of the Snowy 2.0 proposal and associated civil works, and is structured as follows:

- **Section 2** provides an overview of the existing Snowy Scheme and the proposed Snowy 2.0 works.
- **Section 3** provides information on the studies undertaken by the Commonwealth Scientific and Industrial Research Organisation (CSIRO).
- **Section 4** provides details of the primary data collection exercises that were undertaken in the field and in the laboratory.
- **Section 5** provides an overview of the modelling that has been undertaken and the findings with regard placement activities.
- **Section 6** provides details of the modelling undertaken for the operational phase of Snowy 2.0. This also includes the Sediment Disturbance Study that was undertaken.

2 Description of the Project

This section provides a summary of the Snowy 2.0 Main Works project. It outlines the functional infrastructure required to operate Snowy 2.0, as well as the key construction elements and activities required to build it. A more comprehensive detailed description of the project is provided in Chapter 2 (Project description) of the EIS, which has been relied upon for the basis of this technical assessment.

2.1 Overview of Snowy 2.0

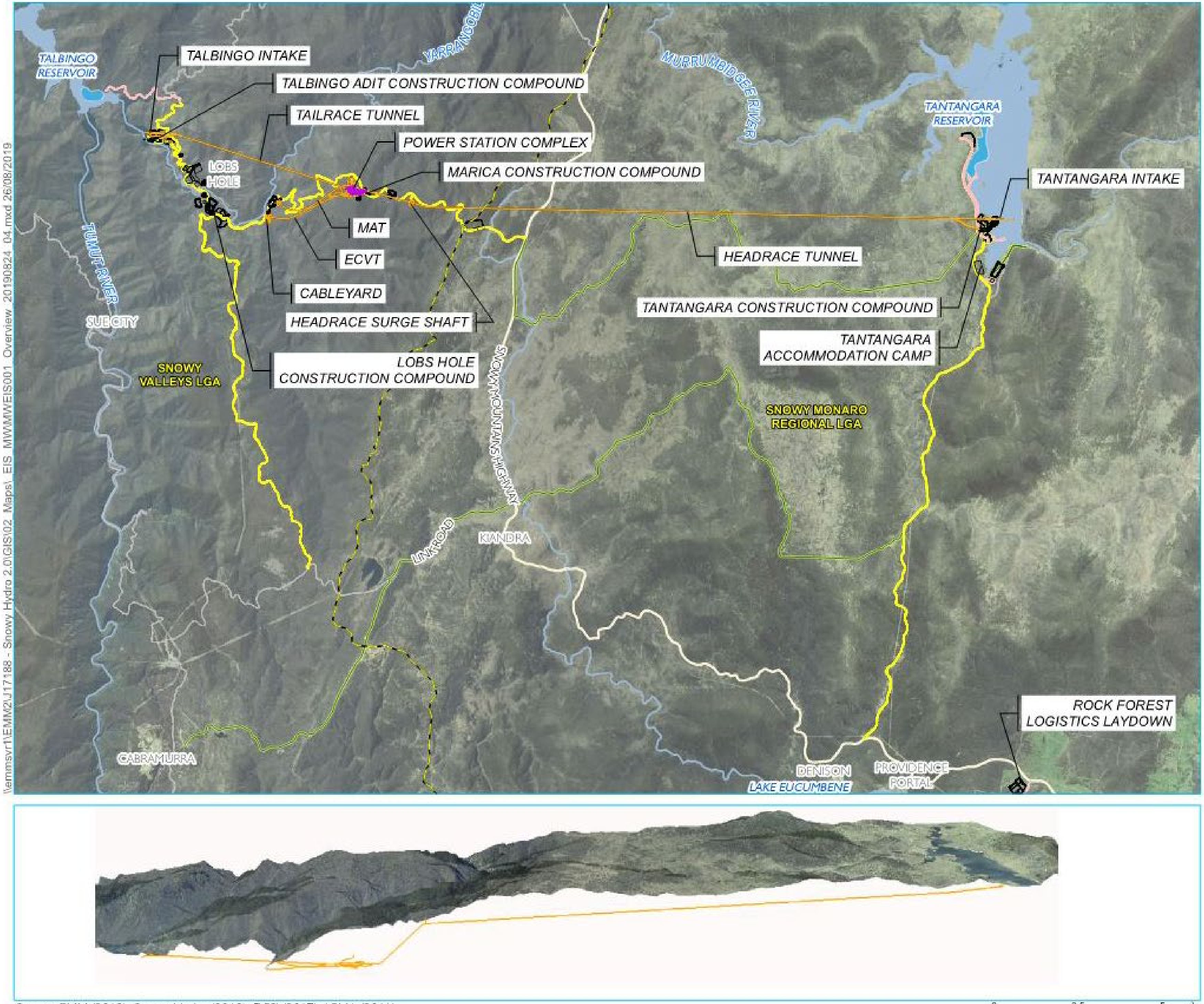
Snowy 2.0 will link the existing Tantangara and Talbingo Reservoirs within the present Snowy Scheme through a series of new underground tunnels and a hydro-electric power station will be build underground.

An overview of Snowy 2.0 is shown on **Figure 2-1**, and the key project elements of Snowy 2.0 are summarised in **Table 2-1**.

Table 2-1 Overview of Snowy 2.0 Main Works

Project Element	Summary of the Project
Project area	The Project area is the broader region within which Snowy 2.0 will be built and operated, and the extent within which direct impacts from the Project are anticipated.
Permanent infrastructure	Snowy 2.0 infrastructure to be built and operated for the life of the assets include: ● Intake and gate structures and surface buildings at Tantangara Reservoir and Talbingo Reservoir ● power waterway tunnels primarily comprising the headrace tunnel, headrace surge shaft, inclined pressure tunnel, pressure pipelines, tailrace surge tank and tailrace tunnels ● underground power station complex comprising the machine hall, transformer hall, ventilation shaft and minor connecting tunnels ● access tunnels (and tunnel portals) to the underground power station comprising the MAT and ECVT. ● a portal building and helipad will be established at the MAT portal ● communication, water and power supply including the continued use of the Lobs Hole substation ● cable yard located adjacent to the ECVT portal to facilitate the connection of Snowy 2.0 to the NEM ● access roads and permanent bridge structures needed for the operation and maintenance of Snowy 2.0 infrastructure, and ● fish control structures on Tantangara Creek and near Tantangara Reservoir wall.
Temporary infrastructure	Temporary infrastructure required during the construction phase of the Project are: ● construction compounds, laydown, ancillary facilities and helipads ● accommodation camps for construction workforce ● construction portals and adits to facilitate tunnelling activities ● barge launch ramps ● water and wastewater management infrastructure (treatment plants and pipelines) ● communication and power supply ● temporary access roads.

Project Element	Summary of the Project
Disturbance area	The disturbance area is the extent of area required for construction works required to build Snowy 2.0. The maximum temporary disturbance area is about 1 680 hectares. Parts of the disturbance area will be rehabilitated, including for recreational use, retained as upgraded roads, or retained for operation (permanent).
Operational footprint	The operational footprint is the area at the surface required for permanent infrastructure to operate Snowy 2.0. The maximum operational footprint is about 99 hectares. The final footprint will be determined as part of detailed design and in consultation with the National Parks and Wildlife Service (NPWS).
Tunnelling and excavation method	The primary tunnelling method for the power waterway and access tunnels is by tunnel boring machine (TBM), with tunnel portals and adits using drill and blast methods. Excavation for other underground caverns, chambers and shafts will be via combinations of drill and blast, blink sink, and/or raise bore techniques.
Excavated rock management	Excavated rock will be generated as a result of tunnelling activities and earthworks. The material produced through these activities will be stockpiled and either reused by the contractor (or NPWS), placed permanently within Tantangara or Talbingo reservoirs, used in final land forming and rehabilitation of construction pads in Lobs Hole, or transported offsite.
Construction water and wastewater management	Water supply for construction will be from the two existing reservoirs (Talbingo and Tantangara) and reticulated via buried pipelines (along access roads). Raw water will be treated as necessary wherever potable water is required (for example at accommodation camps) Wastewater (comprising process water, wastewater and stormwater) will be treated before discharge to the two existing reservoirs (Talbingo and Tantangara): • Treated process water will be reused onsite where possible to reduce the amount of discharge to reservoirs, however excess treated water will be discharged to the reservoirs • Collected sewage will be treated at sewage treatment plants to meet the specified discharge limits before discharge and/or disposal, and • Stormwater will be captured and reused as much as possible.
Rehabilitation	Rehabilitation of areas disturbed during construction including reshaping to natural appearing landforms or returning to pre-disturbance condition, as agreed with NPWS and determined by the rehabilitation strategy. This includes construction areas at Lobs Hole which comprise surplus cut materials that are required for the construction. Areas to be used by Snowy Hydro in the long-term may be re-shaped and rehabilitated to maintain access and operational capabilities (e.g. intakes and portal entrances)
Construction workforce	The construction workforce is expected to peak at around 2 000 personnel
Operational life	The operational life of the project is estimated to be 100 years
Operational workforce	The operational workforce is expected to be 8-16 staff, with fluctuations of additional workforce required during major maintenance activities
Hours of operation	onstruction of Snowy 2.0 will be 24/7 and 365 days per year Operation of Snowy 2.0 will be 24/7 and 365 days per year
Capital investment	Estimated $4.6 billion



KEY

Existing environment
- Main road
- Local road
- Watercourse
- Waterbodies
- Local government area boundary

Snowy 2.0 Main Works operational elements
- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements
- Temporary construction compounds and surface works
- Temporary access road
- Indicative rock emplacement area

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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Snowy 2.0 project elements

Snowy 2.0
Reservoir assessment overview
Main Works
Figure 2.1

2.2 Construction of Snowy 2.0

A number of construction activities will be carried out concurrently, and across a number of different sites. Specific details on these activities as well as an indicative schedule of construction activities is provided in Chapter 2 (Project description) of the EIS. This section summarises the key construction elements of the project. **Table 2-2** provides an overview of the construction elements, their purpose and location within the Project area.

Table 2-2 Snowy 2.0 Construction Elements

Construction Element	Purpose	Location
Construction sites	Due to the remoteness of Snowy 2.0, construction sites are generally needed to: • Provide ancillary facilities such as concrete batching plants, mixing plants and on-site manufacturing; • Store machinery, equipment and materials to be used in construction; • Provide access to underground construction sites; and • Provide onsite accommodation for the construction workforce.	Each construction site needed for Snowy 2.0 is shown on **Figure 2-2** to **Figure 2-6**.
Substations and power connection	One substation is required to provide permanent power to Snowy 2.0, at Lobs Hole. This substation will be built as part of Exploratory Works with a capacity of 80 mega volt amp (MVA). It will continue to be used for Main Works, however requires the establishment of further power supply cables to provide power to the work sites and TBM at Tantangara, as well as Talbingo, in particular to power the TBMs via the MAT, ECVT, Talbingo and Tantangara portals.	The supporting high voltage cable route mostly follows access roads to each of the work sites, using a combination of aerial and buried arrangements.
Communications system	Communications infrastructure will connect infrastructure at Tantangara and Talbingo reservoirs to the existing communications system at the T3 power station (via the submarine communications cable in Talbingo Reservoir established during Exploratory Works) and to Snowy Hydro's existing communications infrastructure at Cabramurra.	The cable will be trenched and buried in conduits within access roads. Crossing of watercourses and other environmentally sensitive areas will be carried out in a manner that minimises environmental impacts where possible, such as bridging or underboring.
Water and waste water servicing	Drinking water will be provided via water treatment plants located at accommodation camps. Water for treatment will be sourced from the nearest reservoir. There are three main wastewater streams that require some form of treatment before discharging to the environment, including: • Tunnel seepage and construction wastewater (process water)	Utility pipelines generally follow access roads. Water treatment plants (drinking water) will be needed for the accommodation camps and will be located in proximity.

Construction Element	Purpose	Location
	- Domestic sewer (wastewater), and - Construction site stormwater (stormwater).	Waste water treatment plants will similarly be located near accommodation camps. Process water treatment plants will be at construction compounds and adits where needed to manage tunnel seepage and water during construction.
Temporary and permanent access roads	Access road works are required to: - provide for the transport of excavated material between the tunnel portals and the excavated rock emplacement areas - accommodate the transport of oversized loads as required and - facilitate the safe movement of plant, equipment, materials and construction workers into and out of construction sites. The access road upgrades and establishment requirements are shown on **Figure 2-2** to **Figure 2-6**. These roads will be used throughout construction including use of deliveries to and from site and the external road network. Some additional temporary roads will also be required within the footprint to reach excavation fronts such as various elevations of the intakes excavation or higher benches along the permanent roads.	The access road upgrades and establishment requirements are shown across the project area. Main access and haulage to site will be via Snowy Mountains Highway, Link Road and Lobs Hole Ravine Road (for access to Lobs Hole), and via Snowy Mountains Highway and Tantangara Road (for access to Tantangara Reservoir) (see **Figure 2-1**).
Excavated rock management	Approximately 9 million m^3 (unbulked) of excavated material will be generated by construction and require management. The strategy for management of excavated rock will aim to maximise beneficial reuse of materials for construction activities. Beneficial re-use of excavated material may include use for road base, construction pad establishment, selected fill and tunnel backfill and rock armour as part of site establishment for construction. Excess excavated material that cannot be re-used during construction will be disposed of within Talbingo and Tantangara reservoirs, used in permanent rehabilitation of construction pads to be left in situ in Lobs Hole, or transported for on-land disposal if required.	Placement areas are shown on **Figure 2-2** and **Figure 2-6**.
Barge launch facilities	Barge launch facilities on Talbingo Reservoir will have already been established during Exploratory Works for the placement of the submarine communications cable, and will continued to be used for Main Works for construction works associated with the Talbingo intake structure. The	Barge launch sites are shown on **Figure 2-2** and **Figure 2-6**.

Construction Element	Purpose	Location
	Main Works will require the establishment of barge launch facilities on Tantangara Reservoir to enable these similar works (removal of the intake plug).	
Construction workforce	The construction workforce will be accommodated entirely on site, typically with a FIFO/DIDO roster. Private vehicles will generally not be permitted and the workforce bused to and from site.	Access to site will be via Snowy Mountains Highway.

The key areas of construction are shown on **Figure 2-2** to **Figure 2-6** and can be described across the following locations:

- **Talbingo Reservoir** – Talbingo Reservoir provides the lower reservoir for the pumped hydro-electric project and will include the tailrace tunnel and water intake structure. The site will also be used for temporary construction compounds and other temporary ancillary activities.
- **Lobs Hole** – this site will be used primarily for construction (including construction of the MAT and ECVT portals and tunnels to the underground power station and the headrace tunnel (and headrace tunnel surge shaft), underground tailrace surge shaft and a temporary accommodation camp).
- **Marica** – the site will be used primarily for construction to excavate the ventilation shaft to the underground power station as well as for the excavation and construction of the headrace surge shaft.
- **Plateau** – the land area between Snowy Mountains Highway and Tantangara Reservoir is referred to as the Plateau. The Plateau will be used to access and construct a utility corridor, and construct a fish weir on Tantangara Creek.
- **Tantangara Reservoir** – Tantangara Reservoir will be the upper reservoir for the pumped hydro project and include the headrace tunnel and intake structure. The site will also be used for a temporary construction compound, accommodation camp and other temporary ancillary activities, and
- **Rock Forest** – a site to be used temporarily for logistics and staging during construction. It is located beyond the KNP along the Snowy Mountains Highway about 3 km east of Providence Portal.

During the construction phase, all work sites will be restricted access and closed to the public. This includes existing road access to Lobs Hole via Lobs Hole Ravine Road. Restrictions to water-based access and activities will also be implemented for public safety and to allow safe construction of the intakes within the reservoirs. Access to Tantangara Reservoir via Tantangara Road will be strictly subject to compliance with the safety requirements established by the contractor.

A key construction element for the project is the excavation and tunnelling for underground infrastructure including the power station, power waterway (headrace and tailrace tunnels) and associated shafts. The primary methods of excavation for each of the key Snowy 2.0 elements are shown in **Figure 2-8** and include:

- **Open cut** – this involves the removal of soil or rock from a site to form an open face, hole or cavity using tools, machinery or explosives. It involves excavating down to below ground level to the desired depth. Open cut methods will be used for the intake structures and access roads (if required).
- **D&B** – this involves the drilling of holes into a rock face (or ground) and inserting explosives to break up and excavate rock. Drill and blast methods will generally be used to excavate tunnel adits and to excavate the penstock, chambers and shafts and caverns for the underground power station.

- **Raise boring** – a process used to create a circular hole between an underground cavern or tunnel and the surface. A pilot hole is drilled down to the underground cavern. Once it has broken through, a reaming head is used to create the required tunnel size by raising the head back up to the surface.
- **Blind sinking** – Initial excavation occurs from the surface and bores down. The shaft 'sinks' as it is lowered into the ground as excavation continues to progress down to the desired depth, and
- **Tunnel boring** – Tunnel boring machines (TBM) are used to excavate tunnels with a circular cross section. TBMs will be the primary method used to excavate underground waterway tunnels (headrace, inclined pressure shaft, tailrace).

2.3 Operation of Snowy 2.0

2.3.1 Scheme Operation and Reservoir Management

Snowy 2.0 would operate within the northern Snowy-Tumut Development, connecting the existing Tantangara and Talbingo Reservoirs.

Tantangara Reservoir currently has the following operational functions within the Snowy Scheme:

- collects releases from the Murrumbidgee River and the Goodradigbee River Aqueduct
- provides a means for storage and diversion of water to Lake Eucumbene via the Murrumbidgee-Eucumbene Tunnel, and
- provides environmental releases through the Tantangara Reservoir river outlet gates to the Murrumbidgee River.

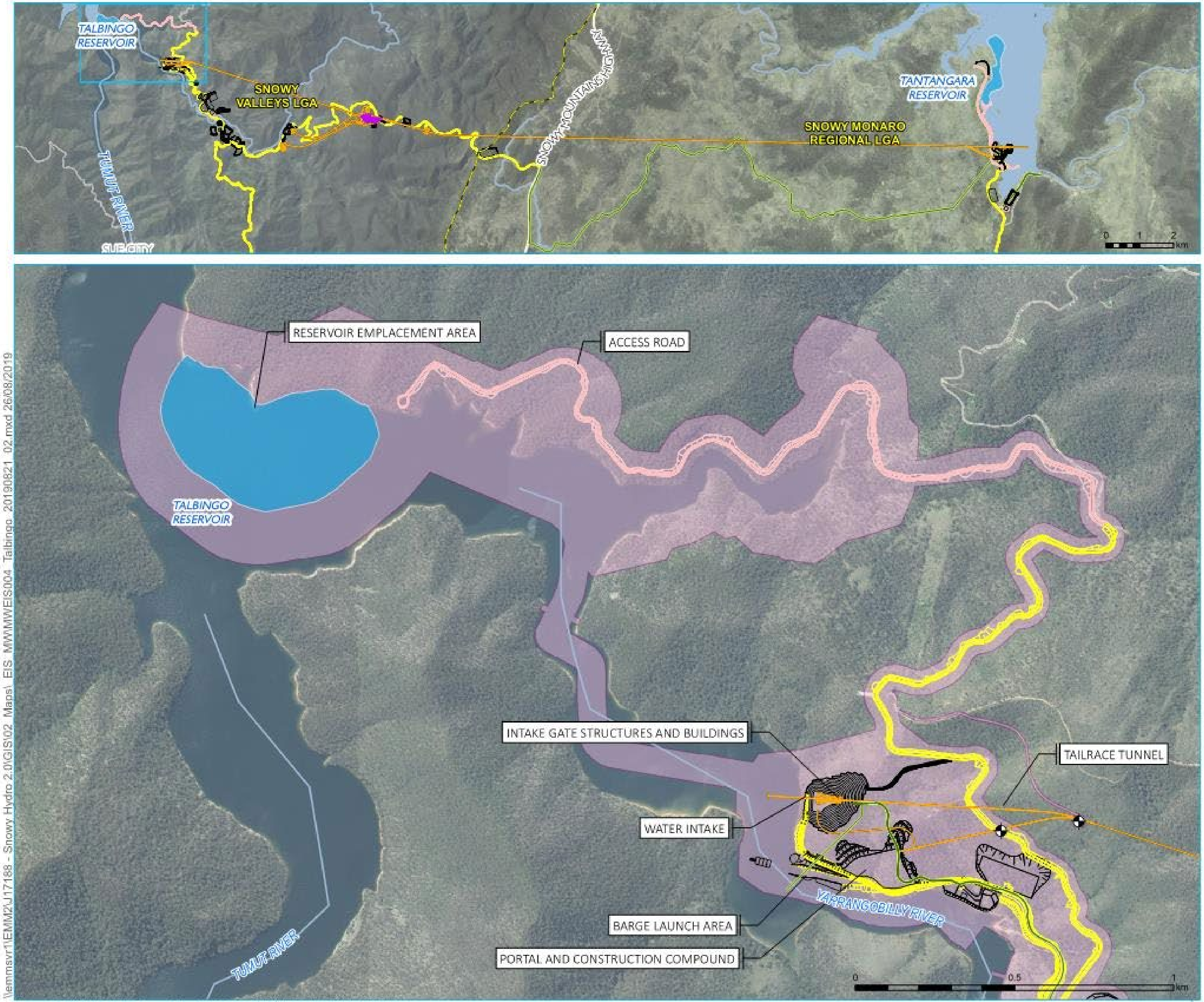
Talbingo Reservoir currently has the following operational functions:

- collects releases from Tumut 2 (T2) power station
- collects releases from the Yarrangobilly and Tumut rivers
- acts as head storage for water pumped up from Jounama Pondage, and
- acts as head storage for generation at T3 power station.

Due to its historic relationship to both the upstream T2 Power Station and downstream T3 Power Station, Talbingo Reservoir has had more operational functions than Tantangara Reservoir in the current Snowy Scheme.

Following the commencement of the operation of Snowy 2.0, both Tantangara and Talbingo reservoirs will have increased operational functions. Tantangara Reservoir will have the additional operational functions of acting as a head storage for generation from the Snowy 2.0 power station and also acting as a storage for water pumped up from Talbingo Reservoir. Talbingo Reservoir will have the additional operational function of acting as a tail storage from Snowy 2.0 generation.

As a result of the operation of Snowy 2.0, the water level in Tantangara Reservoir will be more variable than historically. Notwithstanding this, operations will not affect release obligations under the Snowy Water Licence nor will it involve any change to the currently imposed Full Supply Levels (FSL). No additional land will be affected by virtue of the inundation of the reservoirs through Snowy 2.0 operations. Water storages will continue to be held wholly within the footprint of the existing FSLs.



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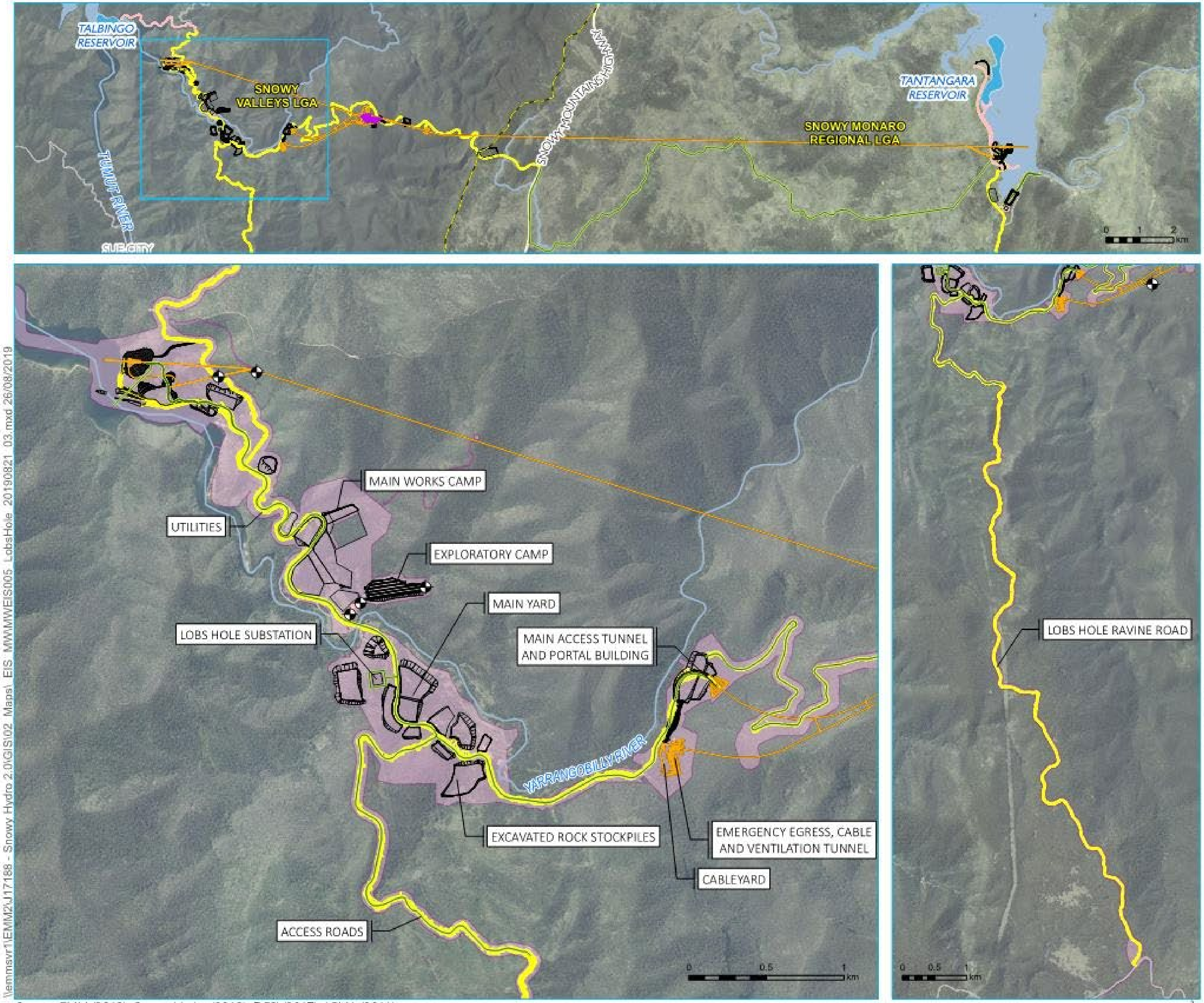
Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during detailed design.

Talbingo Reservoir - project elements, purpose and description

Snowy 2.0
Reservoir assessment overview
Main Works
Figure 2.2

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)



Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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KEY

Existing environment

- Main road
- Local road
- Watercourse
- Waterbodies
- Local government area boundary

Snowy 2.0 Main Works operational elements

- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

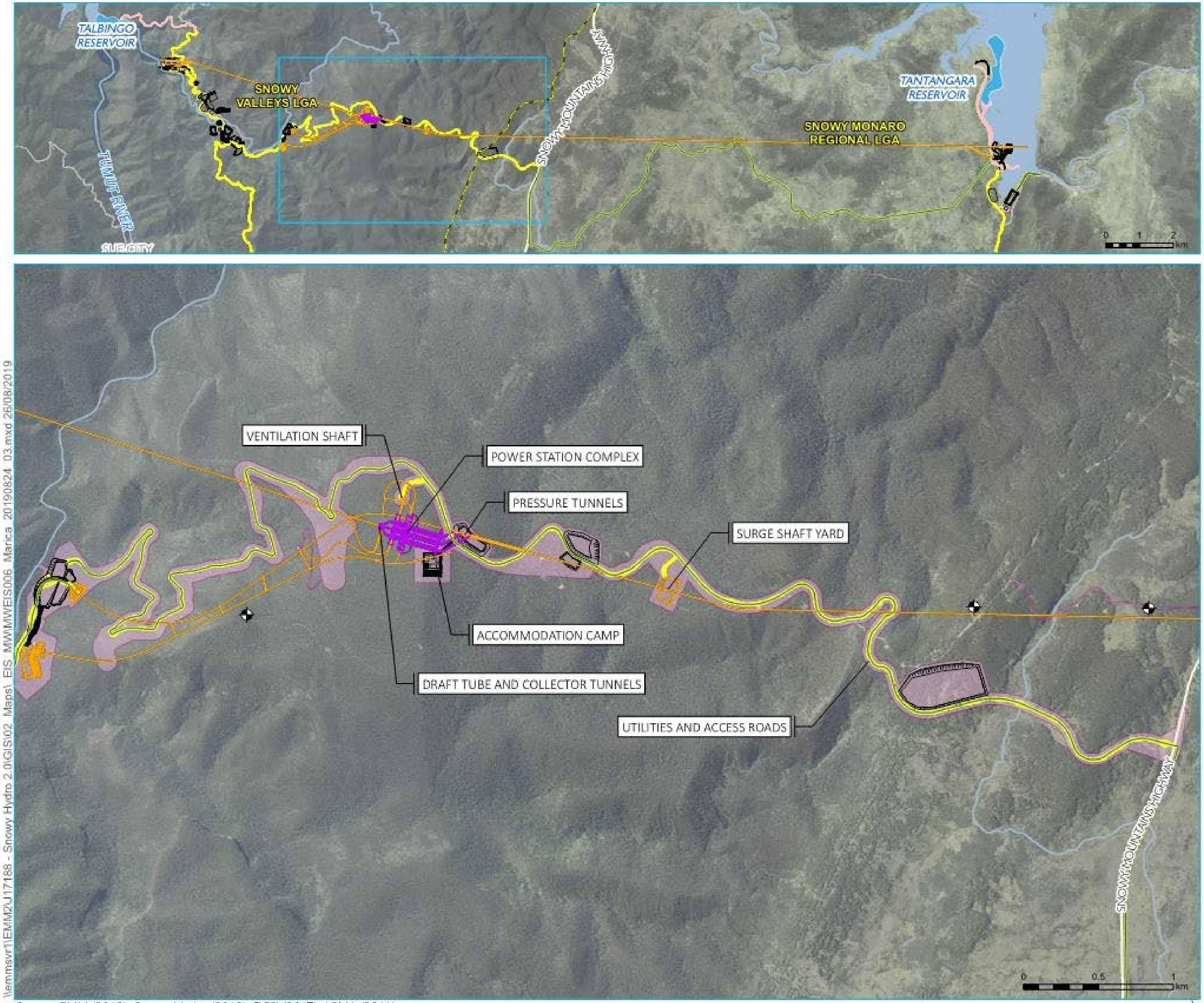
Snowy 2.0 Main Works construction elements

- Temporary construction compounds and surface works
- Temporary access road
- Geotechnical investigation
- Indicative rock emplacement area
- Disturbance area*

Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during detailed design.

Lobs Hole - project elements, purpose and description

Snowy 2.0
Reservoir assessment overview
Main Works
Figure 2.3



Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during detailed design.

Marica - project elements, purpose and description

Snowy 2.0
Reservoir assessment overview
Main Works
Figure 2.4

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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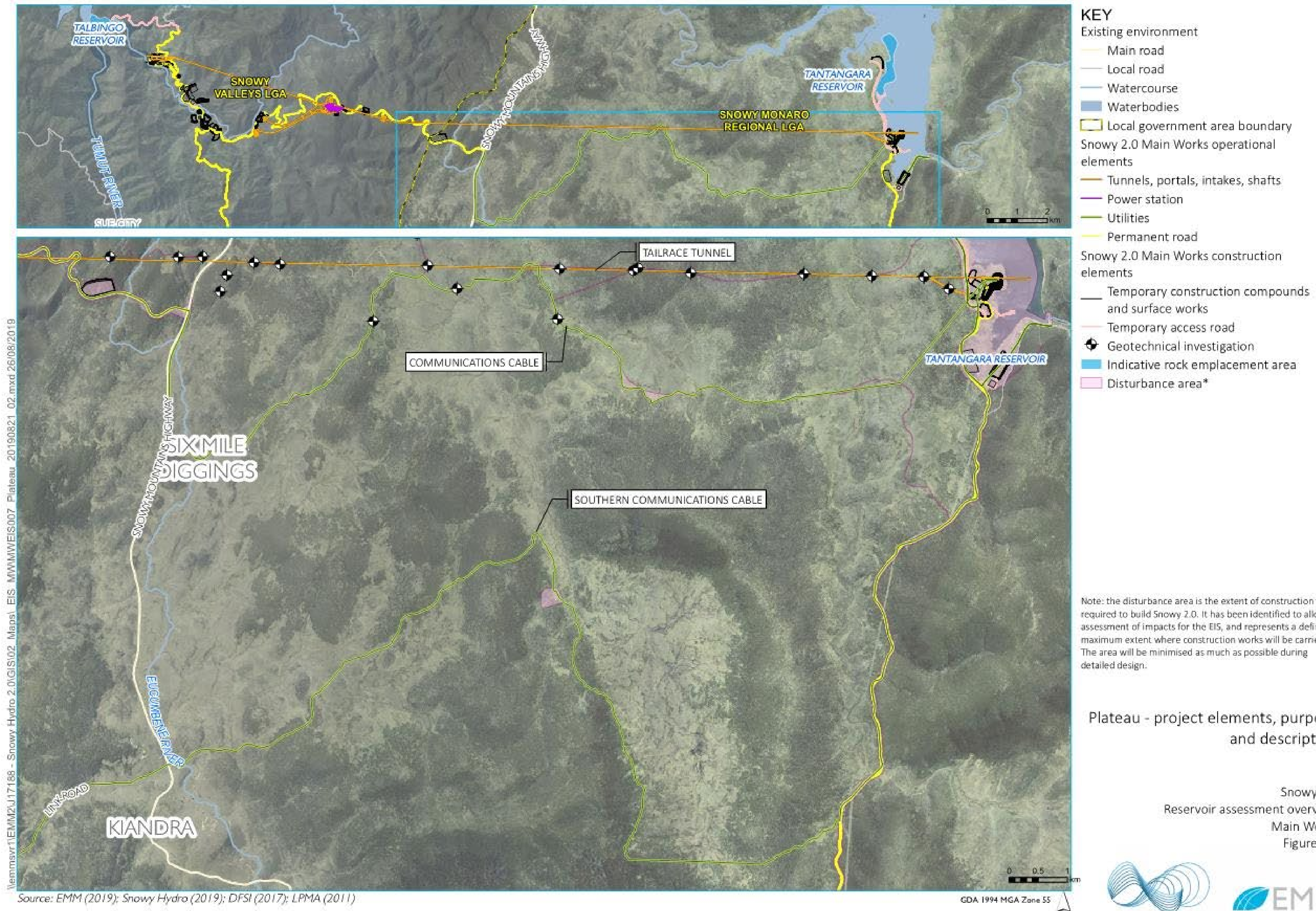
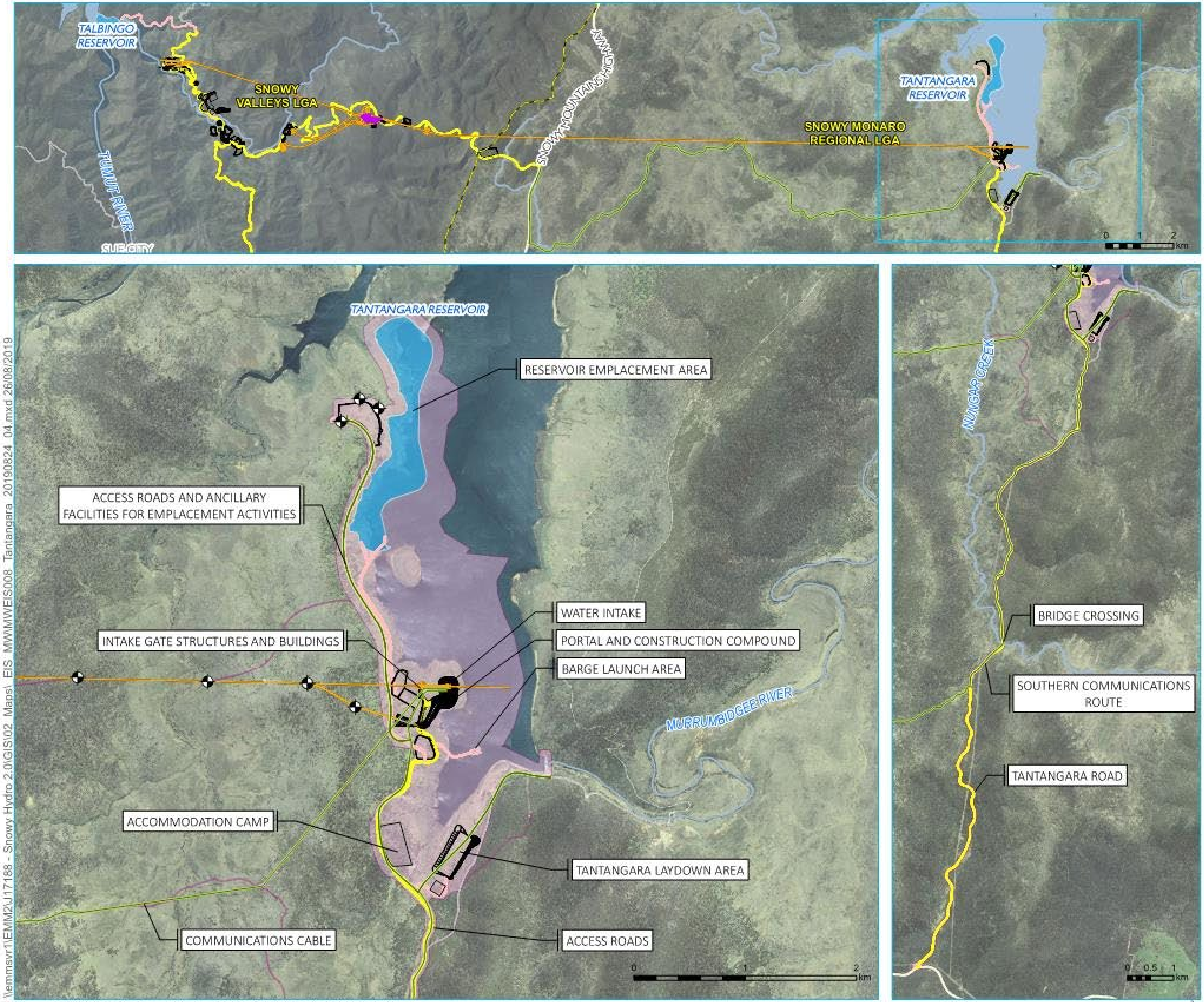


Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during detailed design.

Plateau - project elements, purpose and description

Snowy 2.0
Reservoir assessment overview
Main Works
Figure 2.5



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Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

KEY

Existing environment
- Main road
- Local road
- Watercourse
- Waterbodies
- Local government area boundary

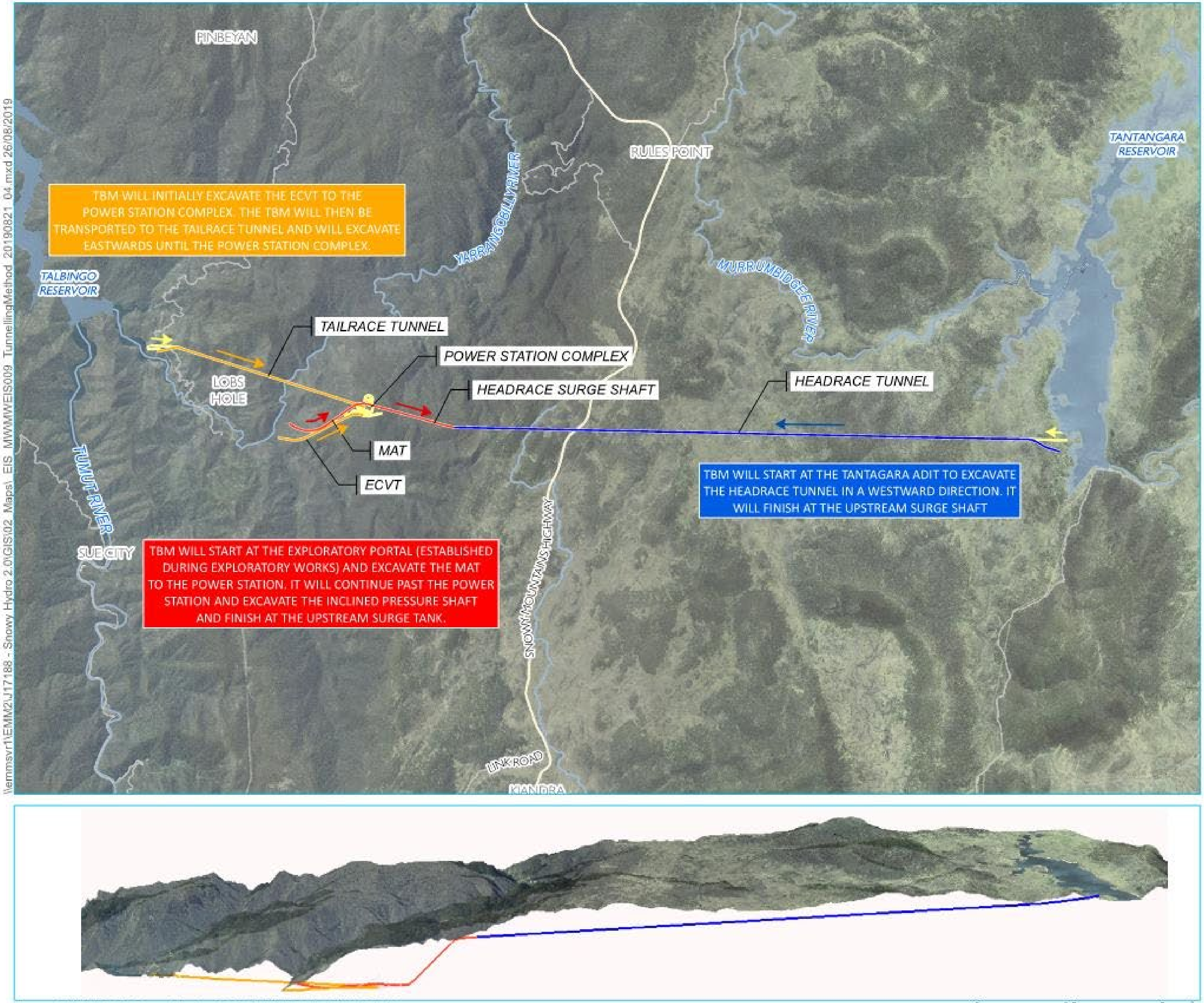
Snowy 2.0 Main Works operational elements
- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements
- Temporary construction compounds and surface works
- Temporary access road
- Geotechnical investigation
- Indicative rock emplacement area
- Disturbance area*

Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during detailed design.

Tantangara Reservoir - project elements, purpose and description

Snowy 2.0
Reservoir assessment overview
Main Works
Figure 2.6



TBM WILL INITIALLY EXCAVATE THE ECVT TO THE POWER STATION COMPLEX. THE TBM WILL THEN BE TRANSPORTED TO THE TAILRACE TUNNEL AND WILL EXCAVATE EASTWARDS UNTIL THE POWER STATION COMPLEX.

TBM WILL START AT THE TANTAGARA ADIT TO EXCAVATE THE HEADRACE TUNNEL IN A WESTWARD DIRECTION. IT WILL FINISH AT THE UPSTREAM SURGE SHAFT

TBM WILL START AT THE EXPLORATORY PORTAL (ESTABLISHED DURING EXPLORATORY WORKS) AND EXCAVATE THE MAT TO THE POWER STATION. IT WILL CONTINUE PAST THE POWER STATION AND EXCAVATE THE INCLINED PRESSURE SHAFT AND FINISH AT THE UPSTREAM SURGE TANK.

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

Primary excavation methods – drill and blast and tunnel boring machine

Snowy 2.0
Reservoir assessment overview
Main Works
Figure 2.8

\\emmsvr1\EMM2\J17188 - Snowy Hydro 2.0\GIS\02_Maps_EIS_MWMWEIS009_TunnellingMethod_20190821_04.mxd 26/08/2019

2.3.2 Permanent Access

Permanent access to Snowy 2.0 infrastructure is required. During operation, a number of service roads established during construction will be used to access surface infrastructure including the power station's ventilation shaft, intake structures and gates, and the headrace tunnel surge shaft. Permanent access tunnels (the MAT and ECVT) will be used to enter and exit the power station.

2.3.3 Maintenance Requirements

Maintenance activities required for Snowy 2.0 will be integrated with the maintenance of the existing Snowy Scheme. Maintenance activities that will be required include:

- maintenance of equipment and systems within the power station complex, intake structures, gates and control buildings
- maintenance of access roads (vegetation clearing, pavement works, snow clearing)
- dewatering of the tailrace and headrace tunnel (estimated at once every 15 to 50 years, or as required), and
- maintenance of electricity infrastructure (cables, cable yard, cable tunnel).

2.3.4 Rehabilitation and Final Land Use

A Rehabilitation Strategy has been prepared for Snowy 2.0 Main Works and provided at **Appendix F** of the EIS.

It is proposed that most areas not retained for permanent infrastructure will be revegetated and rehabilitated. At Lobs Hole, final landform design and planning has been undertaken to identify opportunities for the reuse of excavated material in rehabilitation to provide landforms which complement the surrounding topography in the KNP.

Given that most of Snowy 2.0 Main Works is within the boundaries of the KNP, Snowy Hydro will liaise closely with NPWS to determine the extent of decommissioning of temporary construction facilities and rehabilitation activities to be undertaken following the construction of Snowy 2.0 Main Works.

2.4 Summary of Reservoir Characteristics

A summary of the key features of the two reservoirs modelled in this study are provided in **Table 2-3** and **Table 2-4**.

Table 2-3 Features of Talbingo Reservoir

Talbingo Reservoir	
Total capacity	921 GL
Catchment area	1 093 square kilometres
Surface area	1 936 hectares
Maximum water depth	110 metres

Talbingo Reservoir	
Existing Snowy operations	T2 discharges and T3 pumping/generation
Minimum Operating Level	534.323 m AHD
Full Supply Level	543.223 m AHD
Operation range	8.9 metres – levels currently fluctuate over shorter timescales (days and weeks) in Talbingo Reservoir compared to in Tantangara Reservoir.

Table 2-4 Features of Tantangara Reservoir

Tantangara Reservoir	
Total capacity	254 GL
Catchment area	460 square kilometres
Surface area	2 118 hectares
Maximum water depth	35 metres
Existing Snowy operations	Transfer of water to Eucumbene via Providence Portal and releases (generally environmental flows) to Murrumbidgee River via the Tantangara Dam wall.
Minimum Operating Level	1205.823 m AHD
Full Supply Level	1228.823 m AHD
Operating range	23 metres – the reservoir can experience large variations in water level in response to catchment rainfall, evaporation and releases to Lake Eucumbene.

2.5 Details of Proposed and Alternative ERP Methodologies

2.5.1 Background - Excavated Rock Placement (Construction) Design

The construction methodology (in terms of placement method, grading of excavated rock fractions and rates of placement) has evolved during the course of the project and can be defined by a number of stages including:

a) pre-tender Reference Design
b) initial Tender Design
c) final Tender Design
d) final Design with updated placement rates (i.e. proposed Ravine Bay placement methodology), and
e) an alternative Hybrid Placement option (where only D&B material is placed in Talbingo Reservoir)

Details of the proposed placement methodology are provided in **Section 2.5.2**, while details of the alternative placement methodology are presented in **Section 2.5.3**.

The pre-tender reference design indicated ERP placement would occur subaqueously in both Talbingo and Tantangara Reservoirs. It has since been proposed that with appropriate water level management in Tantangara Reservoir during construction, all placement would occur in the dry.

2.5.2 Contractors Proposed Placement Design

Future Generation (FGJV), a partnership between Australian construction and engineering company, Clough, and global hydropower and tunnelling specialists, Salini Impregilo was awarded the Snowy hydro construction contract on 5th April 2019.

In July 2019, FG provided Snowy Hydro with the excavated rock management strategies for the Talbingo and Tantangara Reservoirs. The documents are provided in Attachment G with key features described below.

The Contractors proposed placement design in Talbingo Reservoir is termed ‘Ravine Bay Placement’.

Talbingo Reservoir

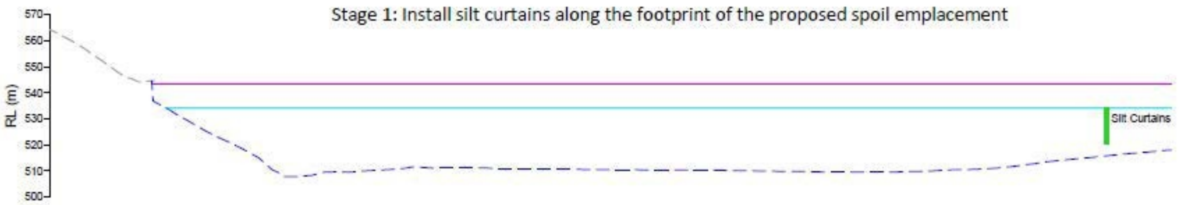
Placement of excavated rock in Talbingo involves pushing excavated rock from the shoreline at Ravine Bay into the reservoir by conventional earth-moving plant, such as dumping trucks and excavators, and installing a rock armour layer formed by larger sized excavated rock (>200mm) along the top edge of the emplacement slope batter.

Placement of excavated rock in Talbingo Reservoir will be carried out in stages when surplus quantity of excavated rocks from construction activities becomes available. The proposed construction staging is presented in **Figure 2-9** and **Figure 2-10**, while the final footprint in presented in **Figure 2-11**.

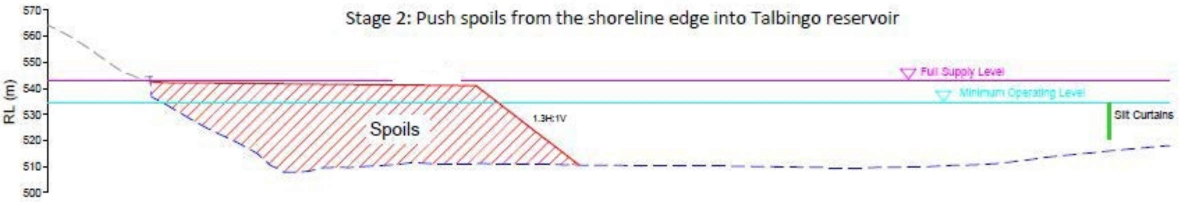
The footprints of emplacement versus time are determined from the quantity of excavated rock available for placement during construction. A summary of the excavated rock volume versus time required for emplacement in Talbingo Reservoir is shown in **Table 2-5** while initial estimates of the volumes above and below 200mm is provided in **Table 2-6**.

Figure 2-9 Talbingo – Excavated Rock Placement Construction Staging

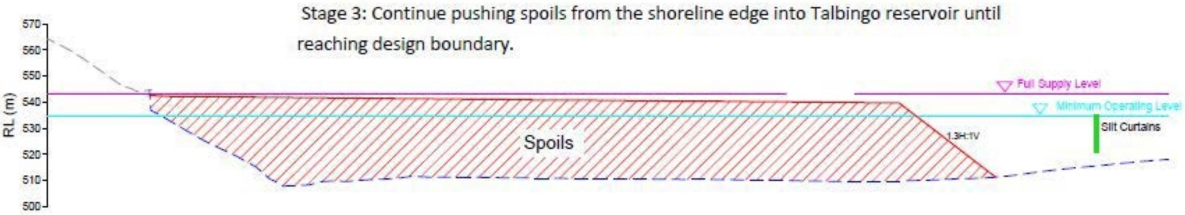
Stage 1: Install silt curtains along the footprint of the proposed spoil emplacement



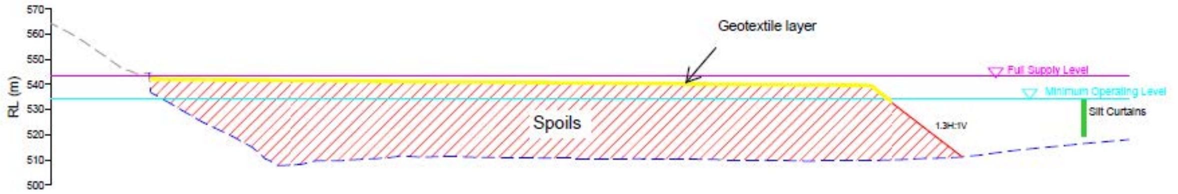
Stage 2: Push spoils from the shoreline edge into Talbingo reservoir



Stage 3: Continue pushing spoils from the shoreline edge into Talbingo reservoir until reaching design boundary.



Stage 4:: Install a geotextile layer on the batter slope of the spoil dump for erosion protection.



Stage 5:Install the rock amour layer (i.e. >200mm spoils) for long term spoil emplacement stability and erosion protection. Barges will be adopted for the installation of the rock amour and spoil forming 2H:1V batter under MOL.

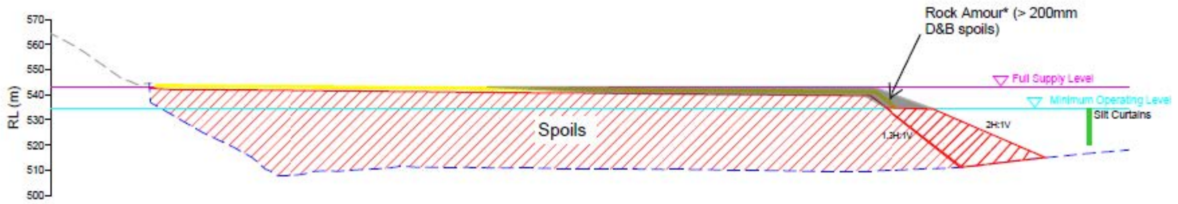


Figure 2-10 Indicative development of Talbingo ERP footprints versus time

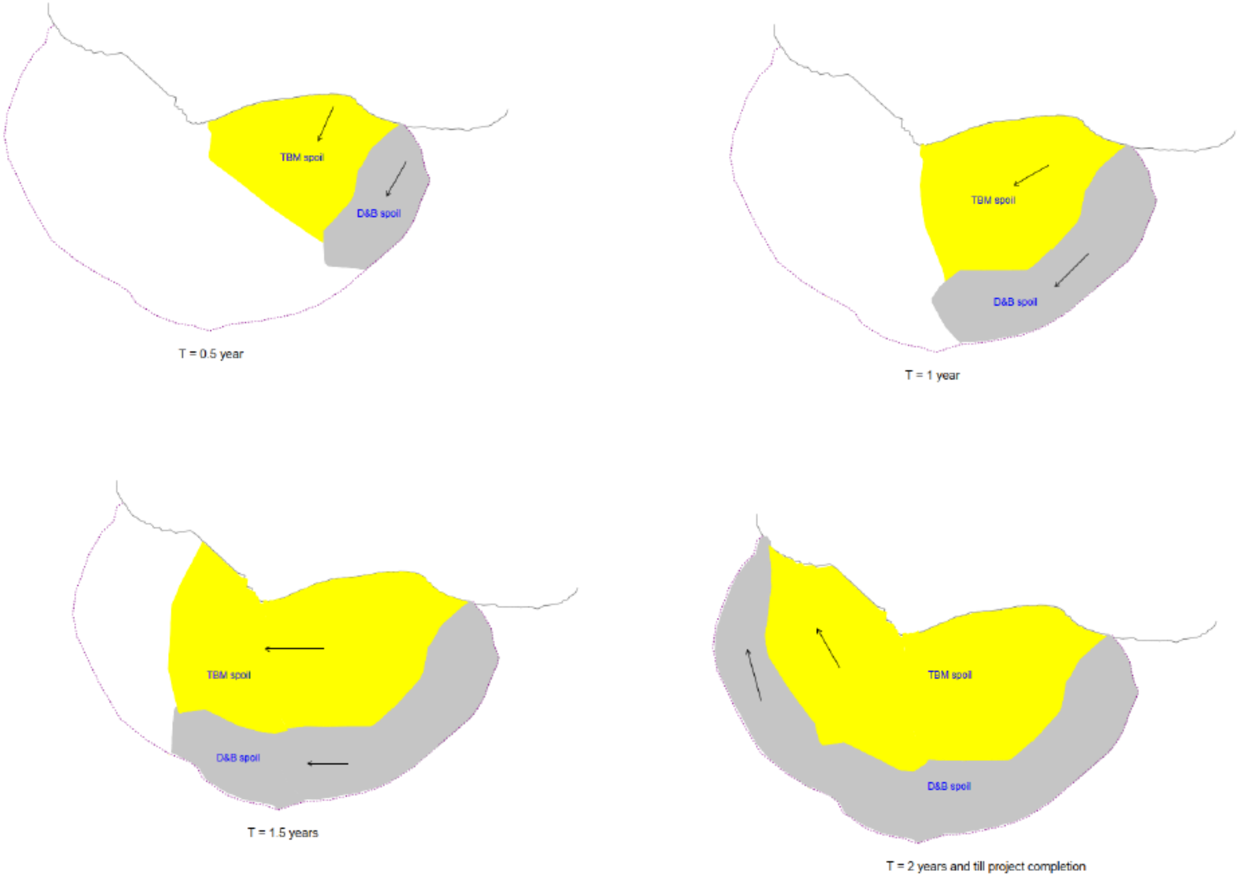


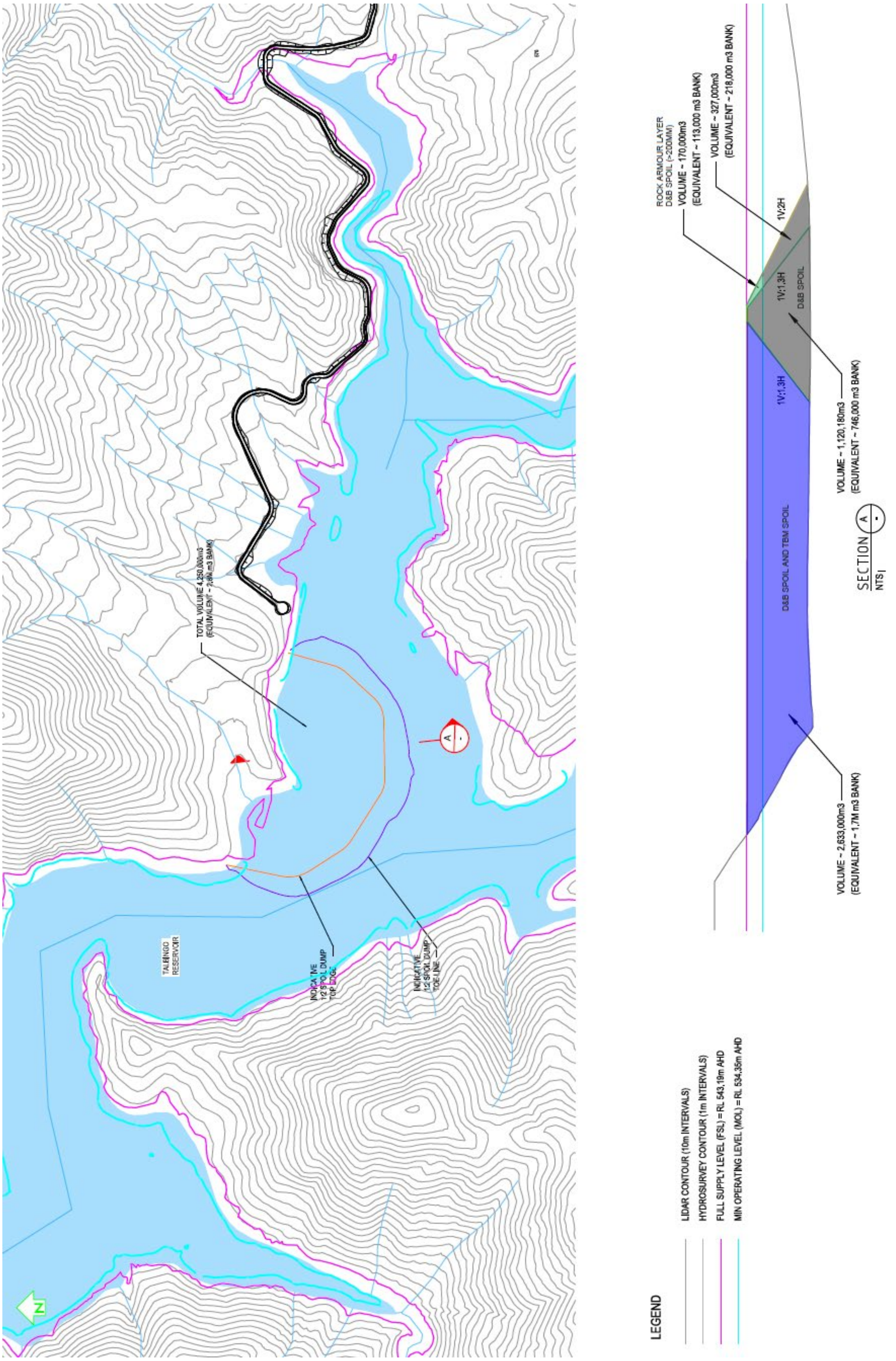
Table 2-5 Excavated Rock volume (Bank volume, m^3) for construction staging at Talbingo

Incremental vol.	0.5 year	1yr	1.5yr	2yrs	Subtotal
TBM	561,129	202,407	377,323	192,512	1,333,371
D&B	332,024	516,565	425,447	253,390	1,527,426
					2, 860, 797

Table 2-6 Volume of excavated rock in different sizes in Talbingo Area (bank volume, m^3)

Rock Size	D&B		TBM		Total	
	100%		100%		100%	
> 200 mm	40%	585,417	0%	0	21%	585,417
0 -200 mm	60%	878,126	100%	1,370,668	79%	2,248,794
	Subtotal	1,463,543		1,370,668		2,834,211

Figure 2-11 Talbingo – Finished excavated rock footprint and section



2.5.3 Contractors Alternative Hybrid (D&B Only to Reservoir) Placement Design

An alternative “Hybrid” excavated rock placement methodology has also been proposed in which only D&B excavated rock is placed in Talbingo Reservoir (Ravine Bay), with land placement being used for all TBM material. This design is termed ‘Hybrid Placement’.

In this scenario it is assumed that 1.4 Million m^3 (bank) of excavated rock would be placed in the reservoir using the Ravine Bay Placement method that was presented in the above Section. The placement time period is assumed to be 27 months at an average placement rate of 1750 m^3/day. The resultant placement footprint would be reduced from that defined in **Section 2.5.2**.

2.5.4 Contractors Proposed Mitigation Measures

To reduce the potential environmental impact related to excavated rock placement in Talbingo Reservoir, silt curtains will be installed around the footprint of the proposed emplacement. Final selection of the silt curtain would occur during the detailed design phase. The silt curtains will be suspended from floatation booms on the surface and will minimise and restrict water and sediment movement in the top 12m of the water column depending on permeability. The silt curtains were assumed to be impermeable for the purposes of modelling undertaken for the ERP studies.

3 CSIRO Studies

3.1 Introduction

CSIRO was commissioned by Snowy Hydro Limited (through RHDHV) to identify and assess the environmental risks associated with the placement of excavated rocks from the development and operations of the proposed Snowy 2.0 scheme. CSIRO's role was to develop and undertake a series of assignments to provide information for environmental risk assessment associated with the handling of excavated rock materials from the proposed works. CSIRO worked with EMM to develop conceptual models and agreed to undertake an initial series of assignments.

RHDHV was engaged to provide additional capability, specifically to take the role of leading the project entitled: "Engineering Options for placement of Excavated Rocks". The CSIRO assignments are summarised in **Table 3-1** below. Further details on each Assignment are included in the sections below. CSIRO's reporting on each assignment is provided in **Annexures A to E**.

Table 3-1 Summary of CSIRO Assignments

P1 - Comprehensive Geochemistry Examination • geochemistry of each geological zone that will be excavated as part of the project highlighting problematic elements (core scanning) • mineralogy of the rocks, highlighting which minerals contain problematic elements (laboratory testing)
P2 - Environmental Risk Categorisation of Rock Materials • mineralogy/geochemistry (chemical composition, structure and reactivity) • potential acid generation • leachability of pollutants (e.g. metals and nutrients) under oxic and anoxic conditions • analysis of existing spillway rock to assist in understanding of the excavated rock weathering
P4 - Environmental Characterisations of Excavated Rock Interactions with and Potential Impacts on Reservoir Waters and Sediments • physical and chemical characterisation of excavated rock materials • physical and chemical characterisation of water and sediments using elutriate tests • pollutant release from excavated rock materials to waters • attenuation of rock pollutants by sediments
P5 - Ecotoxicology Assessment of Excavated Rock Leachates in Water and Excavated Rock-Sediment Mixtures • physical and chemical characterisation of surface sediments and waters • ecotoxicity assessment

3.2 P1 - Comprehensive Geochemistry Examination

As part of the P1 Comprehensive Geochemistry Examination (**Annexure A**), detailed geochemical and mineralogical characterisation was undertaken on drill core and lab samples from the Snowy 2.0 drilling program. Data from this study provides information on the chemical composition and mineralogy of the rocks to be excavated during the proposed Snowy 2.0 scheme. Three sampling techniques were employed to determine the chemical and mineralogical composition:

- continuous chemical analysis of all drill core intersecting rock units likely to be excavated (from power station, surge shaft, head and tail race tunnels), to provide a complete record of the chemical composition of the rocks
- high precision chemical analysis on selected samples from the core sections to complement the continuous analysis, and
- analysis of the selected samples for modal mineralogy to determine the mineral hosts of elements of concern, and their potential mobility with respect to potential environmental impacts.

The analytical techniques employed were:

- high spatial resolution continuous X-ray fluorescence (XRF) logging for continuous core chemistry;
- high precision geochemical analysis of selected samples;
- x-ray diffraction to determine modal mineralogy; and
- scanning electron microscope-based automated mineralogical analysis of accessory mineralogy in selected sulphide-rich and suspected naturally occurring asbestos (NOA) samples.

A summary of the lithological units that would be intersected by the proposed tunnel works are as follows:

- **Byron Range Group:** Siliciclastic rocks, mostly siltstones, shales, sandstones and conglomerates. Mineralogy dominated by quartz and feldspars, with lesser amounts of muscovite, chamosite, calcite and hematite.
- **Boraig Group:** Sedimentary and volcanic rocks, characterised by high quartz and feldspar content, with small amounts of muscovite, chamosite, and calcite. Minor dolomite, hematite, pyrite, scapolite, kaolinite and actinolite are also observed in a few drill holes.
- **Kellys Plain Volcanics:** Volcaniclastic rocks composed of quartz, feldspars, muscovite and chamosite. Minor kaolinite (up to 5%) was only observed in the drill hole BH1115.
- **Ravine Beds:** Interlaminated shales, siltstones, and conglomerates, composed of quartz, feldspars, muscovite and chamosite. Calcite (up to 10%) and dolomite (up to 11%) may occur. Minor pyrite, hematite and scapolite.
- **Tantangara Formation:** Siliciclastic rocks, mainly composed of quartz, feldspars, muscovite and chamosite. Minor dolomite and pyrite only observed in the drill hole BH3101.
- **Temperance Formation:** Volcaniclastic rocks comprised of quartz, feldspars, muscovite, chamosite, actinolite, epidote and diopside, and minor calcite.
- **Shaw Hill Gabbro:** Intrusive gabbro composed of quartz, feldspars, muscovite, chamosite, actinolite, and epidote, with minor calcite and hematite.
- **Gooandra Volcanics:** Volcanics comprised of quartz, feldspars, muscovite, chamosite, and epidote, with minor calcite, dolomite, and hematite.

Results from CSIRO's analysis indicated that two lithological units contained elevated sulphur (S) concentrations: Ravine Beds and Gooandra Volcanics. The Ravine Beds contained a 35m apparent thickness shale unit containing approximately 1.5% S., whilst the Gooandra Volcanics contained a unit of unconstrained thickness with up to 4% S. In addition, a unit in the Gooandra Volcanics was noted to contain naturally occurring asbestos. The unit has been logged as rhyolite during drilling but the composition is more consistent with a basaltic andesite. In lithologies other than the Ravine Beds and Gooandra Volcanics, sulphide minerals, some of which are arsenic and lead bearing, occur in veins but represent a volumetrically minor (<1%) component of the rocks sampled.

CSIRO provided the following recommendations based on the findings of the P1 Assignment:

1. drilling of additional boreholes near BH5102 (Ravine Beds) should be undertaken to confirm the thickness of the observed sulphide zone
2. drilling of additional boreholes near BH4101 (Gooandra Volcanic) should be undertaken to confirm the extent of this unit as this core has a very different character to the cores either side of it. Due to the detection of asbestiform minerals, further drilling within the volcanic part of the Gooandra Volcanics would allow further sampling to determine not only the extent of the sulphidic material but also the asbestos, and
3. any Naturally Occurring Asbestos (NOA) material should be placed in a wet condition into the aquatic environment.

Further work

The CSIRO P1 Assignment was completed in November 2018 and was based on 36 available cores that were available in early 2018. Drilling has continued, with further geochemical test work undertaken since this time. The Snowy 2.0 Contamination Assessment identifies areas of NOA and potentially acid forming rock that may be encountered or impacted during the construction of the project and provides management measures for the identification, handling, transport and disposal of contaminated materials including NOA, PAF rock, contaminated soil and water. This work addresses recommendations 1–3 above.

3.3 P2 - Environmental Risk Categorisation of Rock Materials

The P2 assignment, Environmental Risk Categorisation of Rock Materials (**Annexure B**), assessed the reactivity, leachability, and potential environmental consequences of excavated rock placement if placed on land and/or in the reservoirs. The outputs of Assignment P2 were used in CSIRO Assignment P4: Environmental Categorisation of Rock Interactions with and Potential Impacts on Reservoir Waters and Sediments, and Assignment P5: Ecotoxicology Assessment of Excavated Rock Leachates in Water and Excavated Rock-Sediment Mixtures.

A first principles approach based on the geochemical composition, hand specimen analysis from Assignment P1: Comprehensive Geochemistry Examination, and examination of the regional geology between Tantangara Reservoir and Talbingo Reservoir, was used to define seven geological zones as a basis for the work conducted in Assignment P2:

- (1) Ravine Group and (2) Byron/Boraig Group, around the western portion of approximately 13 km of the tunnel transect and surge shaft
- (3) Shaw Hill Gabbro, which is the only gabbro in the tunnel transect and constitutes approximately 1 km tunnel transect intersection
- (4) Gooandra Volcanics, that comprises around 5 km of tunnel transect
- (5) Peppercorn/Tantangara/Temperance Formations that constitute around 9 km of the tunnel transect of a mostly similar geology
- (6) Kellys Plain Volcanics, which are in the intake area at the Tantangara Reservoir and constitute around 2 km of the tunnel, and

- (7) Felsic/Granite/Gneiss/Ignimbrite which is a compilation of granitic/extrusive equivalents present at various places along the tunnel transect.

A further classification based on a comparison with the Post-Archean Australian Shale, which is considered an average upper crustal composition (reference), was used to assist in the selection of a Baseline Group and an Enriched Group for each of the seven geological zones. The most common attribute of the Enriched Group being elevated S and trace element concentrations (including metals and metalloids) compared to the Baseline Group.

Following this classification, a total of 115 samples, encompassing Baseline and Enriched Groups for each geological zone were selected for acid-base accounting and leachate analysis. Key outcomes are summarised below:

Acid-Base Accounting

- total S and hence Maximum Potential Acidity (MPA) varied by a factor of 15 between Baseline and Enriched Groups, respectively
- water-rock leaching tests indicate no samples had acidic pH and all samples had low leachable salts
- only 23% of samples could be classified as having a Net Acid Generation (NAG) capacity. Mean Acid Neutralisation Capacity (ANC) was similar in both Baseline and Enriched Groups
- The ANC is in excess of MPA for all samples with 93% nominally classified as very low risk (refer to **Figure 3-1** and **Figure 3-2**), and
- A relative risk ranking based on mean ANC and MPA suggests the greatest potential for generation of acidity from the Gooandra Volcanics, Byron/Boraig Groups and Peppercorn/Tantangara/Temperance Groups.

Figure 3-1 Comparison of MPA (kg H^2SO^4/t) and ANC (kg H^2SO^4/t)

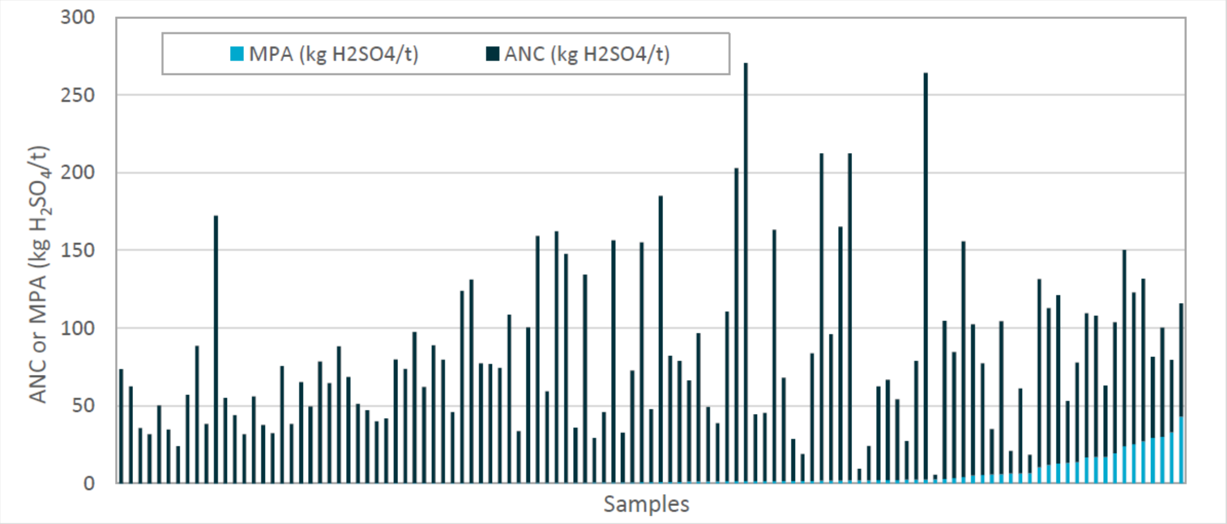
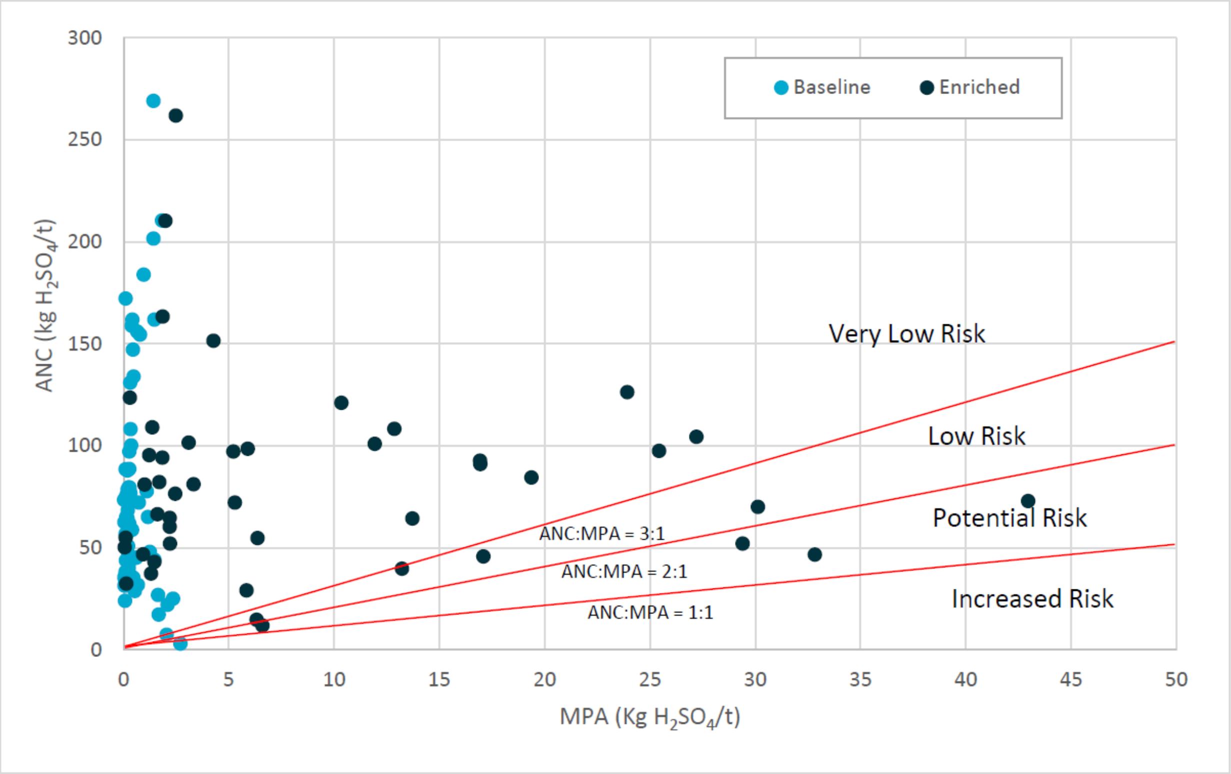


Figure 3-2 Categorisation of ANC (kg H^2SO^4/t) versus MPA (kgH^2SO^4/t) risk



Leachate testing

The findings of the leachate testing were as follows:

- Talbingo Reservoir water used in the leachate studies had a circumneutral pH and low dissolved salts and nutrient concentrations similar to that of modified rainwater
- the leaching ratio used (1:20) is similar to the projected volume of rock to solute (5%) to be deposited in Talbingo Reservoir and Tantangara Reservoir. After initial nearfield mixing processes have concluded, much lower TSS levels are expected, and
- under both oxic and anoxic conditions, major and trace element leaching appears to be limited, although elevated over what is essentially the modified rainwater composition of Talbingo Reservoir. Given the particle size of the ground samples used in the testing, it is likely, however, that element release in deposited rock with a substantially large particle size and reduced effective/reactive surface area will be largely attenuated with considerably slower water-rock reaction kinetics.

Spillway rock analysis

A study was undertaken on 12 rock specimens that had been immersed in the Talbingo Reservoir spillway for approximately 50 years. Distinct weathering rinds were present on some of the rocks. A geochemical traverse across the rinds indicated elevated iron (Fe) and Mn with concurrent enrichment in calcium (Ca), scandium (Sc), vanadium (V), arsenic (As) and the light rare earth elements suggesting that at least some rock types may, via surface reaction following immersion, have the capacity to act as a sink for a range of trace elements.

CSIRO provided the following recommendations based on the findings of P2:

1. whilst the MPA is generally low relative to the ANC, and hence a potential for the generation of acidity is low in most samples characterised in this study, relative rates of acidity versus alkalinity generation are uncertain and require further investigation
2. for many of the geological zones there still remains insufficient information on the natural compositional variation, and hence it is recommended that where possible, additional drilling, sampling, and analysis is undertaken, particularly in areas where larger volumes of excavated rock will be generated to better quantify potential risks of acidity generation and contaminant release over and above this initial study. If this cannot be completed prior to construction of the tunnel, sampling and analysis of excavated rock prior to placement should be undertaken
3. while ambient concentrations of nutrients are low in Talbingo Reservoir, considerable N and Si were released during leaching of a range of rock types. On this basis, a study into the potential of the nutrients to reduce growth limitation with respect to phytoplankton should be undertaken, and
4. considerable turbidity generated from samples used in the leachate studies highlight the potential for widespread turbidity to occur during in-reservoir deposition of excavated rock. Hence, a study of the generation of turbidity and methods to facilitate the flocculation of suspended solids is recommended.

Further work

The CSIRO P2 Assignment was completed in January 2019 based on 36 available cores that were available in early 2018. Drilling has continued, with further geochemical test work undertaken since this time. The Snowy 2.0 Contamination Assessment identifies areas of potentially acid forming rock that may be encountered or impacted during the construction of the project and provides management measures for the identification, handling, transport and disposal of these materials. This work addresses recommendations 1–2 above.

The results of the CSIRO P2 Assignment were considered in determining the experimental design (including analytes) for the CSIRO P4 Assignment elutriate tests. The stressors and contaminants of potential concern that could leach into reservoir water at levels were determined. This included consideration of the nutrients, N and Si. These were not identified as stressors or contaminants of potential concern. This work addresses recommendation 3 above.

The generation of suspended sediment (turbidity) from the placement of excavated rock in reservoir waters was the subject of extensive laboratory test work (see **Section 4.1**) and detailed hydrodynamic and sediment transport modelling (see **Section 5**). This work addresses recommendation 4 above.

3.4 P4 - Environmental Characterisations of Excavated Rock

Assignment P4 Environmental Characteristics of Excavated Rock (**Annexure C**) provided scientific information to help assess the potential impacts of the excavated rock materials on water and sediment quality within the reservoirs. CSIRO conducted test work on reservoir water/excavated rock mixtures to:

- identify stressors of potential concern (SOPC) and contaminants of potential concern (COPC), and
- provide information on the types, forms, and behaviour of stressors (physical, physico-chemical and chemical) released from excavated rock material upon mixing with reservoir waters and sediments

Rock materials for testing were sourced from seven geological units based on findings from Assignment P2: Environmental Risk Categorisation of Rock Materials. The waters and sediments used were from locations where excavated rock placement may potentially occur (Talbingo and Tantangara Reservoirs). A range of exposure scenarios and conditions (i.e. temperature) were evaluated for the interaction of the rock materials with the reservoir waters and sediments, and analyses of changes to water quality associated with the release/attenuation of substances from the rock materials.

The waters of the Talbingo and Tantangara Reservoirs provided to CSIRO to perform the analyses were classified as having neutral pH (6.9-7.3), low conductivity (26-30 µS/cm), and low turbidity (0.2-0.6 Nephelometric Turbidity Units (NTU)). The background/baseline waters contained no COPCs when compared to Australian national water quality guideline values (ANZG, 2018). Rock from core samples supplied to CSIRO were crushed and milled to <75 µm. For each geological unit, between four and nine samples were used to prepare composites.

Tests were undertaken to determine the:

1. physical and chemical characteristics of composited excavated rock samples
2. physical and chemical characteristics of waters and natural sediments used in elutriate tests
3. substance release from excavated rock to reservoir waters, and
4. attenuation of substances released from excavated rock due to interaction with existing reservoir sediments.

During the anticipated placement period, significant amounts of fine rock material may remain present in the water column, and the finest fractions may take many days or weeks to settle after the placement activities cease (see **Section 5.4**). The release of substances from the rock materials was, therefore, assessed using a series of elutriate tests that involved mixing and leaching rock materials with reservoir water and covered a wide range of mixing-leaching scenarios and conditions. Items (3) and (4) above used mixing-leaching tests (a form of elutriate test). Variables examined included changes to:

- liquid to solid ratios (L/S)
- mixing duration
- excavated rock particle size
- Temperature
- rock type
- successive leaching, and
- natural sediment inclusion

The following observations were made with regards to substance release from excavated rock materials in reservoir water that may result in potentially adverse changes to water quality:

- increases in water pH and conductivity are expected due to rapid release of ions that occur via ion solubility and exchange reactions
    - Both high pH (e.g. > pH 9) and high conductivity (e.g. >60 µS/cm) may be classified as SOPCs for some sensitive aquatic organisms.
- dissolved aluminium was the only substance consistently identified as a COPC
    - Dissolved aluminium concentrations may exceed the Default Guideline Values (DGV)
    - Sustained release of aluminium may occur from excavated rock materials
    - Dissolved aluminium release was negligible for rock materials >2 mm in size
    - Dissolved aluminium release increases significantly with decreasing particle size <0.21 mm and
    - Dissolved aluminium release is markedly lower in waters with temperature of 6°C than at 21°C.

- dissolved As and Cr were infrequently identified as COPCs, but only when waters contained >20 g/L fine solids (L/S <50), and
- resuspension of existing sediments within the reservoirs may buffer the pH closer to that of the reservoir waters, but significant attenuation of dissolved aluminium was not observed in tests.

Overall, Assignment P4 identified changes in water pH, conductivity and dissolved aluminium concentrations as the primary SOPCs/COPCs in both Talbingo and Tantangara Reservoirs, and that the risk of adverse impacts from these SOPCs/COPCs will increase as concentrations of fine excavated rock materials increase and the duration the rock materials remaining suspended in the water column increases.

Subject to confirmation of the disposal method and particle size distribution (PSD) of the excavated rock, CSIRO identified a number of knowledge gaps and provided the following recommendations:

1. testing of the longer-term release of substances from the clay to fine silt sized (<2 µm to 6.3 µm) excavated rock materials that are predicted to remain suspended within the reservoir water for periods of many months
2. testing of the effects of cycling water exposure to excavated rock materials, representing inundation/draining, and wetting/drying that may occur at shorelines
3. testing of longer term effects of water pH on attenuation of dissolved Al release, including potential cycling from dissolved and precipitated forms if pH cycles up and own, and
4. field trials of rock placement scenarios that may be used.

Further Work

The longer-term release of substances from the clay to fine silt sized (<2 µm to 6.3 µm) excavated rock materials has not been determined through laboratory testing. However, the most spatially extensive change to water quality in Talbingo Reservoir is predicted to be increased TSS and turbidity which has been assessed in detail (see **Section 5**).

Aluminium was the only toxicant that was identified as a contaminant of potential concern. Aluminium was the subject of further assessment by CSIRO (see **Section 3.6**). This work generally addresses recommendation 3.

The construction schedule is such that there is insufficient time available for field trials (recommendation 4), and trials are not proposed. Detailed monitoring of reservoir water will be carried out during and following excavated rock placement.

3.5 P5 - Ecotoxicology Assessment of Excavated Rock

Assignment P5, Ecotoxicology Assessment of Excavated Rock Leachates in Water and Excavated Rock Sediment Mixtures (**Annexure E**) provided information on the potential toxicity of leachates of excavated rock and excavated rock-sediment mixtures and assessed the potential impacts of the excavated rock materials on water and sediment quality within the reservoirs.

Rock materials for testing were sourced from the seven geological units identified by Assignment P2. The waters and sediments used were from locations where excavated rock placement was being considered in the Talbingo and Tantangara Reservoirs. The toxicity to microalgae and three invertebrate species under various interactions of the rock materials and reservoir waters/sediments was evaluated, relevant to a range of scenarios and environmental conditions.

The ecotoxicity of reservoir waters and sediment before and after the addition of excavated rock material was assessed to provide information on the potential for the excavated rock to cause toxicity to organisms that inhabit the water column and sediments at the proposed placement sites. Standardised bioassays with sensitive species were used to assess whether direct effects (acute and chronic) may occur due to excavated rock leachates within waters (effects to water-column species) and excavated rock-sediment mixtures (benthic species). The species comprised:

- Microlagae, Raphidocelis subcapitata and Chlorella vulgaris bioassays
- Water flea, Ceriodaphnia dubia
- Blackworms, Lumbriculus variegatus
- Midge larvae, Chironomus tepperi

Tests were undertaken for the ecotoxicology assessment to determine:

1. physical and chemical characteristics of composited excavated rock samples
2. physical and chemical characteristics of waters and natural sediments used in elutriate tests
3. effects to water-column species via leachate testing, and
4. effects to benthic species via excavated rock and sediment testing.

The acute and chronic toxicity of contaminants (inorganics including metals) and physico-chemical stressors such as pH, electrical conductivity (EC), dissolved oxygen (DO) and turbidity released from excavated rock materials were assessed to:

- assess toxicity to aquatic organisms due to fine suspended sediments from excavated rock material interacting with the reservoir water, and
- assess toxicity to benthic organisms due to fine deposited sediments from excavated rock material interacting with the reservoir sediments.

In the first set of experiments, leachates from excavated rock and water with ratios of 1 to 10 (1:10 mass/mass, sample to water ratio), were used for ecotoxicological assessment. Leachates of excavated rock had high levels of suspended solids (turbidity) that did not completely settle out of solution after 24h. Therefore, the toxicity of leachates was assessed with water fleas, midges and blackworms for three scenarios:

- raw leachate after 24 hour settling
- after 12 day settling, and
- filtered leachates

Microalgae were only tested with filtered leachates. The toxicity tests using raw leachates represented the ‘worst case’ scenarios during excavated rock placement. Please note that these tests were very conservative as modelling identifies that TSS outside the silt curtain is expected to be far less than 500mg/L and downstream of the placement is likely to be less than 100mg/L. For all rock groups excepting the Byron Range group, this will be less than 100 NTU downstream of the silt curtain.

In the second set of experiments, sediment/excavated rock toxicity tests were carried out with two benthic species (midge and blackworms) and covered three excavated-rock and sediment mixture scenarios. The three scenarios which were tested comprised:

- excavated rock becoming the dominant substrate in an area. This was called the ‘Rock scenario’

- excavated rock mixed with reservoir sediment to form a smaller fraction of the substrate. The 'Mixed scenario', and
- thin layers of excavated rock on top of reservoir sediment i.e. excavated rock materials that may spread and deposit at locations away from the main disposal area. The 'Top scenario'.

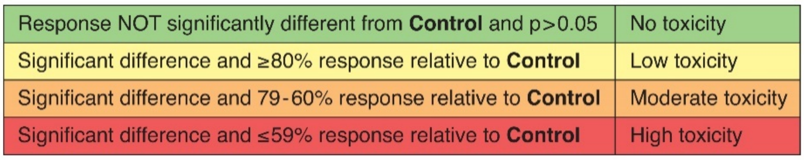
Table 3-2 below provides a summary of the toxicity tests undertaken and the material tested.

Table 3-2 Summary of Toxicity Tests undertaken in CSIRO P5 Assignment

Species	Endpoint (Acute or Chronic)	Exposure (d)	Material Tested
Water (leachate) tests			
Microalga, *Raphidocelis subcapitata*	Population growth rate inhibition (chronic)	3	(i) Reservoir water (0.45 µm filtered) (ii) Leachates of excavated rock representing 7 geological units (each with a Baseline and Enriched composite) prepared with reservoir water (and filtered to 0.45 µm prior to toxicity testing)
Water flea (cladoceran), *Ceriodaphnia dubia*	(i) Survival (acute)	2	(i) Reservoir water (ii) Leachates of excavated rock representing 7 geological units (each with a Baseline and Enriched composite) prepared with reservoir water representing three treatments a) Raw leachate as a worst-case scenario a) 12-day settled leachate Filtered leachate
Water flea (cladoceran), *Ceriodaphnia dubia*	Reproduction (chronic)	8	(i) Reservoir water (ii) Leachates of excavated rock representing 6 geological units (each with a 0.45 µm filtered Enriched composite) prepared with reservoir water
Midge *Chironomus tepperi*	Immobilisation (acute)	2	(i) Reservoir water (ii) Leachates of excavated rock representing 7 geological units (each with a Baseline and Enriched composite) prepared with reservoir water representing three treatments
Blackworm, *Lumbriculus variegatus*	Immobilisation (acute)	2	As above
Sediment (excavated rock) tests			

Species	Endpoint (Acute or Chronic)	Exposure (d)	Material Tested
Midge larvae, *Chironomus tepperi*	(i) Survival (chronic) (ii) Growth (length) (chronic)	7	(i) Reservoir sediment (ii) Reservoir water as overlying water a) excavated rock representing 7 geological units (each with a Baseline and Enriched composite) b) mixed with reservoir sediment c) as a surface layer on top of reservoir sediment d) 100% Enriched excavated rock as a worst-case scenario
Blackworm, *Lumbriculus variegatus*	(i) Reproduction (chronic) (ii) Biomass (chronic)	28	As above

The acute and chronic toxicity data generated using one microalgae and three macroinvertebrate species was summarised by using the following ranking system:

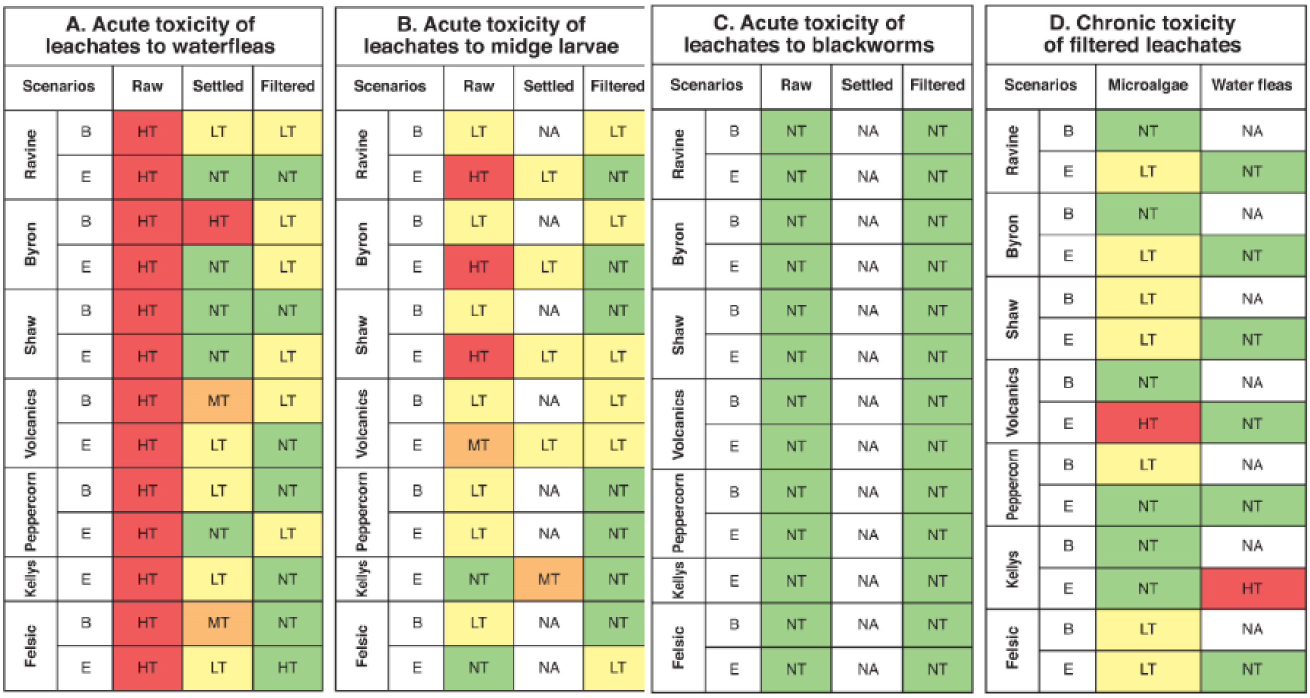


Response NOT significantly different from **Control** and p>0.05	No toxicity
Significant difference and ≥80% response relative to **Control**	Low toxicity
Significant difference and 79-60% response relative to **Control**	Moderate toxicity
Significant difference and ≤59% response relative to **Control**	High toxicity

Leachate Toxicity Results

Table 3-3 provides a summary of the ecotoxicological assessment of the Baseline and Enriched leachates for the three scenarios to (A) water fleas, (B) midges and (C) blackworms and chronic toxicity to microalgae and water fleas (D). Three scenarios tested were (1) Raw –24 h settled leachate (2) settled-12-day settled leachate (3) Filtered – 0.45 µm filtered leachate.

Table 3-3 Summary of Leachate Toxicity Results



Scenarios		A. Acute toxicity of leachates to waterfleas			B. Acute toxicity of leachates to midge larvae			C. Acute toxicity of leachates to blackworms		
		Raw	Settled	Filtered	Raw	Settled	Filtered	Raw	Settled	Filtered
Ravine	B	HT	LT	LT	LT	NA	LT	NT	NA	NT
	E	HT	NT	NT	HT	LT	NT	NT	NA	NT
Byron	B	HT	HT	LT	LT	NA	LT	NT	NA	NT
	E	HT	NT	LT	HT	LT	NT	NT	NA	NT
Shaw	B	HT	NT	NT	LT	NA	NT	NT	NA	NT
	E	HT	NT	LT	HT	LT	LT	NT	NA	NT
Volcanics	B	HT	MT	LT	LT	NA	LT	NT	NA	NT
	E	HT	LT	NT	MT	LT	LT	NT	NA	NT
Peppercorn	B	HT	LT	NT	LT	NA	NT	NT	NA	NT
	E	HT	NT	LT	LT	NA	NT	NT	NA	NT
Kellys	E	HT	LT	NT	NT	MT	NT	NT	NA	NT
Felsic	B	HT	MT	NT	LT	NA	NT	NT	NA	NT
	E	HT	LT	HT	NT	NA	LT	NT	NA	NT

Scenarios		D. Chronic toxicity of filtered leachates	
		Microalgae	Water fleas
Ravine	B	NT	NA
	E	LT	NT
Byron	B	NT	NA
	E	LT	NT
Shaw	B	LT	NA
	E	LT	NT
Volcanics	B	NT	NA
	E	HT	NT
Peppercorn	B	LT	NA
	E	NT	NT
Kellys	B	NT	NA
	E	NT	HT
Felsic	B	LT	NA
	E	LT	NT

NT-No toxicity, LT-Low toxicity, MT Moderate toxicity, HT High toxicity and NA- not analysed.

A preliminary water flea toxicity assessment of the dilutions of raw leachate (after 24 h settling) from a Byron Baseline sample was also conducted and compared to a control representing the reservoir water.

The observed toxicity for the dilution series of the leachate is shown in **Table 3-4** and **Figure 3-3** below and also expressed as turbidity. The results show a trend of higher toxicity with higher turbidity. There is a large gap in information from 3.8 NTU to 1638 NTU.

Table 3-4 Observed Toxicity from Leachate Tests

Treatment	NTU	% survival
control	3.8	94
12%	1638	50
25%	2778	8
50%	6400	0
100%	20608	0

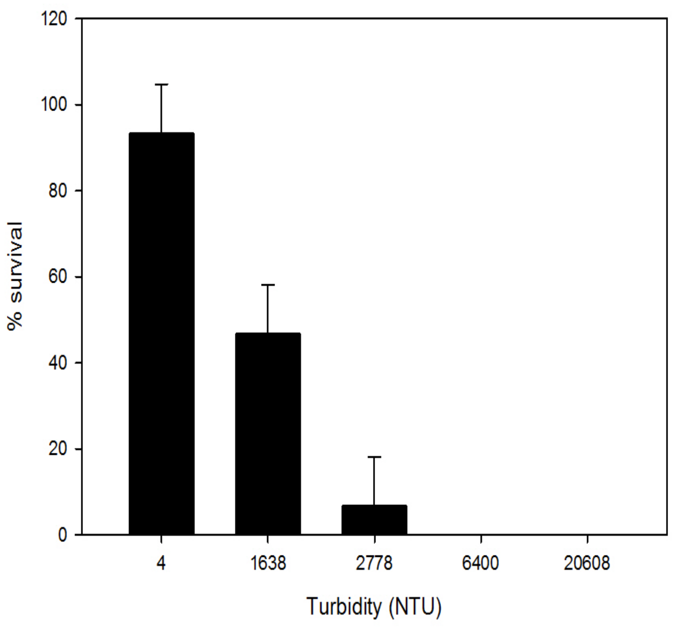


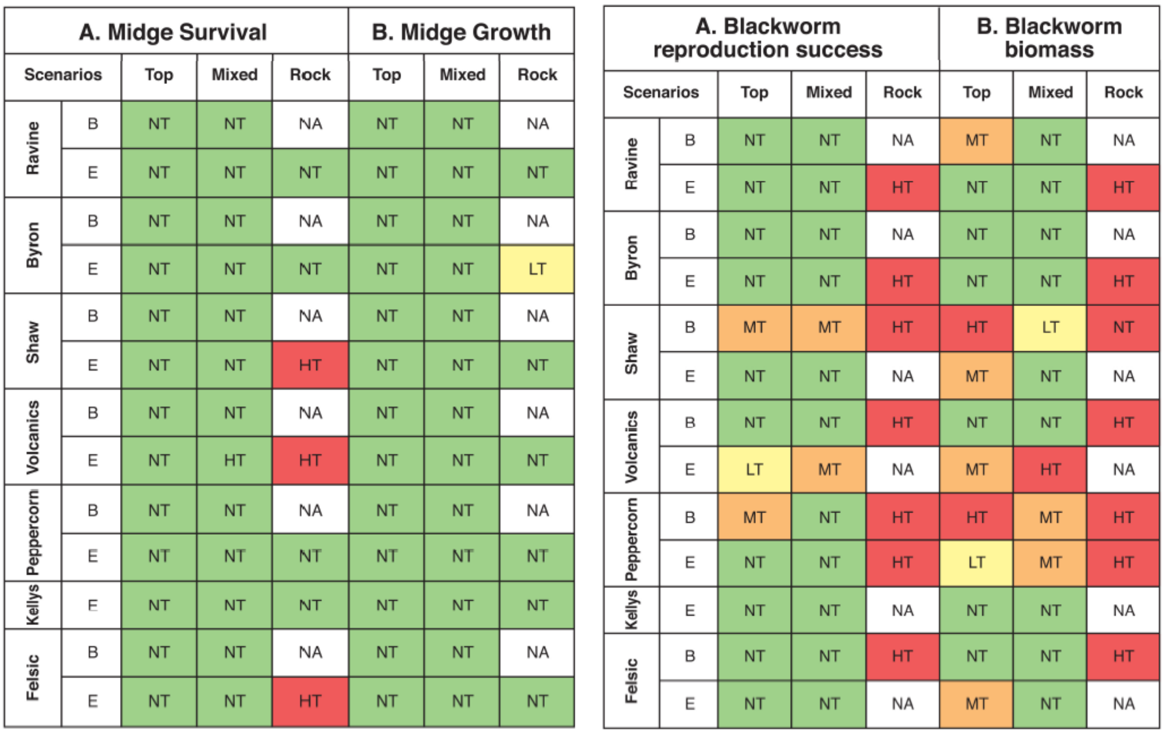
Figure 3-3 Observed Toxicity from Leachate Tests (illustrated)

It should be noted that the modelling predicts that NTU values of 100+ would only be encountered outside of the silt curtain during the ERP construction phase for up to 1 to 2 km upstream (away from the Talbingo Reservoir dam wall) along the Yarrangobilly and Tumut River arms for a period of 1 to 2 weeks (**Annexure F**).

Sediment and Excavated Rock combination Toxicity

Table 3-5 provides a summary of the ecotoxicological assessment of Baseline and Enriched samples for (A) midge larvae survival and (B) growth and (A) blackworm reproduction success and (B) total biomass. Three scenarios were tested (1) Top –as a surface layer on top of reservoir sediment (2) Mixed – mixed with reservoir sediment (3) Rock - 100% Enriched excavated rock.

Table 3-5 Sediment & Excavated Rock Combination Toxicity Assessment Results



		A. Midge Survival			**B. Midge Growth**		
Scenarios		**Top**	**Mixed**	**Rock**	**Top**	**Mixed**	**Rock**
Ravine	B	NT	NT	NA	NT	NT	NA
	E	NT	NT	NT	NT	NT	NT
Byron	B	NT	NT	NA	NT	NT	NA
	E	NT	NT	NT	NT	NT	LT
Shaw	B	NT	NT	NA	NT	NT	NA
	E	NT	NT	HT	NT	NT	NT
Volcanics	B	NT	NT	NA	NT	NT	NA
	E	NT	HT	HT	NT	NT	NT
Peppercorn	B	NT	NT	NA	NT	NT	NA
	E	NT	NT	NT	NT	NT	NT
Kellys	E	NT	NT	NT	NT	NT	NT
Felsic	B	NT	NT	NA	NT	NT	NA
	E	NT	NT	HT	NT	NT	NT

		A. Blackworm reproduction success			**B. Blackworm biomass**		
Scenarios		**Top**	**Mixed**	**Rock**	**Top**	**Mixed**	**Rock**
Ravine	B	NT	NT	NA	MT	NT	NA
	E	NT	NT	HT	NT	NT	HT
Byron	B	NT	NT	NA	NT	NT	NA
	E	NT	NT	HT	NT	NT	HT
Shaw	B	MT	MT	HT	HT	LT	NT
	E	NT	NT	NA	MT	NT	NA
Volcanics	B	NT	NT	HT	NT	NT	HT
	E	LT	MT	NA	MT	HT	NA
Peppercorn	B	MT	NT	HT	HT	MT	HT
	E	NT	NT	HT	LT	MT	HT
Kellys	E	NT	NT	NA	NT	NT	NA
Felsic	B	NT	NT	HT	NT	NT	HT
	E	NT	NT	NA	MT	NT	NA

NT-No toxicity, LT-Low toxicity, MT Moderate toxicity, HT High toxicity and NA- not analysed

Overall, the following observations were made with regards to the potential toxicity of leachates of excavated rock and excavated rock-sediment mixtures:

- 100% raw leachates as suspended sediments in the reservoir and neat excavated rock material represent the worst-case exposure scenarios tested in this study
- high toxicity was observed for both worst-case scenarios, but it is noted they have a low probability of occurring outside the silt curtains surrounding the works, and
- No toxicity or low to moderate toxicity was observed for the majority of the other scenarios tested.

Preliminary acute and chronic toxicity testing of dilutions of raw leachate to the water flea provide a useful indication of the trend of lower toxicity with lower turbidity but the data is limited particularly at the lower NTU expected to be observed outside the silt curtain surrounding the works.

CSIRO concluded that increased turbidity and metals and metalloids such as aluminium may be introduced to the water body from the excavated rock placement and/or due to sedimentation. These multistressors could result in a low level of toxicological, physiological or physical impacts on fish and macroinvertebrates during the works where the turbidity is high. CSIRO provided suggestions for collection of further biological assessment data for Talbingo and Tantangara Reservoirs, including ecotoxicological effects and an ongoing in-situ monitoring program.

3.6 Dissolved Aluminium Assessment for Talbingo Reservoir

Assignment P4 determined that the mixing of excavated rock materials (<75 µm) within the Talbingo Reservoir waters would result in concentrations of dissolved aluminium frequently exceeding the Australian national DGV for freshwaters of 55 µg/L (ANZG, 2018), accompanied by an increased pH (from approximately pH 7 to 9.5) and conductivity (from approximately 30 to 150 µS/cm).

The Assignment P4 tests characterised differences in dissolved aluminium release that may occur due to differences in the concentration of solids in the water (liquid/solid ratio; L/S), time, repeat/successive leaching, rock particle size, temperature, and attenuation of substances released due to interactions with sediments. The more important observations were that dissolved aluminium release from fine rock into Talbingo water was lower at 6°C, than at 21°C , and greater with increased mixing duration, indicating potential ongoing release.

CSIRO was subsequently requested to undertake a desktop assessment of dissolved aluminium for Talbingo Reservoir to estimate where and after how much time aluminium concentrations would return to below the DGV and baseline concentrations (see **Annexure E**).

Data from CSIRO Assignment P4 were summarised and used to develop relationships between the concentration of fine excavated rock materials suspended in Talbingo Reservoir water (mg/L) and concentrations of dissolved aluminium (µg/L). The relationships considered the water temperature and the duration that excavated rock materials are predicted to be suspended within the water. Using these relationships, the hydrodynamic model for Talbingo Reservoir was used to predict total suspended solids concentrations (TSS, mg/L) of excavated rock within surface, middle and bottom waters at ten locations within the reservoir. The predictions were made for the 2-year duration of the proposed works (for the proposed Ravine Bay placement) and for 1-year following their completion, and considered the seasonal heating/cooling periods.

The assessment indicates that dissolved aluminium concentrations are likely to exceed the DGV of 55 µg/L within the placement area contained by the silt curtain (Location 1 – see **Figure 3-4**). Outside the silt curtain, a gradient (mixing zone) is expected to develop, along which dissolved aluminium released in Location 1 will dilute and some further aluminium release from particles will occur. In the 500 m between Location 1 and Location 2, the dissolved aluminium concentrations may exceed the DGV. Beyond Location 2, the dissolved aluminium concentrations are predicted to remain below the DGV, and within a factor of 2-3 of the background aluminium concentrations of 5-10 µg/L.

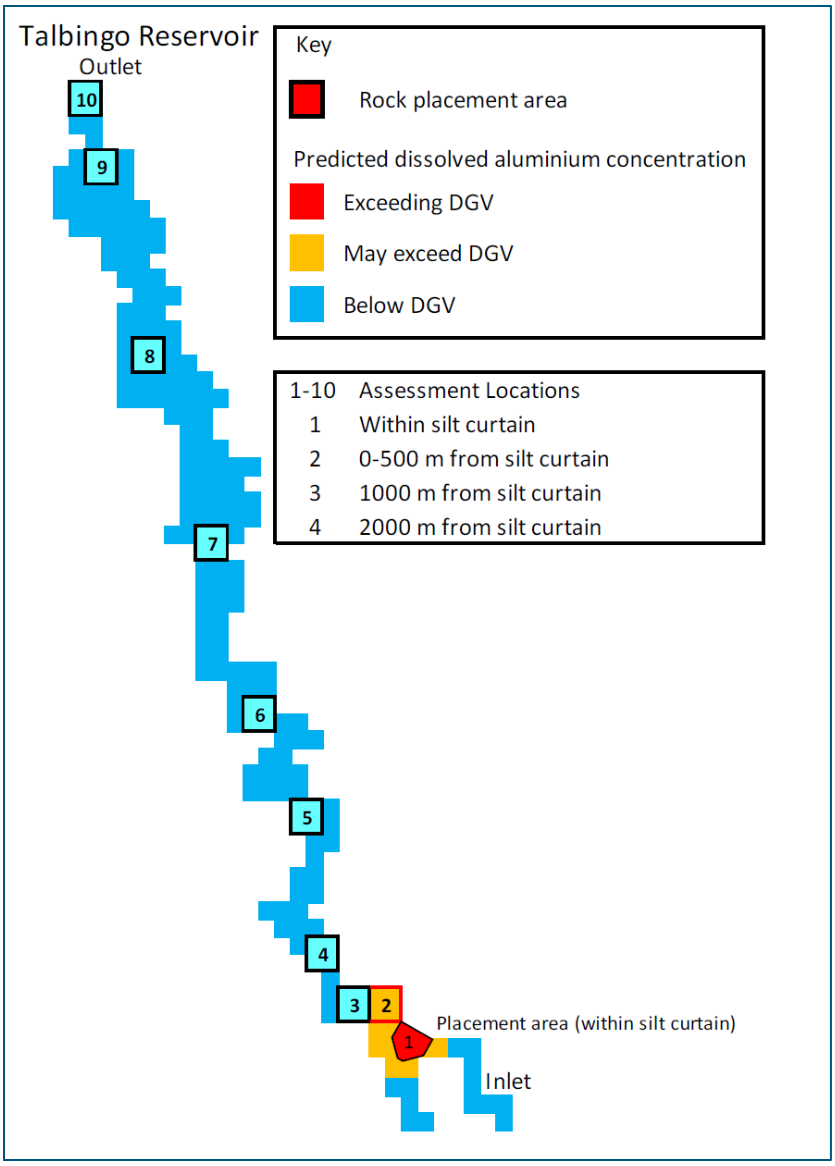
Significant uncertainty exists with the predictions on both the high side (higher dissolved aluminium) and low side (lower dissolved aluminium). Assignment P4 describes a number of data/knowledge gaps that influence this uncertainty. Higher TSS concentrations and higher water pH are considered the primary drivers for higher dissolved aluminium concentrations. Lower water temperatures will result in lower dissolved aluminium concentrations. At Location 1 (placement area), should the pH not rise as high in the field environment as it did in the laboratory tests (Assignment P4), then the dissolved aluminium concentrations in the field may be considerably lower within Location 1 than those predicted here.

Greater rates of water dilution will lower dissolved aluminium concentrations in Location 1, and the result in less aluminium being transported to locations further down the reservoir, so aluminium concentrations may not substantially increase at these locations. The predictions may have 50% uncertainty on both the high or low sides for Location 1 and 2.

At Locations 2-10 (i.e. with increasing distance from the placement area), attenuation reactions that result in lower water pH may result in substantially lower aluminium release from TSS. The dilutions may also be greater than those predicted by the hydrodynamic and sediment transport models (see **Sections 5** and **6**), resulting in lower dissolved aluminium concentrations.

The following figure depicts the area where dissolved aluminium may exceed the water quality DGV of 55 μg/L.

Figure 3-4 Showing where Dissolved aluminium may exceed Water Quality Guidelines



4 Primary Data Collection and Analysis

4.1 Laboratory Assessment – Settlement Characteristics of Fine Crushed Rock

As part of the ERP studies, RHDHV completed laboratory based investigations to assess the settling performance of crushed samples from the geological formations that would be encountered during excavation of Snowy 2.0. In total, nine main geological formations are expected to be encountered within the tunnel alignment. A brief description of the geology has been provided previously in **Section 3.2**.

4.1.1 Scope of Work

Samples of the rock core from the geotechnical investigation were provided to RHDHV. RHDHV deployed various methods to crush the rock in order to simulate production of fines from the proposed two excavation methods: TBM and D&B. The preferred method to crush the rock core involved mechanical crushing the core prior to using a jaw crusher and a ring mill to produce a sufficient quantity of fines. The crushed rock samples were sieved to finer than 250 µm for the laboratory investigation.

The scope of work for the laboratory investigations comprised four detailed tests which were undertaken for each geological formation, comprising:

1. a column test to establish TSS-turbidity relationship
2. a settlement test to determine the settling behaviour of crushed rock
3. a flocculation trial to assess whether a chemical flocculant would clarify the water, and
4. critical particle size analysis to determine the maximum particle size remaining in suspension.

A detailed methodology for each detailed test is provided in the Laboratory Testing report which is contained in **Annexure F**.

The order of analysis of the geological formations is provided below in **Table 4-1**

Table 4-1 Order of analysis of the geological zones

Borehole ID	Test No. / Appendix	Geological Zone	Rock Type	Assumed Disposal Location (water for test)	Date Commenced
BH1115	7	Kellys Plain Volcanics	Igneous (extrusive)	Tantangara	23-10-18
BH2103	8	Tantangara Formation	Metamorphic	Tantangara	06-11-2018
BH3102	9	Temperance Formation	Metamorphic	Talbingo	07-11-2018
BH3106	4	Boggy Plain Suite	Igneous (intrusive)	Talbingo	09-10-18
BH3108	5	Gooandra Volcanics	Igneous (intrusive)	Talbingo	9/10/18 and 10/10/18
BH5105	6	Byron Range Group	Completely weathered rock	Talbingo	23-10-18
BH5105	2	Boraig Group	Igneous (extrusive)	Talbingo	26-09-18
BH5105	3	Boraig Group	Sedimentary	Talbingo	26-09-18

Borehole ID	Test No. / Appendix	Geological Zone	Rock Type	Assumed Disposal Location (water for test)	Date Commenced
BH8106	1	Ravine Beds	Sedimentary	Talbingo	16-08-18

The column tests (Test D) and settlement test (Test A and Test B) were carried out in large settling columns to minimise the 'wall effects' of the column sides on settling behaviour. The settlement columns are shown below in **Figure 4-1**. The settling columns had a diameter of 200 mm and an overall height of 2000 mm. Each column was filled with approximately 50 L of water collected from either Tantangara or Talbingo Reservoir, depending on the proposed ERP location of each geological formation noted previously**.**

The flocculation trial was undertaken in the large settlement columns, approximately 9 to 12 days after commencement of the Settlement test. The chemical flocculant selected for the test was alum (aluminium sulphate). Alum is a readily available inorganic salt used in water purification and waste water treatment. Alum neutralises the charge of colloids, which promotes suspended impurities to coagulate into larger particles and then settle. It should be noted that the particular chemical flocculant selected for the test was arbitrary for illustration purposes and has not been approved for use during construction (use of an aluminium product would in fact would not be advisable). Surface turbidity inside the column was measured approximately 24 to 72 hours after addition of alum.

The critical particle size analysis was undertaken in 1L glass measuring cylinders, filled water collected from either Tantangara or Talbingo Reservoir, depending on the proposed placement location of the relevant geological formation. Samples were analysed from approximately 50 mm below the water surface (850 mL mark on the measuring cylinder) and 230 mm below the water surface (300 mL mark on the measuring cylinder) at the required time intervals of 15 minutes, 2 hours, 6 hours and 24 hours. The particle size distribution of suspended crushed rock was analysed by laser method using the Mastersizer 2000.

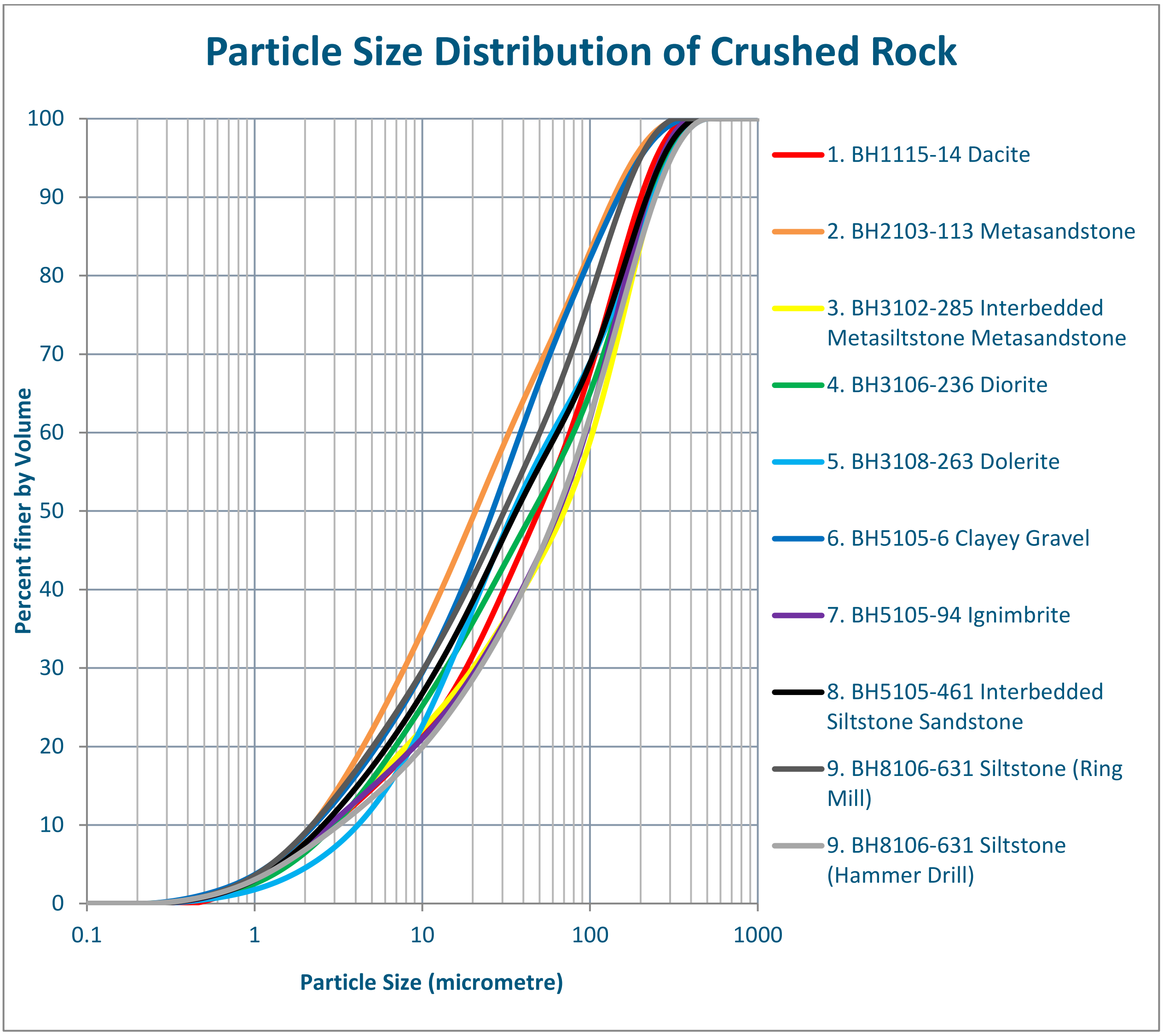
Figure 4-1 *Settling columns used for column test*

* Photographs were obtained ~5 to 35 minutes after commencement of Test 2D to 7D (from left to right)

4.1.2 Results

The PSD of the crushed rock, sieved to finer than 250 µm, was analysed with a Mastersizer 2000, as noted above. The PSDs for the 8 geological zones are presented in **Figure 4-2**.

Figure 4-2 PSD of crushed rock sieved to finer than 250 µm



The PSDs indicate that approximately 45 to 75% of the crushed rock samples were classified as fines (silt and clay sized particles less than 63 µm) and 10 to 20% of the crushed rock samples contain clay sized particles (less than 4 µm). These samples comprised fines that would be expected in D&B and TBM ERP and which were anticipated to lead to long term TSS. Coarser sediments, as also found in D&B and TBM, were not tested as it was recognised that they would settle quickly and would not contribute to the long term TSS.

It is apparent from the column tests (**Figure 4-3**), settlement tests (**Figure 4-4**) for surface placement and for placement through a fall pipe 50 cm below the water surface(**Figure 4-5**) that once fine crushed rock enters the water column, a portion of the finer particles remain in suspension for extended periods, in the order of several weeks (possibly longer). Crushed rock from the Tantangara Formation (Test 8), Ravine Beds (Test 1) and Boraig Group (Tests 2 and 3) geological zones generally resulted in extended periods of higher surface turbidity. In comparison, crushed rock from the Gooandra Volcanics (Test 5) geological zone settled out of suspension relatively quickly. Crushed rock from the Byron Range Group (Test 6) geological zone behaved differently to the other rock zones. While the material settled quickly in the settlement tests, elevated surface turbidity was recorded (higher than other tests) for an extended period when the water and crushed rock mixture was agitated for the column test.

Figure 4-3 Surface turbidity measured during the column tests (Test D)

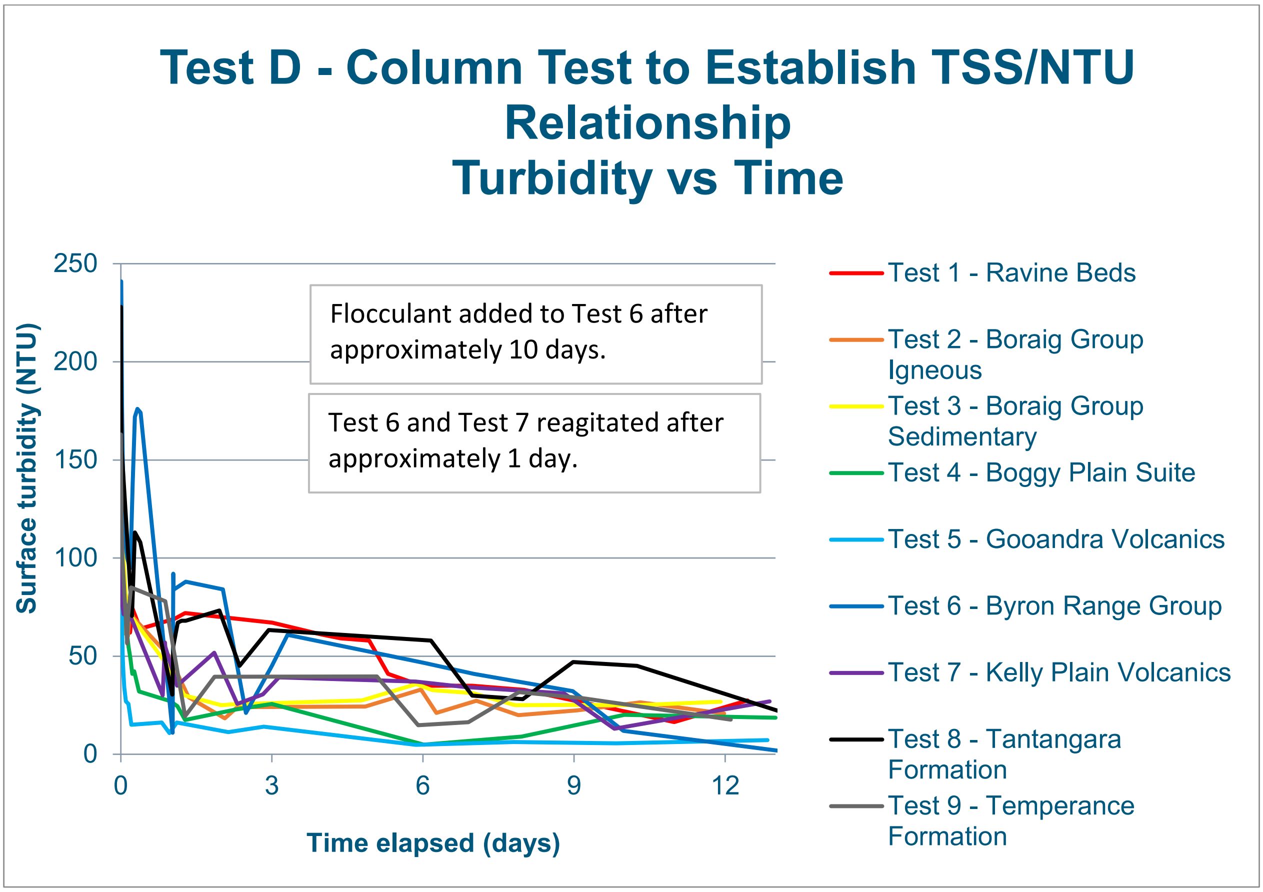
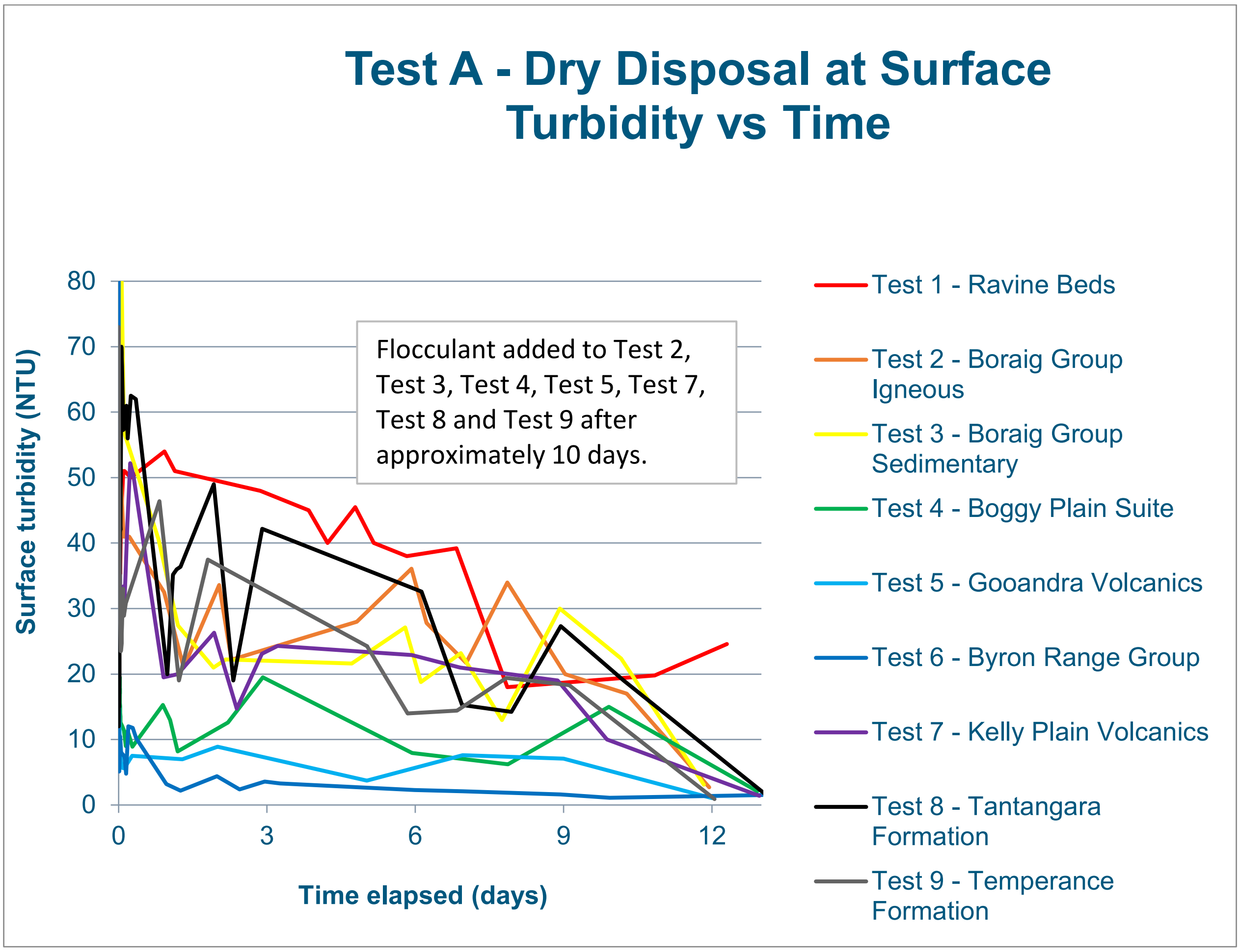
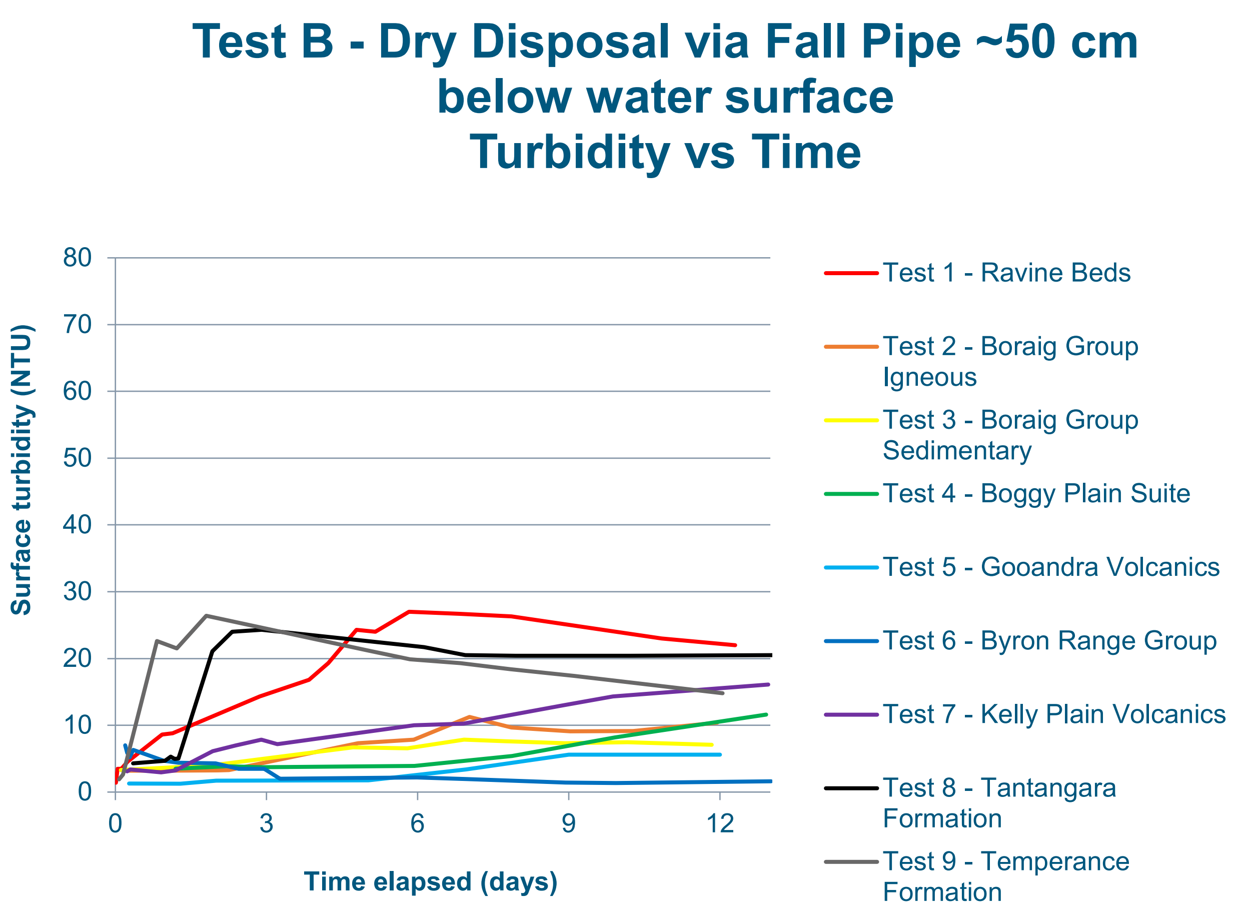


Figure 4-4 Surface turbidity measured during the settlement tests (Test A)



* simulating placement of dry crushed rock on the surface (Test A)

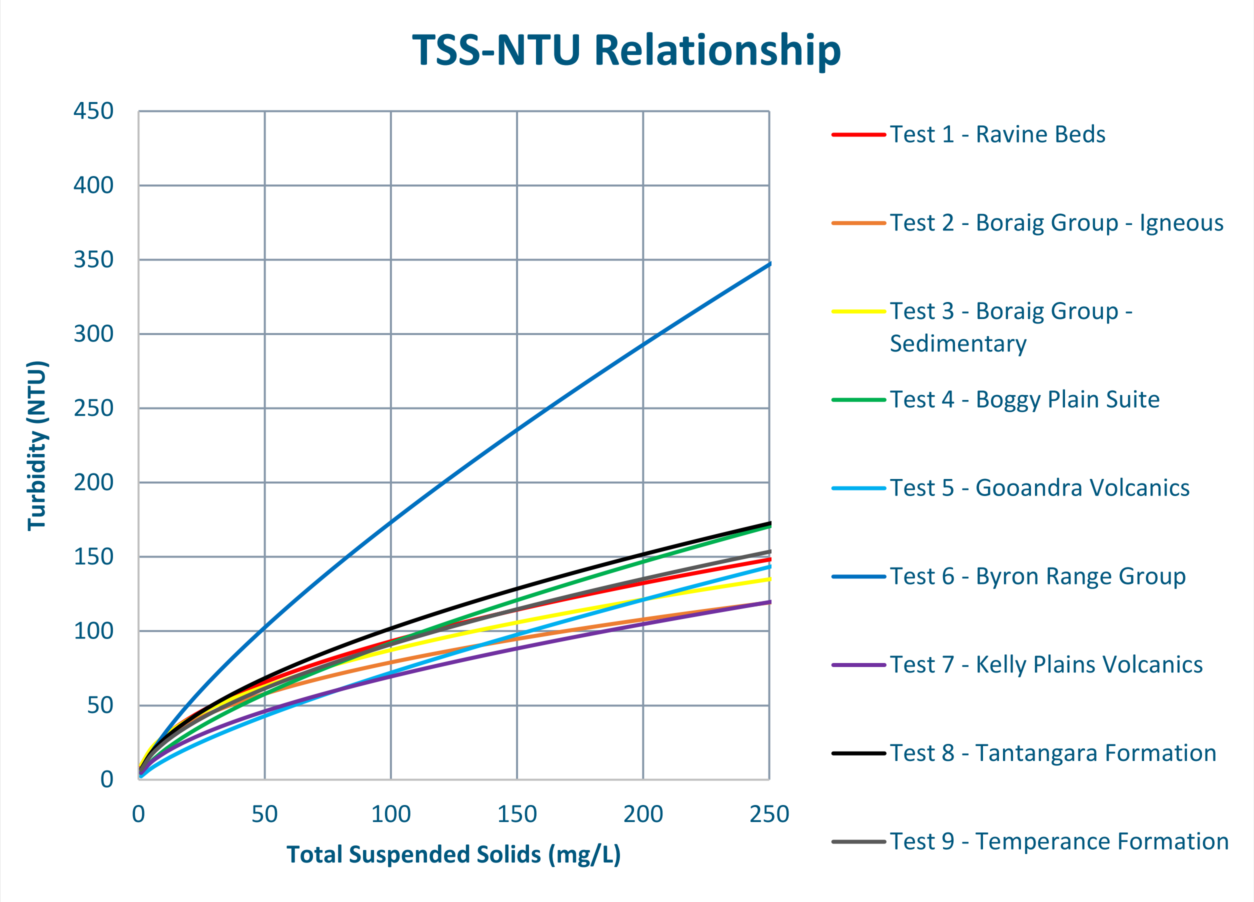
Figure 4-5 Surface turbidity measured during the settlement tests (Test B)



* simulating placement of dry crushed rock through a short fall pipe (Test B)

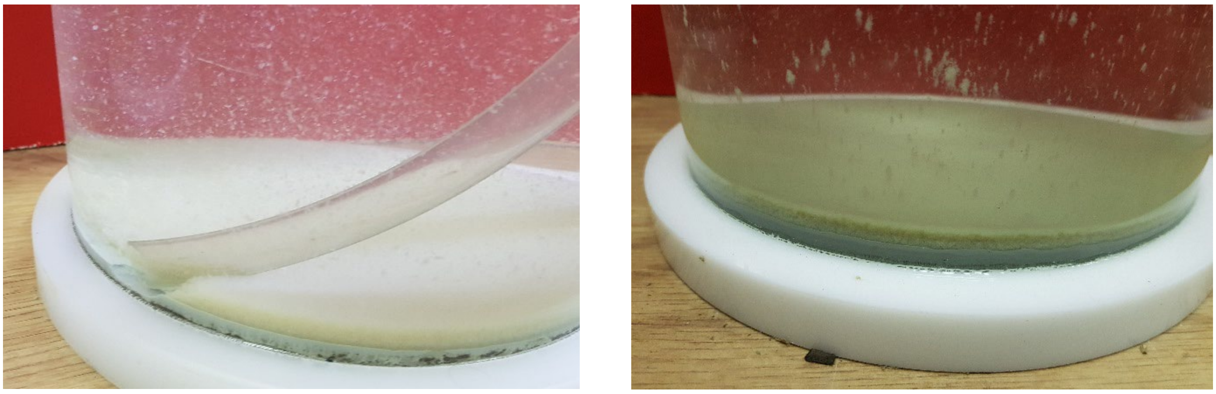
With the exception of the Byron Range Group, the TSS-turbidity correlations for the geological zones were similar. The TSS-turbidity correlations are shown in **Figure 4-6.** Turbidity equivalent to a TSS concentration of 50mg/L varied between 43 NTU (Test 5 – Gooandra Volcanics) and 68 NTU (Test 8 – Tantangara Formation and Test 1 - Ravine Beds). The crushed rock was generally light grey to grey/blue in colour, with the exception of Byron Range Group, which was red-orange. The darker colour results in less light penetration and higher turbidity for an equivalent TSS concentration. Turbidity equivalent to a TSS concentration of 50 mg/L was 102 NTU for Test 6 - Byron Range Group.

Figure 4-6 *Trendline of best fit through datasets - Power Function*



The flocculation trial indicated alum, a readily available inorganic salt, is effective in clarifying the water and reducing surface turbidity. Photographs showing the settlement columns after the addition of alum are shown in **Figure 4-7**.

Figure 4-7 *Settlement columns following addition of flocculant*

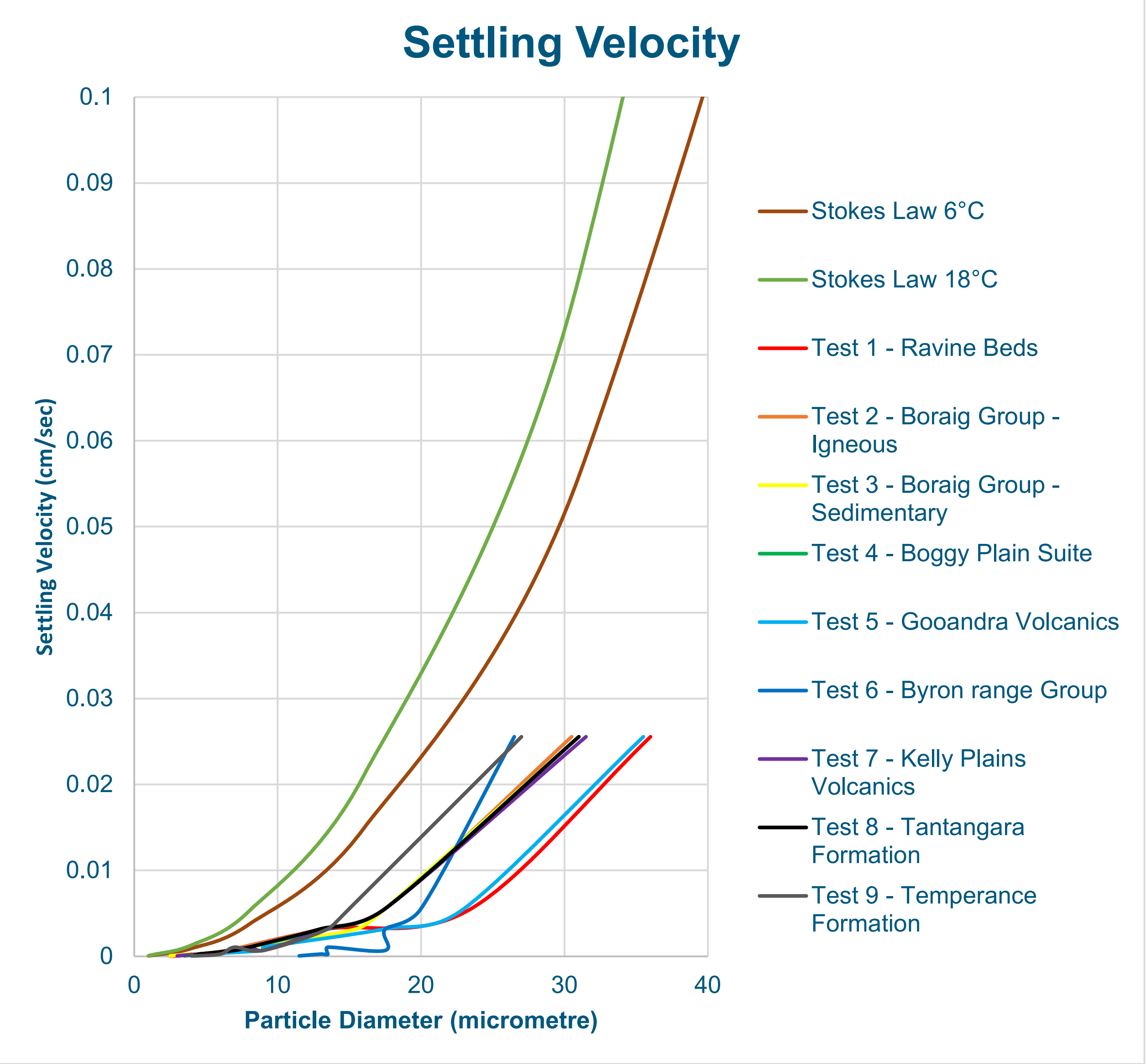


* Left, Test 4A – Boggy Plain Suite and right, Test 8A – Tantangara Formation.

The critical particle size analysis aimed to determine the maximum particle size in suspension after a given period of time. After 15 minutes, the maximum particle size in suspension was 15 µm to 37 µm reducing to 2.5 µm to 6 µm after 24 hours, except for Test 6 - Byron Range Group. As expected, the particle size distribution was coarser at depth within the columns.

Based on the maximum particle size in suspension, at a given depth and after a predefined time interval, the settling velocity can be calculated. The settling velocities calculated from the critical particle size analysis are provided in **Figure 4-8** along with theoretical settling velocities determined by Stokes Law for a water temperature of 6 °C and 18 °C. Water temperature was not monitored as part of the critical particle size analysis. However, the temperature would have been similar to that used in the settlement columns, which was between 15 °C and 25 °C (average 17.4 °C to 21.5 °C) for all tests. Settlement velocities determined from the critical particle size analysis are slower than those predicted by Stokes Law and could be due to a number of factors including hindered settling.

Figure 4-8 Settling velocity calculated from the critical particle size analysis



Quality assurance tests were undertaken to ensure the results are repeatable and reliable. Overall, the reliability of the settlement test results were considered reasonable as the general trends are repeatable. Reliability of the particle size analysis undertaken using laser techniques is considered excellent while noting that this technique can produce different results compared to conventional mechanical sieving and hydrometer methods.

Additional testing on the sensitivity of key parameters (Test 10) was conducted on crushed rock from a single geological zone, the Ravine Beds geological zone, which was also assessed during Test 1. Key findings from the sensitivity testing were that settlement performance is sensitive to:

1. the length of the fall pipe, with longer fall pipes resulting in significantly lower surface turbidity levels, and
2. temperature fluctuations, where a variation in water temperature was observed to result in an increase in surface turbidity. The increase in surface turbidity is hypothesized to be a result of convection currents.

Water temperature has a predictable influence on settlement behaviour as explained by Stokes Law. However, the effect of temperature was not significant to the outcome of the laboratory investigation.

Based on the laboratory investigation, it is inferred that:

- placement of crushed rock near the bed of the reservoir reduces turbidity within the water column
- placement at depth within the reservoirs when a thermocline is apparent (i.e. during summer) is less likely to result in vertical mixing and advection of crushed rock towards the surface
- management measures that minimise or control the release of such fine fractions may improve the management of surface turbidity during rock placement activities, and
- minor disturbances to the water column during field rock placement activities in the reservoirs (e.g. due to fresh water flows, operational flows from the existing Snowy scheme (T2 and T3) wave action and propeller wash) are likely to disrupt the settlement process and/or re-suspend fine particles.

4.2 Sediment Sampling Investigations

4.2.1 Background

Two sediment sampling campaigns have been undertaken by RHDHV, as follows:

1. Sediment sampling investigation in Talbingo Reservoir undertaken in August 2018. The aim of the investigation was to obtain sediment samples for laboratory contamination testing, to estimate the rate of historic sedimentation, and to obtain information to assist in the design of dredged channels and excavated rock placement locations proposed as part of the exploratory works. Of particular interest is the depth of sediment overlying bedrock and density/consistency of the various sediment strata. The investigation collected three to five sediment samples from five locations as follows:

    a. Middle Bay exploratory works dredge footprint – no longer proposed
    b. Talbingo Reservoir intake structure - proposed location of the power waterway intake
    c. Ravine Bay - potential subaqueous excavated rock placement location
    d. Plain Creek Bay - potential subaqueous excavated rock placement location for reference design
    e. Cascade Bay - potential subaqueous excavated rock placement reference design

2. Sediment sampling investigation in Talbingo Reservoir and Tantangara Reservoir undertaken in March 2019. The aim of the investigation was to assess the physical properties of the sediment and to determine the thickness of sediment layers. This information, in conjunction with hydrodynamic modelling, was required to estimate the propensity for erosion and sediment entrainment under Snowy 2.0 commissioning/operational flows (see **Section 6**). The investigation collected:
    a. 22 samples from Tantangara Reservoir, and
    b. 21 samples from Talbingo Reservoir.

Three different coring methods were utilised for the sediment sampling. The preferred coring method was dependent on the water depth and type of material. The coring method and sampling equipment included:

- piston corer
- gravity driven piston corer, and
- medium weight vibrocorer.

Laboratory testing included physical analysis of the sediments to determine the PSD for both investigations. The initial sediment sampling investigation in August 2018 also included geochemical analysis to determine the total concentration of contaminants including:

- metals
- nutrients
- total organic carbon and
- total S.

In addition, random samples were tested for a broader suite of parameters to confirm these substances are not present. The broader suite of parameters comprised:

- BTEX (refers to the chemicals benzene, toluene, ethylbenzene and xylene)
- organochlorine pesticides
- organophosphorus pesticides
- polycyclic aromatic hydrocarbons (PAH)
- total recoverable hydrocarbons - 1999 NEPM Fractions
- total recoverable hydrocarbons - 2013 NEPM Fractions, and
- volatile organics

4.2.2 Results

Tantangara Reservoir

A total of four sediment strata, of different origin, were sampled. These were:

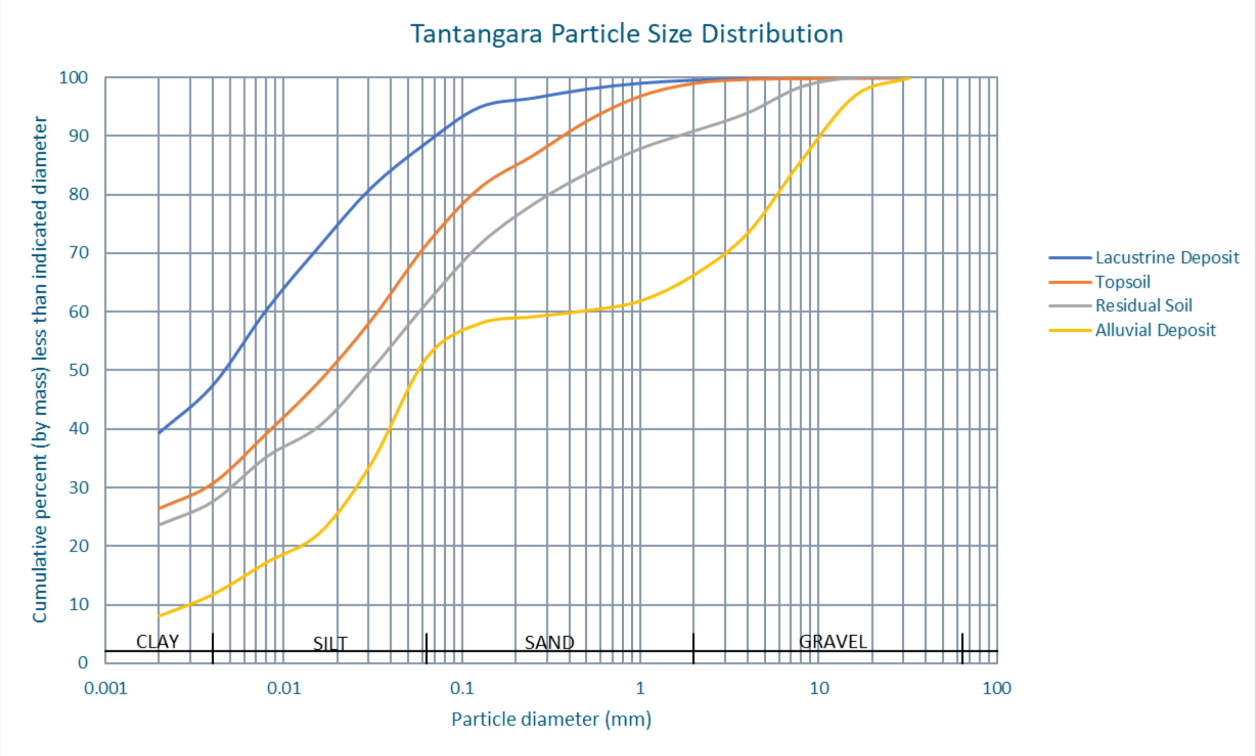
- Lacustrine (reservoir) deposits – unconsolidated surface material deposited by standing water, such as a reservoir
- Topsoil – terrestrial surface layer of a soil profile. Topsoil typically exhibits some organic accumulation and is darker and more fertile than underlying layers. Topsoil is generally a sub-profile of the underlying soil that has been reworked over a long period of time
- Alluvial deposits – a deposit formed by flowing water, prior to flooding of the valley, and

- Residual soil – in-situ weathering of parent rock to form a soil profile that has experienced minimal lateral movement.

Bedrock was also encountered on the eastern side of the reservoir.

A total of 7 samples of the lacustrine deposit, 15 samples of topsoil, 2 samples of alluvial deposit and 3 samples of residual soil were submitted for laboratory analysis. An average PSD of the 4 sediment strata, of varying origin, is provided in **Figure 4-9**.

Figure 4-9 Average PSD for the sediment strata recovered at Tantangara Reservoir



The encountered geology was notably different on the eastern and western side of the flooded Murrumbidgee River.

The eastern side of the channel thalweg was characterised by steep sided slopes and shallow soil profiles overlying rock. Core recovery was generally not possible.

The western side of the reservoir was characterised by a deep weathered residual soil profile overlain by well-developed topsoil. The primary difference between the residual soil and the topsoil is the colour attributed by the organic content. Erosion near the boat ramp at the southern end of Tantangara Reservoir clearly portrays the typical soil profile with dark brown topsoil overlying red gravelly clay as shown in **Figure 4-10**. A notable gravel horizon is evident near the upper extent of the residual soil stratum. The size of the gravel and thickness of horizon would not allow for penetration by the coring methods.

Figure 4-10 Eroded soil profile near the boat ramp

* representative of a typical profile along the western portion of Tantangara Reservoir. Shallow, well developed topsoil profile overlying residual soil

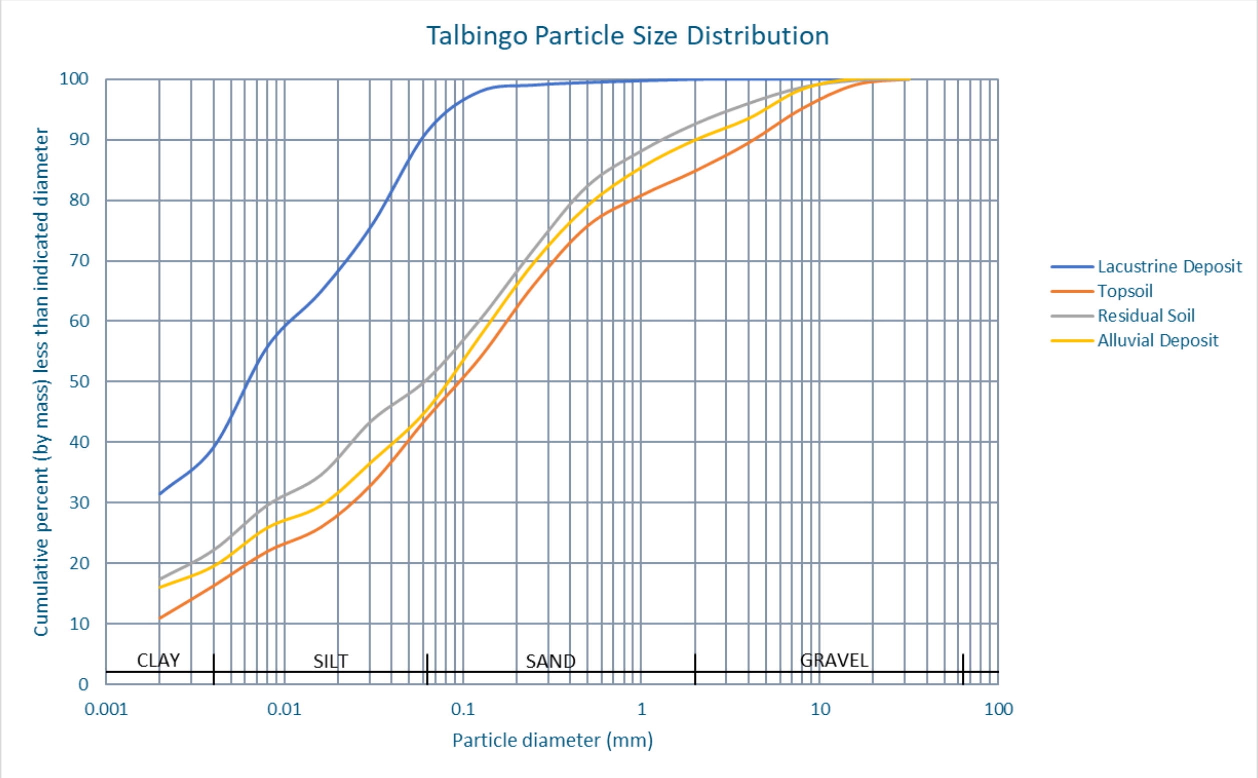
The estimated average rate of sedimentation across the reservoir is between 0 mm and 3 mm per year. Sedimentation is marginally higher along the western side of the reservoir. There is no obvious increase in sedimentation near the thalweg.

Talbingo Reservoir

A total of 4 sediment strata, of different origin, were sampled as for Tantangara Reservoir. Bedrock was also encountered at numerous locations.

A total of 7 samples of the lacustrine deposits, 1 sample of topsoil, 4 samples of alluvial deposits, 5 samples of residual soil and were submitted for laboratory analysis. An average PSD of the 4 sediment strata, of varying origin, is provided in **Figure 4-11**.

Figure 4-11 Average PSD for the sediment strata recovered at Talbingo Reservoir



The geology at Talbingo Reservoir is generally uniform across the area of investigation. Shallow bedrock was generally encountered across the site. Relatively deep alluvial deposits were encountered near the flooded Yarrangobilly River. The thickness of topsoil and residual soil was relatively thin.

The estimated average rate of sedimentation is:

- 5 mm per year near the proposed intake structure
- up to 20 mm per year upstream of the proposed intake structure, higher near the inflow of the Yarrangobilly River, and
- negligible throughout the remainder of the reservoir, with the exception of the thalweg, where the rate of sedimentation is anticipated to be up to 6 mm per year.

Laboratory results of the chemical testing have been summarised and compared to the screening levels provided in the National Assessment Guidelines for Dredging (NAGD) 2009. The NAGD screening levels are generally the same values as the DGV provided in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality: Sediment Quality Guidelines.

The NAGD screening levels and ISQG low trigger values form the basis for the assessment of risk that any sediment contaminants might pose to the environment. Concentrations less than the NAGD screening levels or ISQG low trigger values pose a low risk. Concentrations greater than the screening levels or ISQG low trigger values require further investigations in accordance with the ANZECC/ARMCANZ tiered framework for the assessment of contaminated sediments.

The concentrations in the samples tested for the full suite of parameters were all below laboratory detection levels or below screening levels for the following parameters:

- BTEX (refers to the chemicals benzene, toluene, ethylbenzene and xylene)
- organochlorine pesticides
- organophosphorus pesticides
- polycyclic aromatic hydrocarbons (PAH)
- total recoverable hydrocarbons - 1999 NEPM Fractions
- total recoverable hydrocarbons - 2013 NEPM Fractions, and
- volatile organics

The results of the total metal analysis indicated:

- concentrations of antimony and silver were all below laboratory detection in all samples
- concentrations of arsenic, chromium, mercury, and cadmium were all below the NAGD screening levels
- concentrations of nickel were greater than the NAGD screening levels in the majority of samples
- concentrations of lead were greater than the NAGD screening levels in three samples in the vicinity of the intake structure and one sample in Plain Creek Bay
- concentrations of copper exceeded the screening levels for one sample at Middle Bay, and
- Concentrations of zinc (Zn) exceeded the screening levels for one sample near the intake structure.

5 Modelling Study - Construction

5.1 Introduction

Hydrodynamic and sediment models of both reservoirs have been developed to investigate and assess the key hydrodynamic and sediment transport processes (e.g. freshwater flow, thermal stratification and sedimentary processes) in the study area. These models have been used to characterise the existing (pre-placement or baseline) conditions and to then investigate the likely changes to the reservoirs during and following placement of material.

This section discusses the following:

- the models that have been developed
- the placement modelling that has been undertaken, and
- the conclusions reached.

The reader is referred to the **Snowy 2.0 Talbingo Reservoir Modelling – Construction** report which is included as **Annexure G**.

As discussed in **Section 2.5.1,** the pre-tender reference design indicated that subaqueous ERP would occur in both Talbingo and Tantangara Reservoirs. It has since been proposed that with appropriate water level management in Tantangara Reservoir, all placement will occur in the dry. This means that 3D reservoir modelling of plume behaviour from ERP in Tantangara Reservoir is no longer required (i.e. as such the construction modelling focussed on Talbingo Reservoir only).

Details of the proposed placement methodology (Ravine Bay Placement) are provided in **Section 2.5.2**, while details of the alternative placement methodology (Hybrid Placement) are presented in **Section 2.5.3**.

5.2 Model Selection

The MIKE-3-FM (https://www.mikepoweredbydhi.com/products/mike-3) was selected to satisfy the modelling scope and objectives. MIKE-3-FM is a three-dimensional (3D) flexible mesh finite volume model code that solves the basic fluid dynamic equation used to describe the movement of the water (currents), the distribution of temperature and salinity, and reservoir water level. It is particularly suited to the study of stratified systems and has been validated with field measurements across a range of sites, including large lakes and stratified reservoirs, estuaries and coastal lagoons and the coastal ocean.

MIKE-3 considers other important processes such as:

- wind driven circulation
- circulation due to changes in reservoir level
- density driven circulation
- river and catchment run-off
- transport of heat and salt
- Coriolis effect due to the rotation of the earth, and
- bottom friction.

Further details of model bathymetry, model geometry and boundary condition data adopted for the reservoir model is provided in the main construction modelling report.

5.3 Data Used for Model Development

Development of computer models requires a considerable amount of data to adequately represent hydrodynamic, thermal stratification/mixing, wind induced current/wave, sediment transport processes occurring in the reservoir. In general, a model requires the following key datasets to adequately calibrate and/or simulate hydrodynamic, baroclinic and advection-dispersion processes:

- **Bathymetric survey data** – used to describe the topography of a reservoir over the domain of a numerical model system.
- **Water level and current/flow data** – used to calibrate and/or verify model predictions. Water level and inflow and outflow data are most commonly used to ensure the model adequately represents the water balance or hydrodynamics of the waterbody.
- **River flow data** – used to define river flow conditions of major freshwater inputs. For Talbingo Reservoir, there are several large river inflows, namely the Tumut River and Yarrangobilly River.
- **Local catchment runoff data** – used to define freshwater inputs to the water body from adjacent catchment areas draining laterally to the water body.
- **Physico-chemical water quality data** – used to define initial conditions (i.e. vertical profiles of water temperature, conductivity, TSS / fine sediment in the reservoirs) and to calibrate and/or verify model predictions.

Additional data specific to the study area has also been required for calibrating and / or simulating other heating, cooling and transport processes. This additional data has included environmental forcing data, which may be used to define meteorological conditions (e.g. rainfall, air temperature, wind speed, solar radiation, and relative humidity) or other model constituents (e.g. salinity, water temperature, turbidity, nutrients) during a calibration or simulation period. Where gauged flow data was not available (e.g. local sub-catchments fringing the reservoirs), a catchment model was used to estimate runoff volumes from the ungauged sub-catchments.

Details of the catchment model developed as part of the ERP modelling study is provided in the main construction modelling report. Please note that whilst catchment models are available for the study catchments, modelled runoff was not used to estimate local catchment runoff to the reservoirs, and instead flow at ungauged sites was estimated using area ratio and the gauged flow at Yarrangobilly River.

A summary of the data used for the development (and calibration) of the reservoir models is provided in **Table 5-1**.

Table 5-1 Data Used for Model Development and Calibration

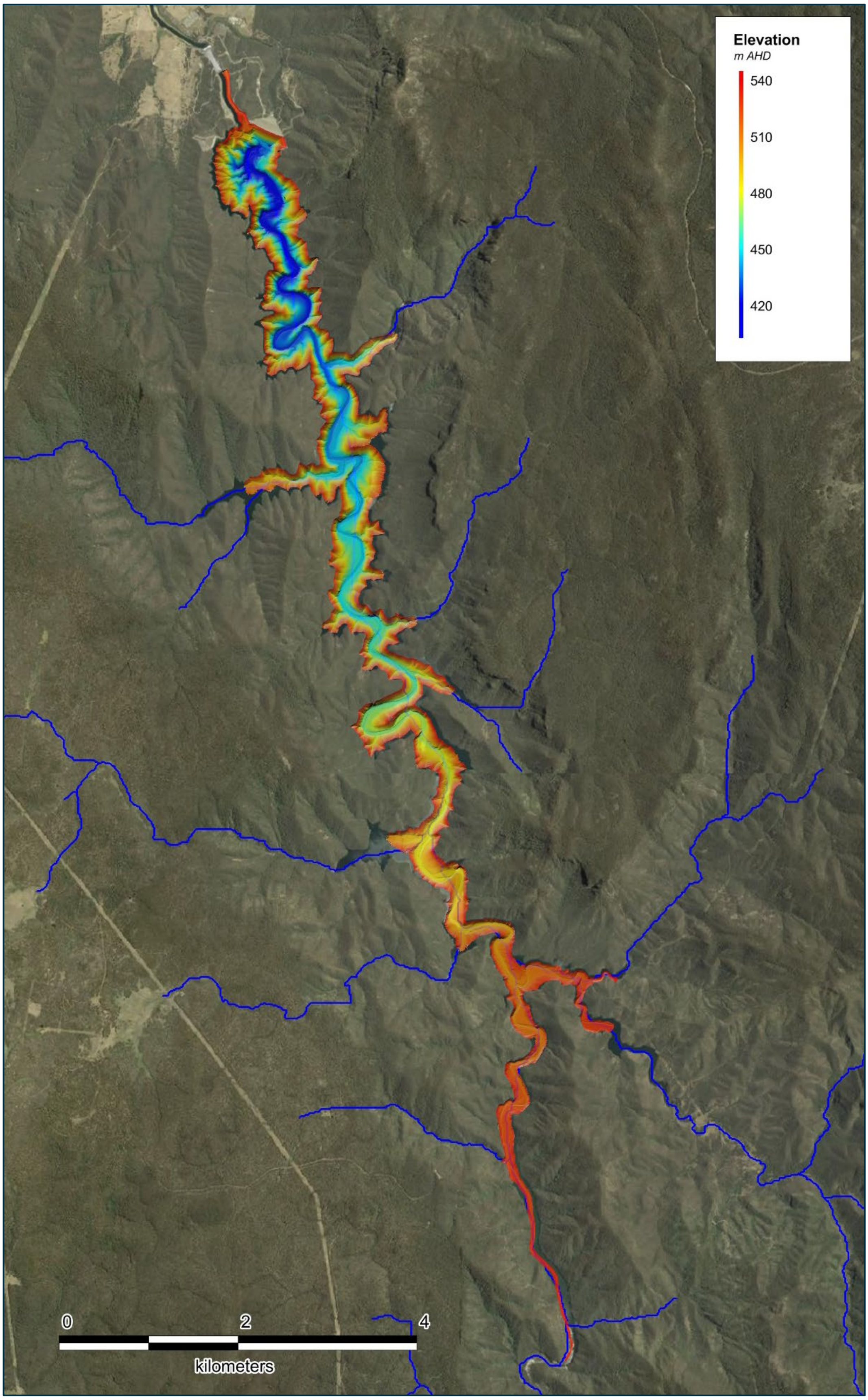
Data Requirement	Used for…	Data Sources
Meteorological data measured at weather stations in the study catchment: • Rainfall • Evaporation • Solar (short wave) radiation • Air temperature • Relative humidity • Wind speed.	creating boundary conditions to surface of model (inputs needed for the heat budget).	Weather Underground https://www.wunderground.com Snowy Hydro. Cardno field data collection program.

Data Requirement	Used for…	Data Sources
Snowy Hydro operations for Talbingo and Tantangara Reservoirs: • Inflows (flow, water temperature, TSS, conductivity). • Outflows (flow rate only). • Environmental flow releases (flow rate only).	assessing the water balance and defining boundary conditions to the model for baseline (existing) conditions.	Snowy Hydro.
Streamflow data for stations within the study catchments: • Gauging location • Flow gauging's and rating curves • Measured streamflow.	understanding the hydrology, overall water balance of the system – data used to calibrate the rainfall-runoff (catchment) model.	Water Data Online http://www.bom.gov.au/waterdata Snowy Hydro.
Bathymetric data (hydro survey).	reservoir model development (a key model requirement to define the storage properties of the reservoirs).	Snowy Hydro.
Ground elevation data (LiDAR or similar) of the study region.	extending bathymetry data to define land-water boundary and other low-lying floodplain areas that surround the reservoirs. Terrain analysis and catchment mapping.	ELVIS - Elevation Foundation Spatial Data http://elevation.fsdf.org.au. Snowy Hydro.
Historical reservoir water level and flow data.	calibrating hydrodynamics of the reservoir models.	Snowy Hydro.
Crest levels of dam spillway and outlet configuration (e.g. outlet dimensions, gate configurations).	representing the water balance and configuring the reservoir model geometry and defining boundary conditions to the model for baseline (existing) conditions.	Snowy Hydro.
Water quality data (conductivity, temperature and turbidity).	calibration of water temperature (heat budget) and sediment transport (TSS/turbidity).	Snowy Hydro Cardno field data collection program.

Recent bathymetry data of the study reservoir was used for model development. Bathymetry data (based on 2017-18 hydrographic survey) provided by Snowy Hydro is shown below for Talbingo Reservoir in **Figure 5-1**.

The hydrographic survey data was checked to confirm its applicability for model development and processed in GIS for input into the MIKE-3 model. Minor data gaps in the hydrographic survey for Talbingo Reservoir were manually accounted for by interpolating the edge of the hydrographic survey with surrounding topography based on available ground elevation data.

Figure 5-1 Hydrographic Survey Data for Talbingo Reservoir



5.4 Construction Modelling Conclusions

Approximately 2.8 million m^3 (banked) of excavated rock material is to be placed in Talbingo Reservoir. It is estimated that approximately half this material would be from a TBM, with the remaining 1.4 million m^3 (banked) from D&B excavation. This study uses numerical modelling techniques to provide a prediction of the sediment plume resulting from the proposed methodology over a two year period (Ravine Bay Placement).

An alternative Hybrid Placement option, in which only the 1.4 million m^3 (banked) D&B excavated rock is placed in the reservoir was also assessed.

Sensitivity testing of the assumed PSD was also undertaken for both the above approaches.

A model of Talbingo Reservoir has been developed to assist with conceptual engineering design and impact assessment of construction activities associated with the proposed Snowy 2.0. The model has been calibrated against observed water levels, water temperatures and current speeds. In some cases, certain model boundary conditions were approximated or based on data measurements for locations beyond the immediate study region (i.e. short wave solar radiation).

The model was also setup to simulate the potential sediment plumes associated with the excavated rock placement activities. While the existing model is suitable for comparative assessments, recent data collection exercises and additional proposed data collection will allow for further model refinement and calibration/verification exercises to be undertaken to improve the accuracy and reliability of model predictions.

The assessment of the impact of placement of excavated rock is based on a three year simulation of suspended sediment behaviour which includes two years of placement and a year to simulate the return of the reservoir to near background suspended sediment levels.

A range of model outputs have been provided to assess the potential impacts of the excavated rock placement in Talbingo Reservoir including:

- **Maps of Maximum TSS Concentration**: these maps show the maximum TSS concentration during the simulation. These are summarised in **Table 5-2.**
- **TSS Concentration Time Series Plots**: Time series of TSS at the surface, mid-depth and bed for various locations along the reservoir. A summary of the peaks is provided in **Table 5-2**.
- **Sediment Mass Flux Calculations**: which summarise the mass of sediment leaving the reservoir through the T3 outlet near the dam wall. These are summarised in **Table 5-3**.
- **Sediment Deposition Depth Plots**: which present the total thickness of sediment deposited over the simulation period. Refer **Figure 5-2, Figure 5-3, Figure 5-4** and **Figure 5-5**. A summary of predicted deposition rates is provided in **Table 5-4.**

Figure 5-2 Sediment Deposition Thickness (End 36 month) Ravine Bed Placement

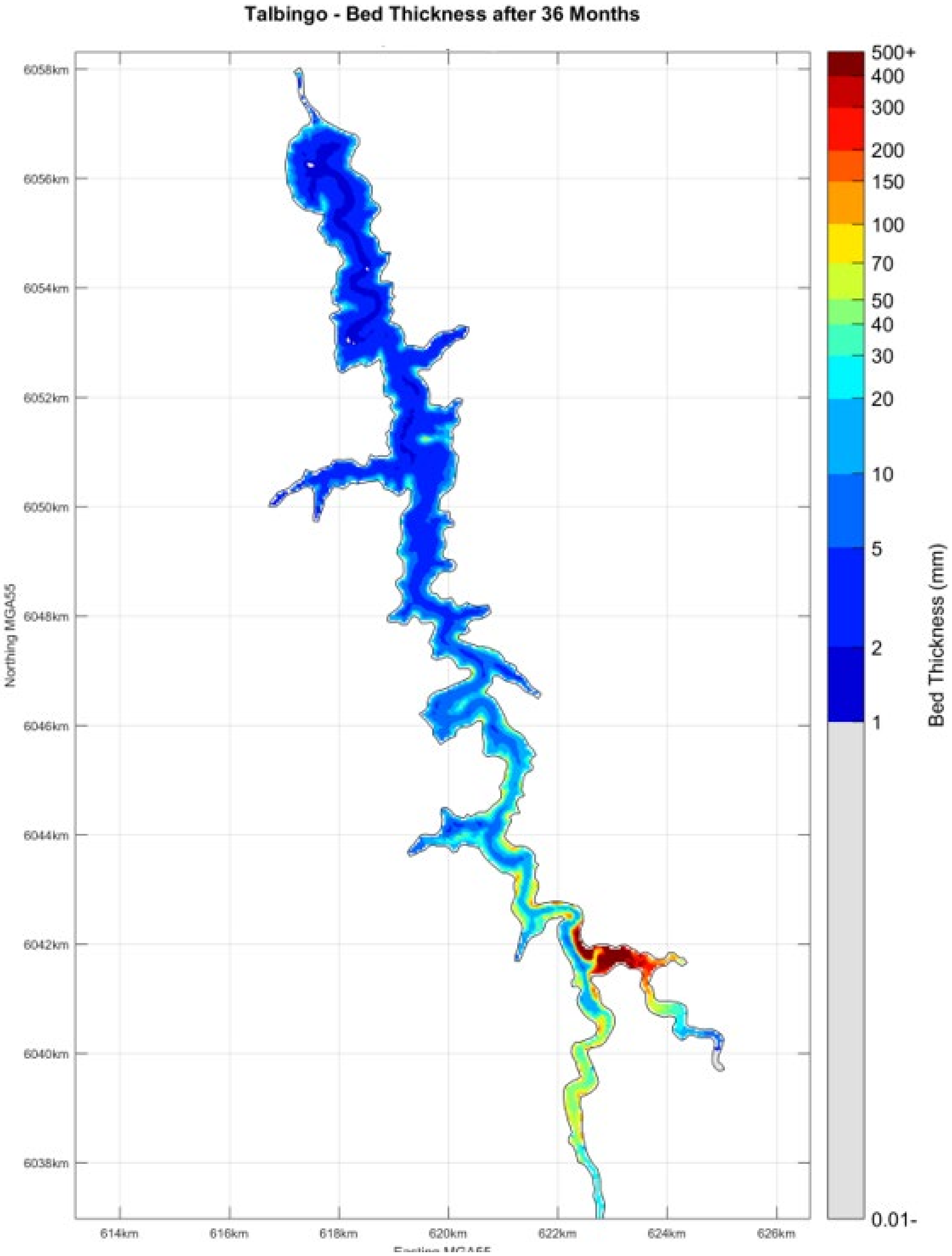


Figure 5-3 *Sediment Deposition Thickness (End 36 month) for Hybrid Placement*

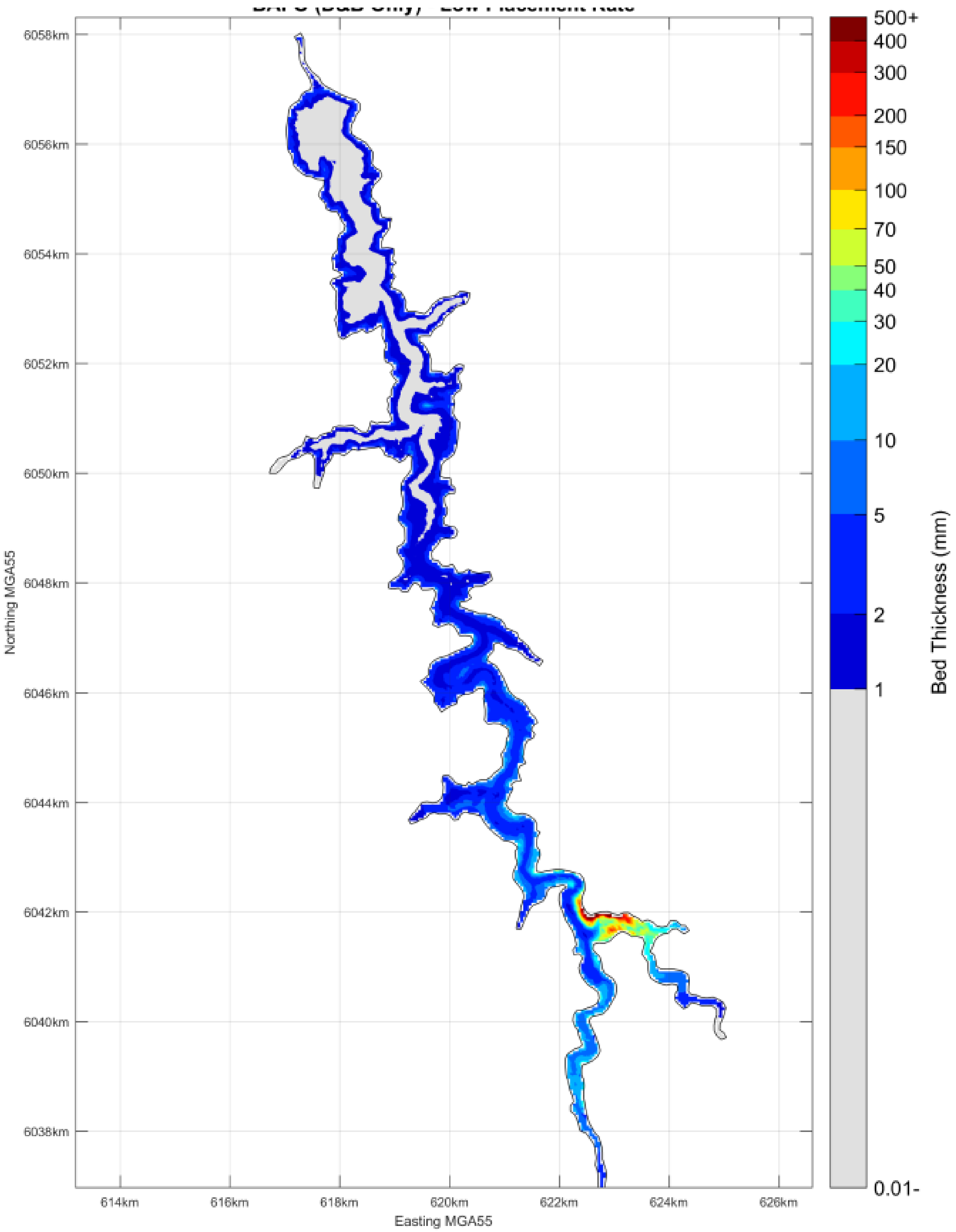


Figure 5-4 Sediment Deposition Thickness (End 36 month) Ravine Bay Placement

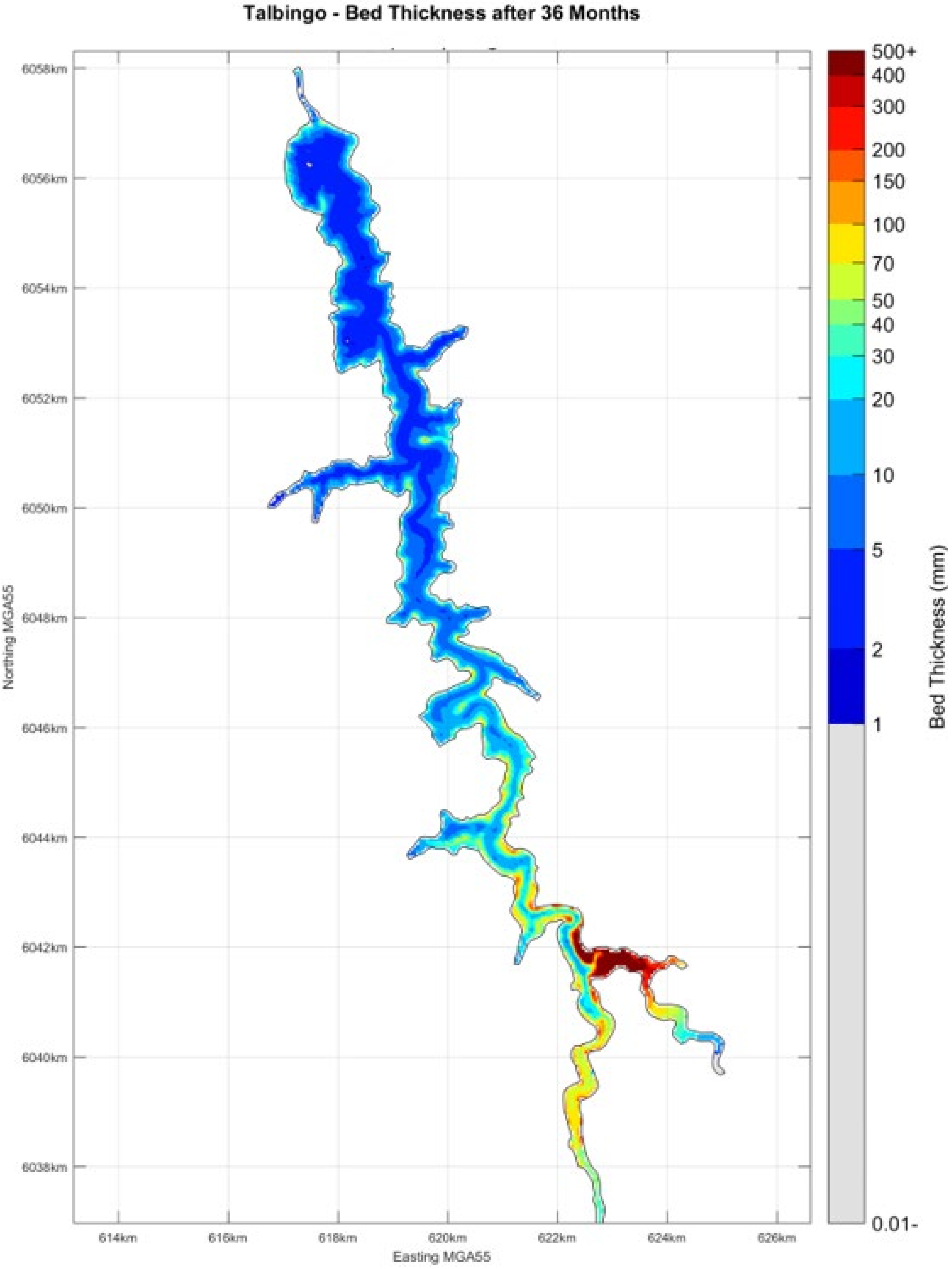


Figure 5-5 *Sediment Deposition Thickness for Hybrid Placement*

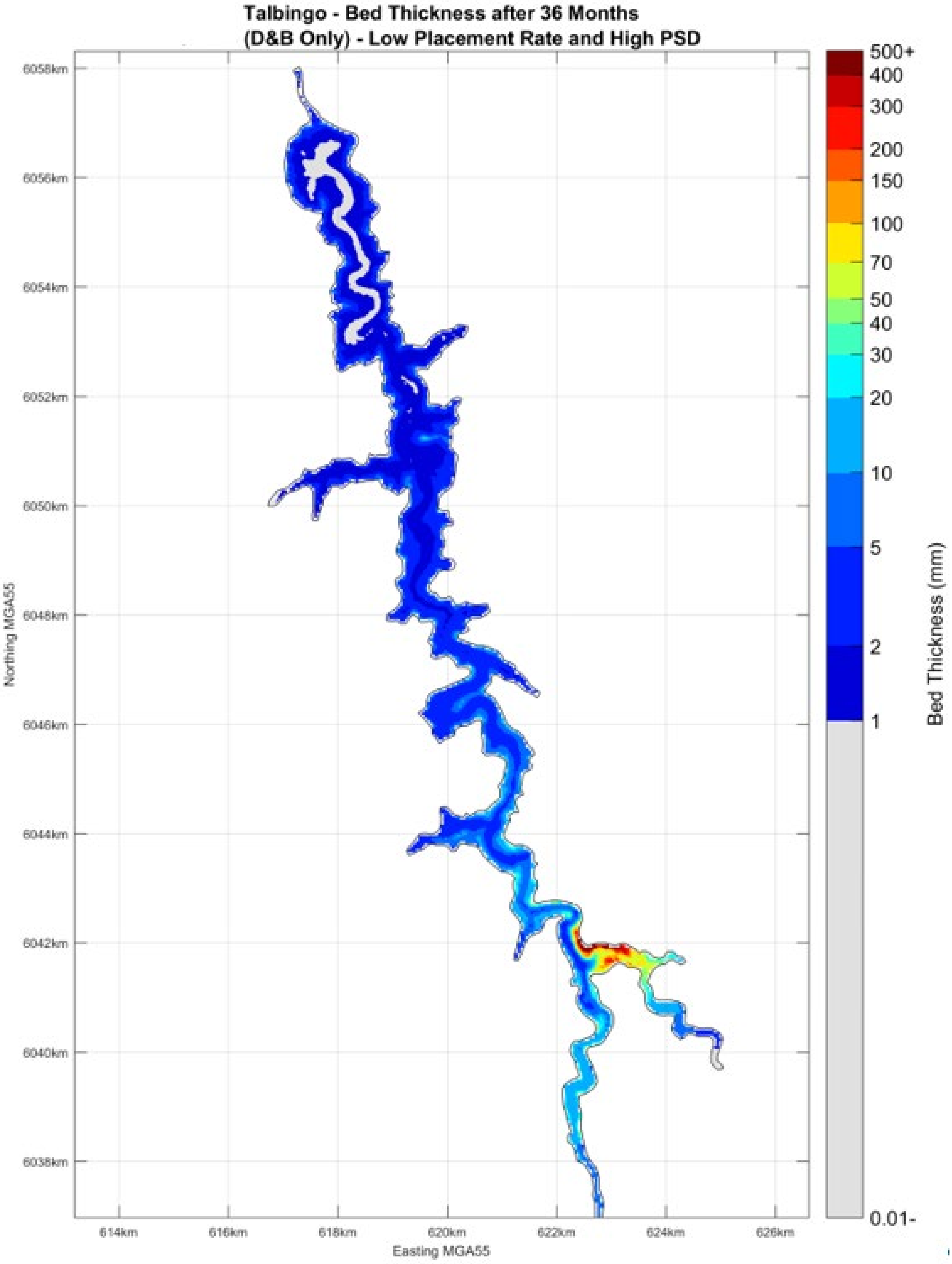


Table 5-2 Summary of TSS Time-Series Results (Proposed, Alternative Hybrid (D&B Only))

Location	Peak Surface TSS (mg/l)) - Proposed	Peak Surface TSS (mg/l)) – Alternative	Peak Surface TSS (mg/l)) – Proposed (with High PSD)	Peak Surface TSS (mg/l)) – Alternative (with High PSD)
Location 1 (near dam wall)	16	3-4	24	5
Location 4 (Lick Hole Creek)	25	<5	39	7
Location 9 (~1 km North of Placement Area)	32	7	48	11
Location 11 (500m East of Placement Area)	80	33	120	50

Table 5-3 Summary of Modelled TSS Mass Leaving Talbingo Reservoir

Location	Mass Tonnes - Proposed	Mass Tonnes - Alternative	Mass Tonnes - Proposed (with High PSD)	Mass Tonnes - Alternative (with High PSD)
Mass of silt leaving the reservoir (tonnes)	6,018	1,209	8,930	1,778
Mass of clay leaving the reservoir (tonnes)	10,003	2,858	16,007	4,761
Total Mass fines leaving the reservoir (tonnes)	16,021	4,067	24,937	6,539

Table 5-4 Summary of Modelled Deposition Rates (mm/yr)

Location	Proposed	Alternative	Proposed (with High PSD)	Alternative (with High PSD)
Northern Half of Reservoir	1-10	< 3	2-15	< 5
Southern Half of Reservoir	5-30	1-8	7-45	2-12
Near Ravine Bay	> 100	> 20	> 150	>30

Because the Alternative Hybrid places only half the volume of excavated rock into Talbingo Reservoir, and D&B material has less than half the volume of fines of the TBM and D&B materials combined, TSS concentrations and deposition thickness for the Alternative Hybrid are typically only 25% of the proposed option. The sensitivity testing option investigated a scenario where the PSD comprised 50% more fines than the amount of fines assumed in the "base case" scenario. TSS concentrations and deposition thickness for the sensitivity model runs are typically 50% more than that of the "base case" (proposed and alternative) options.

A more detailed summary of time-series TSS concentration data including an estimation of the equivalent turbidity values is presented below in **Table 5-5**.

Table 5-5 A summary of predicted surface TSS concentrations

Location	Location description	Estimated TSS concentration (mg/L)				Estimated turbidity (NTU)[3]		
			Annual	Warming	Cooling	Annual	Warming	Cooling
Talbingo Reservoir background level (2018–2019)		**<1–6 mg/L[1]**				**1-5 NTU[4]**		
Default guideline value		**note 2**				**1-20 NTU[5]**		
11	Yarrangobilly Arm, approximately 500 m of placement area	Median	18	43	9	39	61	28
		Maximum	80	80	70	83	83	78
9	Approximately 1 km north of placement area	Median	7	18	7	24	39	24
		Maximum	31	31	25	52	52	46
4	Adjacent Lick Hole Creek, approximately half-way along the reservoir	Median	8	15	5	26	36	20
		Maximum	26	26	22	47	47	43
1	Adjacent the dam wall	Median	6	10	3	22	29	16
		Maximum	16	16	14	37	37	34

1. Discrete water quality samples collected 2018-2019.
2. There is no default ANZECC/ARMCANZ (2000) TSS concentration guideline value.
3. Ravine beds: $\text{NTU} = 9.0649 \times \text{TSS}^{0.506}$
4. Time-series results from mooring in reservoir (2018/2019), 1st-percentile to 99th-percentile
5. Default turbidity guideline value for freshwater lakes and reservoirs in South-Eastern Australia (ANZECC/ARMCANZ 2000)

6 Modelling Study – Commissioning

6.1 Introduction

A Reservoir Modelling Commissioning Phase Operations Study has been undertaken as part of the ERP studies for the Snowy 2.0 Main Works (**Annexure H**). Hydrodynamic and sediment transport models were developed to investigate and assess the key processes (e.g. freshwater flow, thermal stratification and sedimentary processes) in the reservoirs. The final report documents the results of the modelling undertaken for the **commissioning phase** of Snowy 2.0 and also show the effects of operational flows on current speeds and sediment transport, and the resultant operational (generation/pumping) conditions.

National Electricity Rules (NER) compliance testing will be undertaken by Snowy Hydro to demonstrate to the AEMO that Snowy 2.0 is ready to be connected to the grid. The six Snowy 2.0 turbine/pumps will be commissioned sequentially over 2 years. The water flow from the intake-outlet structures during this time will vary significantly over the commissioning period. As such, this assessment focuses on short-term (days and weeks) simulations for a range of flows that may arise during commissioning tests (during both pumping and generation).

The scenarios investigated were primarily focussed on those commissioning tasks with the longest duration and greatest flow rate (270 m^3/s during pumping and 372 m^3/s generation) as these operational conditions would result in the greatest impact on hydrodynamic and sediment transportation potential in the reservoirs under low operating water levels (e.g. near MOL).

6.2 Operational Modelling Results

6.2.1 Talbingo Reservoir

Based on the predicted current speed and shear stress in Talbingo Reservoir for peak flows during commissioning, a number of general observations were made based on the proposed Ravine Bay excavated rock placement method:

- currents and bed shear stresses are higher during generation than during pumping, within the inlet channel
- during generation, peak near bed current speeds in the order of 0.5 to 0.7 m/s are predicted along the Yarrangobilly Arm extending downstream as far as the Ravine Bay placement area. During pumping, peak currents of up to 0.5 m/s between the placement area and the Snowy 2.0 intake structure are predicted
- the relatively narrow 'throat' section between Middle Bay and Ravine Bay is an area of higher currents and higher bed shear stress, and
- there is a particular 'hot spot' of higher currents and bed shear stress adjacent to the south-eastern edge of the placement area.

6.2.2 Tantangara Reservoir

Based on the predicted current speed and shear stress in Tantangara Reservoir for peak flows during commissioning, a number of general observations were made:

- currents and bed shear stresses are higher during generation than during pumping, within the inlet channel

- during generation water is drawn mainly from the northern section of the reservoir
- during pumping the exit jet is directed along the axis of the inlet channel towards the opposite shore of the reservoir before turning northwards
- the proposed placement area, situated between MOL and FSL, is located well to the north of the intake structure and does not interact with generation and pumping flows to any material extent
- during generation, peak near bed current speeds in the order of 0.4 to 0.8 m/s are predicted along the intake approach channel. During pumping, peak currents along the intake approach channel of between 0.2 m/s and 0.4 m/s are predicted
- within the main body of the reservoir, current speeds are much lower than the intake channel, with peak current speeds of less than 0.1 m/s predicted. For other locations (e.g. near the dam wall and areas more than 500 metres from the main intake channel), modelled current speeds are less than 0.05 m/s
- during generation (outflow from Tantangara Reservoir), bed shear stress of between 0.4 and 0.7 Newtons per square metre (N/m^2) is predicted along the intake approach channel. During pumping (discharge to Tantangara Reservoir), bed shear stress of between 0.2 and 0.4 Newtons per square metre N/m^2 is predicted. Localised areas near the intake channel are subject to higher bed shear stress conditions in the range of 0.5 to 1 N/m^2 during pumping and generation modes of operation. This indicates high sediment transport potential along the intake approach channel, and
- beyond the intake approach channel, bed shear stress is less due to lower peak current speeds and greater water depth conditions in the main body of the reservoir.

6.3 Assessment of Potential Disturbance of Sediments

The bed shear stress can be compared to the critical bed shear stress for mobility, for the range of possible sediments on the bed of the reservoirs**,** namely:

- fine excavated rock (sediment) that has settled away from the placement area during the construction phase, and
- existing (*in situ*) sediments.

The potential for these sediments to be disturbed in each reservoir is summarised below.

6.3.1 Talbingo Reservoir

The sediments formed by migrated excavated rock material would have a ‘fluffy’ consistency with little or no shear strength. The predicted bed shear stresses indicate that the fine settled material would be expected to be remobilised during both generation and pumping phases. Remobilisation during generation means that the fine sediments would be transported downstream. Remobilisation during pumping operations means the fine sediments would be transported upstream into the intake and through to Tantangara Reservoir.

All of the existing reservoir bed sediments contain considerable amounts of fines (silt and clay). With the exception of the residual soils which can be firm to stiff, the sediments would have negligible shear strength and would be potentially readily erodible. The lacustrine deposits and the majority of the topsoil and alluvial materials within Middle Bay downstream of the intake works and over large areas of Ravine Bay would be expected to be eroded during both generation and pumping phases for both the Ravine Bay Placement and Hybrid Placement options. No conclusion can be drawn regarding the disturbance of residual soils but erosion of these materials over a similar spatial extent cannot be ruled out.

6.3.2 Tantangara Reservoir

The shear stresses when compared to the critical shear stress values indicate that the lacustrine deposits, topsoil and alluvial materials, plus the very soft to soft clays at depth, located within the intake channel and areas directly offshore and adjacent (mostly to the north), would be expected to be eroded during generation and pumping. No conclusion can be drawn regarding the disturbance of residual soils but erosion of these materials over a similar spatial extent cannot be ruled out.

As the proposed placement area is situated between MOL and FSL and located well to the north of the intake structure such, potential disturbance to the edges of the placement area by generation and pumping flows would be negligible.

It is evident from the above discussion that:

- in **Talbingo Reservoir**, both fine settled material from the construction phase and existing reservoir sediments located within Middle Bay downstream of the intake works and over large areas of Ravine Bay, would be expected to be disturbed by generation and pumping flows for a period of time post-construction until a long term equilibrium is established, and
- in **Tantangara Reservoir**, existing reservoir sediments located within the intake channel and areas directly offshore and adjacent (mostly to the north) would be expected to be disturbed by generation and pumping flows for a period of time post-construction until a long-term equilibrium is established.

For both reservoirs, there is a greater potential for disturbance during generating than during pumping, due to the higher flows involved in the former mode of operation.

Disturbance of sediments would be expected to continue over hours during generation and pumping while bed sediments remain in the area affected by elevated bed shear stresses.

6.3.3 Management

Snowy Hydro has established a number of commitments which are relevant to the matter of sediment disturbance, as listed below:

- minimise turbulence and the creation of surface waves which have the potential to present a hazard to members of the public as a result of sudden commencement of flow through the intake structure
- prevent scour of the approach channel and surrounding areas of the reservoir
- prevent the formation of vortices
- minimise the potential for debris being moved toward the intake (which may then require removal), and
- minimise the amount of sediment being mobilised and drawn into the waterway or dispersed into the reservoir.

In addition to the above, the following studies are to be undertaken to inform construction design:

- sediment mobilisation analysis in order to understand the extent of underwater excavation required as well as the type and extent of surface treatments required, and
- analysis of the structure outlet velocity profiles in both pump and generation mode using CFD to optimise head and eliminate scour and erosion issues.

Options to prevent or minimise bed disturbance that are being considered by Snowy Hydro include:

- modification of the works, e.g. inlet works and placement areas
- removal of sediments from the potential disturbance zones, and
- armouring of the sediments in the potential disturbance zones.

Annexure A CSIRO Comprehensive Geochemistry Examination

CSIRO MINERAL RESOURCES
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Snowy 2.0 P1: Comprehensive Geochemistry Examination

Final Report

Ryan Fraser, Yulia Uvarova, Mark Pearce, Sam Spinks, June Hill, Grant Douglas and Monica leGras

2 Nov 2018

For Snowy 2.0 Scheme, Snowy Hydro Limited
Commercial-in-confidence

Citation

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Important disclaimer

Foreword and Assignment Summary

CSIRO was requested by Snowy Hydro Limited (SHL) in November 2017 to provide scientific expertise and capability in relation to identifying and assessing the environmental risks associated with the placement of excavated rocks from the development and operations of the proposed Snowy 2.0 scheme. EMM Consulting (EMM) had been selected to prepare the Environmental Impact Statement (EIS) on behalf of SHL, and CSIRO's role was to develop and undertake a series of Assignments to provide information for environmental risk assessment associated with handling of excavated rock materials from the proposed works. In December 2017, CSIRO worked with EMM to develop conceptual models to provide information to the environmental risk assessment (ERA). As a result CSIRO agreed to undertake an initial series of five assignments.

In March 2018, Haskoning Australia (HKA) was engaged to provide additional capability, specifically to take the role of leading the project entitled: "Engineering Option for placement of Excavated Rocks". The draft work assignments CSIRO had previously provided to SHL and EMM (in late January 2018) were subsequently updated to ensure they would fulfil the needs of EIS requirements and HKA's "Engineering Option for placement of Excavated Rocks" project. These updated Assignment(s) have been executed and are providing relevant input into the ERA.

This report details the results of one of the Assignments, P1: Comprehensive Geochemistry Examination.

Disclaimer

This Assignment Subcontract and all documents and information provided by CSIRO to HKA under this Assignment Subcontract are prepared (i) as inputs for further scientific services to be performed for HKA by CSIRO under separate Assignment Subcontracts that has been agreed; and (ii) to assist HKA in its development of a excavated rock disposal and management plan as part of the environmental impact assessment process for the proposed Snowy 2.0 Pumped Hydro Electric Scheme("Purpose"), and for no other purpose. This Assignment Subcontract does not involve the provision of advice or recommendations in relation to specific risks or mitigations associated with Excavated Rock disposal and management or design and construction of the Snowy 2.0 project however it is understood that the inputs provided by CSIRO are for the Purpose and are based on CSIRO's professional skill, care and~~,~~ diligence in performing this Assignment Subcontract. In the course of performing this Assignment Subcontract, CSIRO may rely on stated assumptions and/or information provided by HKA or third parties which is not within the control of CSIRO, and this Assignment does not involve CSIRO verifying such assumptions or information except to the extent expressly stated herein. If CSIRO provides any forecasts or projections, CSIRO does not represent that they will be realised as forecast or projected and actual outcomes may vary materially from forecast or projected outcomes. Documents and information provided to HKA under this Assignment Subcontract are to be read as a whole, and if reproduced must be reproduced in full and no part should be read or relied upon out of context. CSIRO does not accept responsibility for, or liability arising from, any error in, or omission in connection with, stated assumptions or third party-supplied information, or reliance on documents or information provided under this Assignment by HKA other than for the Purpose, or by any other person.

Contents

Figures

Tables

Acknowledgments

CSIRO would like to acknowledge the support from Haskoning Australia Pty Ltd with assistance in acquiring all relevant background and associated information for this report.

CSIRO would also like to thank its sub-contractors, particularly Minalyze Pty Ltd and LabWest Minerals Analysis Pty Ltd, who collaborated closely in this research project.

1 Executive Summary

This report covers Assignment P1: Comprehensive Geochemistry Examination. For this assignment, detailed geochemical and mineralogical characterisation was undertaken on drill core and lab samples from the Snowy 2.0 drilling program. Data from this study will be used to provide information on the chemical composition and mineralogy of the rocks to be excavated during the proposed Snowy 2.0 scheme. This information is essential for understanding potential environmental impacts of excavated rock during handling and disposal.

Three sampling techniques were employed to determine the chemical and mineralogical composition:

1. Continuous chemical analysis of all drill core intersecting rock units likely to be excavated (from power station, surge shaft, head and tail race tunnels), to provide a complete record of the chemical composition of the rocks;
2. High precision chemical analysis on selected samples from the core sections to complement the continuous analysis (1); and
3. Analysis of the selected samples for modal mineralogy to determine the mineral hosts of elements of concern, and their potential mobility with respect to potential environmental impacts.

The analytical techniques employed were:

1. High spatial resolution continuous X-ray fluorescence (XRF) logging for continuous core chemistry;
2. High precision geochemical analysis of selected samples;
3. X-ray diffraction to determine modal mineralogy; and
4. Scanning electron microscope-based automated mineralogical analysis of accessory mineralogy in selected sulphide-rich and suspected naturally occurring asbestos (NOA) samples.

Results indicated that two lithological units contained elevated sulphur concentrations: Ravine Beds and Gooandra Volcanics. The Ravine Beds contain a 35m apparent thickness shale unit containing approximately 1.5% S. The Gooandra Volcanics contain a unit of unconstrained thickness with up to 4% S. In addition, this unit in the Gooandra Volcanics contains naturally occurring asbestos. The unit has been logged as rhyolite during drilling but the composition is more consistent with a basaltic andesite. In lithologies other than the Ravine Beds and Gooandra Volcanics, sulphide minerals, some of which are arsenic and lead bearing, occur in veins but represent a volumetrically minor (<1%) component of the rocks sampled.

A summary of the lithological units that will be intersected by the proposed tunnel works is as follows:

Byron Range Group

- Siliciclastic rocks, mostly siltstones, shales, sandstones and conglomerates.
- Mineralogy dominated by quartz and feldspars, with lesser amounts of muscovite, chamosite, calcite and hematite.

Boraig Group

- Sedimentary and volcanic rocks.
- Dominated by quartz and feldspar, with minor muscovite, chamosite, and calcite. Accessory dolomite, hematite, pyrite, scapolite, kaolinite and actinolite are also observed in a few drill holes.

Kellys Plain Volcanics

- Volcaniclastic rocks.
- Quartz, feldspars, muscovite and chamosite with accessory kaolinite (up to 5%) observed in drill hole BH1115.

Ravine Beds

- Interlaminated shales, siltstones, and conglomerates, composed of quartz, feldspars, muscovite and chamosite. Calcite (up to 10%) and dolomite (up to 11%).
- Minor pyrite, hematite and scapolite.

Tantangara Formation

- Siliciclastic rocks, mainly composed of quartz, feldspars, muscovite and chamosite.
- Minor dolomite and pyrite only observed in drill hole BH3101.

Temperance Formation

- Volcaniclastic rocks comprised of quartz, feldspars, muscovite, chamosite, actinolite, epidote, diopside, and minor calcite.

Shaw Hill Gabbro

- Intrusive gabbro composed of quartz, feldspars, muscovite, chamosite, actinolite, and epidote, with minor calcite and hematite.

Gooandra Volcanics

- Volcanics rocks comprised of quartz, feldspars, muscovite, chamosite, and epidote, with minor calcite, dolomite, and hematite.

2 Introduction

This report covers Assignment P1: Comprehensive Geochemistry Examination (herein referred to as P1). For this assignment, a detailed geochemical and mineralogical characterisation study was carried out on drill core samples from the Snowy 2.0 scheme drilling program. Data from this study will be used to provide information on the composition of the rocks to be excavated during the proposed Snowy 2.0 scheme. This information is essential for understanding potential environmental impacts of excavated rock handling and disposal.

P1 is part of a collection of Assignments being conducted by CSIRO on behalf of Snowy Hydro Limited (SHL). The results from P1 have provided information for subsequent assignments: P2, P4 and P5, which are:

- P2: Environmental Risk Categorisation of Rock Materials, i.e. identifying the reactivity of the rock and its risk category;
- P4: Environmental Categorisation of Excavated Rock Interactions with and Potential Impacts on Reservoir Waters and Sediments, i.e. categorising excavated rocks impact on reservoir water and sediments; and
- P5: Ecotoxicology Assessment of Excavated Rock Leachates in Water and Excavated Rock-Sediment Mixtures, i.e. assessing the ecotoxicology impact of placement of the excavated rocks within the reservoir.

P1 involved the development of compositional profiles for each of the geological units (detailed below, Figure 1) which have been intersected by the Snowy 2.0 drilling program (Figure 2). The profiles comprise:

1) Geochemical rock compositions, highlighting potentially environmentally problematic elements; and
2) Mineralogy of the rocks, highlighting which minerals contain problematic elements.

The Proposed Snowy 2.0 scheme transects nine major surface geological units located within the southeast part of the Lachlan Mobile Belt of New South Wales, Australia (Figure 1). The area comprises sedimentary, igneous and metamorphic rocks of Ordovician to Devonian age. These are overlain by Cenozoic basaltic volcanic rocks. The area comprises the following geological groups (lithological units), which are used throughout this report to characterise the geochemistry and mineralogy.

The following zones (1-9) are represented below in Figure 1.

1. **Boraig Group/Byron Group** [(1a & 1b) Sandstone/Shale Zone] - also known as the Exploratory works zone, including Pressure Surge Shaft and Powerhouse.
2. **Ravine Beds** [Yarrangobilly Limestone] - Talbingo Inlet/Outlet and Tailrace

3. **Kellys Plain Volcanics** - Tantangara Inlet/Outlet
4. **Peppercorn Formation** - Tunnel Alignment (headrace)
5. **Tantangara Formation** - Tunnel Alignment (headrace)
6. **Temperance Formation** - Tunnel Alignment (headrace)
7. **Boggy Plains** (formerly listed as Granitoids/quartz) - Tunnel Alignment (headrace)
8. **Gooandra Volcanics** - Tunnel Alignment (headrace)
9. **Shaw Hill Gabbro** – Tunnel Alignment (headrace)

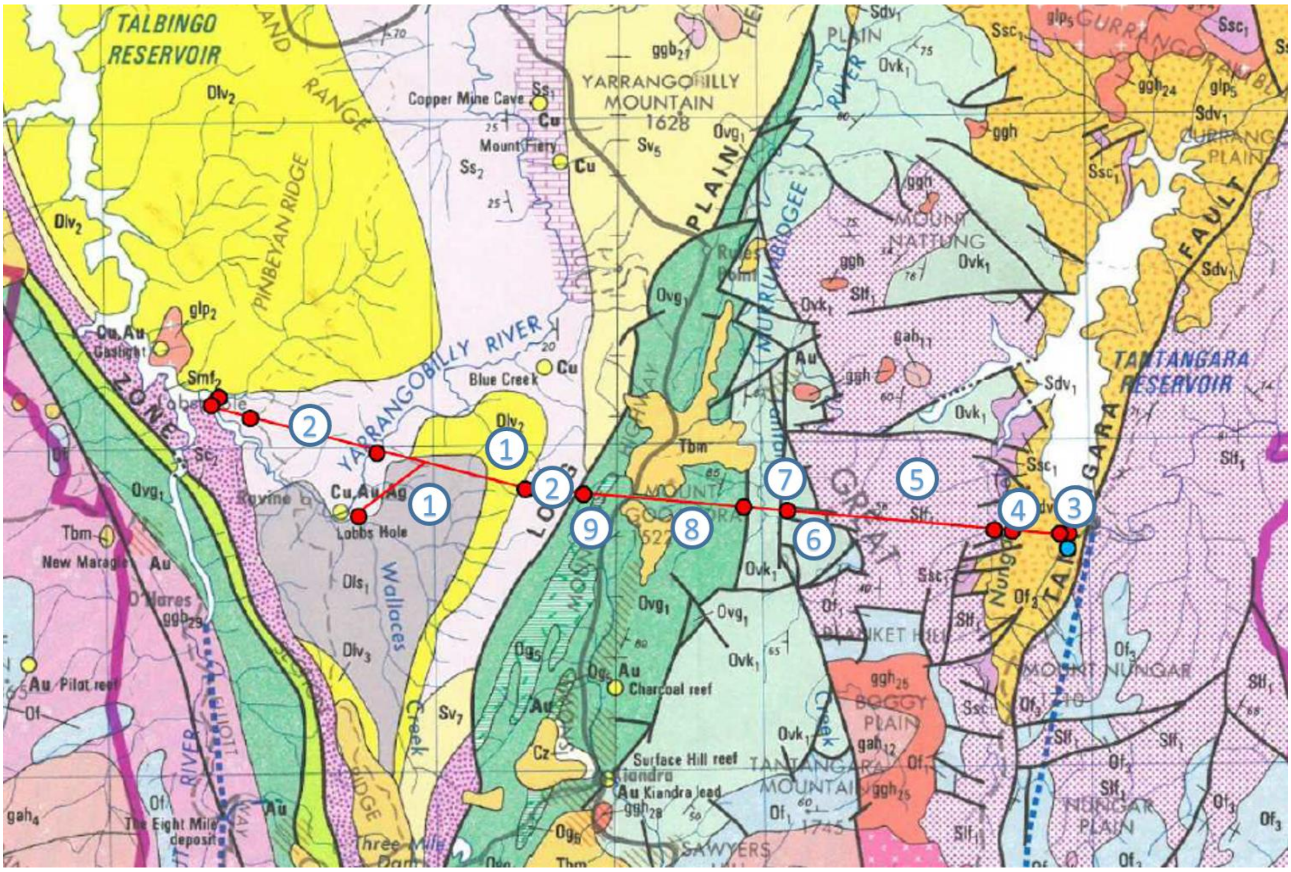


Figure 1. Proposed Snowy 2.0 Scheme divided into Geological Zones (annotated on original from SMEC Geology Appreciation Report)

The location of the boreholes drilled as part of the Snowy 2.0 feasibility studies are available in Appendix A. 37 boreholes were analysed as part of P1 to establish compositional profiles (geochemical rock composition and mineralogy of the rocks).

It should be noted that the drill core samples made available to CSIRO in this study constitute only a small fraction of the rock to be excavated and any potential spatial variation between the drill holes must be taken into account when making decisions. It is intended that the information contained within this report should be used by the client as a guide to decision-making regarding the environmental impact of disposal of the excavated rock material, in particular, whether harmful materials are likely to be released into the environment.

3 Analytical methods

3.1 Overview

The results of P1 provide a comprehensive examination of the geochemical composition and mineralogy of samples from drill core supplied by GHD (GHD were responsible for the drill program for Snowy 2.0). Analytical workflows were designed to work within time constraints and other constraints of the P1 project plan. In particular, a limitation on core preservation, since SHL requested that no core be destroyed other than that already extracted for uniaxial compression strength [UCS] testing. The major analytical techniques used in this study were;

1. High resolution geochemical scanning using the Minalyze Core Scanner along complete sections of drill core (see section on Core Scanning Workflow, below). Almost 4000 m of core was examined, which included analysis of:
    i. complete sections of core that intersected the proposed Surge, Pressure and Power caverns; and
    ii. core that intersected the proposed tunnel alignment (including a 20m buffer above and below to accommodate possible change in alignment);
2. Laboratory analysis of selected samples (previously used for UCS testing) for geochemical analysis (see section on Lab Workflow Geochemistry, below). This analysis provides data with better precision and lower detection limits compared to the Minalyze Core Scanner; and
3. Laboratory analysis of selected samples (previously used for UCS testing) for mineralogical analysis (see section on Lab Workflow Mineralogy, below).

The **Core Scanning Workflow** (see Section 3.2 for more details) involved on-site core scanning using the Minalyzer Core Scanner (CS) which uses X-ray technology to measure a selected list of major and minor element concentrations at 10 mm intervals along the surface of the core. Details of section of cores analysed can be found in Appendix A.

Core Scanning Workflow Output delivers Geochemical Rock Composition, including:

- Continuous, along drill hole, records of the composition of the rocks at high resolution that is capable of locating narrow intervals which could be masked in larger samples used for laboratory analysis, or missed by selective sampling.

Lab Workflow (Geochemistry) Output delivers Geochemical Rock Composition, including:

- Concentrations of elements not detected and measured by the Core Scanning Workflow;
- Datasets for QA/QC of the Core Scanning Workflow data; and
- Mean compositions and estimates of variability for elements not measured by the Core Scanning Workflow.

Mineralogical laboratory analysis (**Lab Workflow (Mineralogy),** see Sections 3.3.2-3.3.3 for more details) utilises CSIRO's X-ray diffraction (XRD) and scanning electron microscope (SEM) analytical facilities. The XRD provides information that allows identification of major minerals and the SEM provides information of mineral associations. The output is used to determine modal mineralogy for each sample (i.e. the proportion of each mineral in the sample), which can then be used to estimate the distribution of the elements within the minerals. This information is useful, for example, in understanding the potential reactivity of elements once they have been disposed of in an aqueous environment.

Lab Workflow (Mineralogy) Output: delivers mineralogy of the rocks, including:

- Identification of samples with minerals that host environmentally problematic elements.

3.2 Core Scanning Workflow

3.2.1 X-Ray Fluorescence (XRF) analysis

The Minalyzer CS provides XRF scanning of drill core. Initially, laser scanning is used to generate a 3D model of each core tray to guide the height of the XRF detector during analysis. For consistent results, it is essential to maintain a constant distance from the detector to the core surface. A high-resolution RGB line scan camera (10 pxnm^{-1}) produces digital photos of the drill core trays which can be draped on the laser profile for enhanced visualisation.

X-Rays are collected from a 2-cm wide strip along the core. The raw spectra are stored in 10-mm intervals down the length of the core. During processing, these intervals are aggregated to produce composite spectra over 10-cm intervals. Background is subtracted, and the spectrum is deconvolved into a series of Gaussian peaks representing different elements. The intensity of a peak is proportional to the elemental concentration. To ensure the accuracy of element concentrations, data are calibrated using certified standards.

The following elements are measured: Aluminium (Al), Silicon (Si), Phosphorus (P), Sulphur (S), Chlorine (Cl), Potassium (K), Calcium (Ca), Titanium (Ti), Vanadium (V), Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), Copper (Cu), Zinc (Zn), Gallium (Ga), Arsenic (As), Rubidium (Rb), Strontium (Sr), Yttrium (Y), Zirconium (Zr), Niobium (Nb), Barium (Ba), Lead (Pb), and Uranium (U).

Within this Assignment, the workflow included the analysis of approximately 4000 m of core, extracted from 37 boreholes drilled by GHD along the tunnel alignment. Analysis of the full length of core drilled was conducted on cores associated with the Powerhouse, Surge and Pressure shafts (BH5102, 5103, 5104), whereas only selected sections of the cores drilled within the tunnel alignment (+/- 20m) were analysed.

3.2.2 Drill Hole Domains

Mathematical methods can be used to composite the continuous XRF sample results into geochemically similar domains which reflect geological rock units. The method uses a boundary detection algorithm to locate boundaries between distinctive geochemical domains and also provides a measure of the strength of the boundary. The strength of the boundary reflects the compositional difference between the domains either side of the boundary as well as the apparent thickness of the domains. The results can be visualised on a depth-scale plot (i.e. tessellation; Hill et al., 2015), where the y-axis is depth and the x-axis is scale (as measured by boundary strength). Tessellation plots of selected elements are provided in Appendix A. The elements illustrated in Appendix A were selected on the basis that they are the most diagnostic for indicating rock type (Si, Cr, Mg, Ca, K) or have potential environmental impact (S), in particular:

- Ca + Mg - often indicate carbonate (Calcite/Dolomite) alteration or the presence of limestone.
- K - higher concentrations of K often indicate shales or clay-rich lithologies but can also be indicative of an alteration zone around a fault (as with Si) as K is one of the more “mobile” elements. Identifying alternative zones is important as they can be made up of multiple lithologies.
- Cr - relatively immobile and in combination with Si assists in distinguishing more mafic lithologies (for example differing volcanics).
- S - depending on concentrations and mineral host type, could have potentially important environmental outcomes.

Geological logs supplied to CSIRO have been included with the tessellation plots in Appendix A to allow direct comparison. Guidelines to interpreting the tessellation plots are as follows:

- The y-axis is depth down hole.
- The horizontal lines represent geological boundaries (i.e. locations of abrupt change in chemical composition).
- The length that the boundary extends to along the x-axis is a reflection of the boundary strength.
- Vertical lines join the boundaries to form geological domains.
- Large scale domains plot to the right of the mosaic and small domains plot to the left.
- The colours of the domains represent the average of the sample values over the depth interval defined by the domain.
- Boundary strength is a combination of amplitude and wavelength of the signal. In geological terms this relates to:
  - Amplitude: how distinctive the composition of the geological unit is compared to its neighbouring units; and
  - Wavelength: apparent thickness of the geological unit.

The files supplied by Minalyze contain two types of missing data which were indicated by No Data (ND) or Below Detection Limit (BDL). The boundary detection algorithm requires values to be at regular intervals, so missing data needs to be replaced by suitable values. ND was interpreted as data missing at random and in this case a linear interpolation was made over the missing data point. BDL indicates that the element was below detection limit. BDL was replaced by a value of 2/3 of the mean detection limit for the element as provided by Minalyze. In places where consecutive intervals of Minalyze data was missing (due to missing core) these are indicated on the tessellation plots by uncoloured (white) rectangles labelled “Missing Data”. Where there was no data for an element (i.e. all intervals either labelled as ND or BDL) or less than 10% of intervals contained data, these variables are represented by empty plots labelled “all data is below detection limit”.

3.2.3 Core Inspection

Following core-scanning using the Minalyze instrument, several intervals were identified as having high S concentrations. These cores were visually examined to determine the following:

- Was the Minalyze analysis representative of that core interval?
- What was the mineralogy of the high S concentrations in the core?
- Was further sampling needed for whole rock geochemistry to indicate the presence of other anomalous elements in those intervals?

3.3 Lab Workflow (Geochemistry and Mineralogy)

The samples provided for laboratory analysis had already undergone UCS testing and had to be thoroughly cleaned prior to use for mineralogical analysis. The CSIRO received 385 UCS samples in 4 batches from GHD. The following workflow was established and was followed for the sample preparation and analyses for the core samples.

1. The samples were cleaned to remove glue and copper sensor stickers so that they didn’t impact the geochemistry analysis that proceeded.
2. The samples were assigned a sample ID, photographed and documented in the sample database using the field acquired information management system. A label with a sample ID was attached to the sample bag.
3. CSIRO geochemists selected 290 of the total 385 samples provided for analysis (removing obvious duplicates or sections of significant similarity), and inserted certified reference materials for quality control purposes.
4. The samples were cut with a diamond saw into three batches: approximately 50% of each sample was sealed in a paper bag and sent to a commercial laboratory for crushing, pulverising, and analysis for multi-element geochemistry (further details given below). 25% of each sample was archived in the original sample bag. The remaining 25% of the sample was placed in labelled plastic bags for analysis in Assignments P2, P4 and P5.
5. Visual inspection by CSIRO geochemists was used to identify potentially important features during sample preparation (e.g. presence of sulphides), in such cases a small slab of the sample was cut for further thin-section preparation and petrography.
6. Once the samples had been cut and prepared, the portion for chemical analysis was conveyed to an accredited National Association of Testing Australia (NATA, ISO/IEC 17025)

laboratory for pulping to 75µm and quantitative elemental analysis by ICP techniques. The sample preparation and analytical protocol for the lab analysis is described below.

7. On completion of the laboratory multi-element geochemistry, the pulps of the samples (approximately 99% of the bulk sample was unused) were returned to CSIRO and used to prepare pressed powder pellets for X-Ray Diffraction (XRD) analysis to obtain information on the sample mineralogy. The sample preparation and analytical protocol for the XRD analysis is described below. This methodology delivers quantitative mineral abundances of the core samples.
8. The remainder of the pulps were made available for tests in Assignments P2, P4 and P5.

3.3.1 Whole-rock geochemistry

Sample preparation and multi-element geochemistry was completed by a NATA accredited laboratory (LabWest Minerals Pty Ltd). The sample preparation is designed to handle low-grade materials without cross-contamination. Samples were dried, crushed (approximately 2mm) and rotary divided where required. Pulverisation was undertaken by a mill and sample preparation bowls were barren-washed between each sample. Pulverisation reduces the sample to pass through <75 micron mesh. The analysis produces multi-element values with rare-earth elements through Microwave-assisted multi-acid techniques (MMA). The MMA technique is a microwave-assisted, hydrofluoric acid (HF) based digestion that effectively offers total recovery for all but the most refractory of minerals. This technique is well suited to materials such as core, rock-chip and lake sediments. A portion of sample was digested in an HF-based acid mixture under high pressure and temperature in microwave apparatus for analysis, with determination of 62 elements (Table 1) by a combination of inductively coupled plasma mass spectrometry (ICP-MS) and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). The samples were accompanied by a number of certified reference materials and duplicates which were randomly inserted amongst the samples for quality control/quality assurance (QA/QC).

Silver (Ag) (0.01)	Aluminium (Al) (10)	Arsenic (As) (0.5)	Barium (Ba) (0.2)	Beryllium (Be) (0.2)	Bismuth (Bi) (0.1)
Calcium (Ca) (10)	Cadmium (Cd) (0.05)	Cerium (Ce) (0.05)	Cobalt (Co) (0.2)	Chromium (Cr) (2)	Cesium (Cs) (0.1)
Copper (Cu) (0.2)	Iron (Fe) (100)	Gallium (Ga) (0.05)	Germanium (Ge) (0.05)	Hafnium (Hf) (0.02)	Mercury (Hg) (0.05)
Indium (In) (0.01)	Potassium (K) (10)	Lanthanum (La) (0.05)	Lithium (Li) (0.5)	Magnesium (Mg) (10)	Manganese (Mn) (2)
Molybdenum (Mo) (0.1)	Sodium (Na) (10)	Niobium (Nb) (0.5)	Nickel (Ni) (2)	Phosphorus (P) (5)	Lead (Pb) (0.2)
Platinum (Pt) (0.001)	Rubidium (Rb) (0.1)	Rhenium (Re) (0.01)	Sulphur (S) (50)	Antimony (Sb) (0.1)	Scandium (Sc) (1)

Selenium (Se) (0.05)	Tin (Sn) (0.2)	Strontium (Sr) (0.1)	Tantalum (Ta) (0.01)	Tellurium (Te) (0.2)	Thorium (Th) (0.02)
Titanium (Ti) (10)	Thallium (Tl) (0.1)	Uranium (U) (0.02)	Vanadium (V) (2)	Tungsten (W) (0.1)	Yttrium (Y) (0.05)
Zinc (Zn) (0.2)			Zirconium (Zr) (1)		
Praseodymium (Pr) (0.05)	Neodymium (Nd) (0.02)	Samarium (Sm) (0.02)	Europium (Eu) (0.02)	Gadolinium (Gd) (0.05)	Terbium (Tb) (0.02)
Dysprosium (Dy) (0.02)	Holmium (Ho) (0.02)	Erbium (Er) (0.05)	Thulium (Tm) (0.05)	Ytterbium (Yb) (0.05)	Lutetium (Lu) (0.02)

Table 1. Detection elements from Whole Rock Geochemistry Analysis (limits given in brackets in parts per million [ppm]).

Results were reported in standard CSV and PDF file formats. Sample pulps were returned to CSIRO.

3.3.2 X-Ray Diffraction analysis for Mineralogy, Major Phases

The pulped samples were analysed by XRD using a lab-based Bruker D4 Endeavor AXS instrument, operating with Co radiation; data collection range of 2θ angle from 5 to 90°, with step size of 0.02°; data collection time of 10 minutes per sample. Sample preparation for the analysis on the Bruker instrument requires the material to be pressed into a special sample holder that is placed into the diffractometer. Quartz contained in the analysed samples was used as an internal standard to verify mineral peak positions and correct for any displacement if required.

The XRD patterns obtained are processed and mineral assemblages are quantitatively estimated using two different software packages: Bruker DIFFRAC.EVA which is based on the Reference Intensity Ratio (RIR) method (Smith et al. 1987) and SIROQUANT which is based on the Rietveld method (Rietveld 1967, 1969). Each peak above the background is examined and mineral identification in the analysed samples is done manually to ensure that all components present in the multiphase mixtures are identified and accounted for, as the quantification data are normalized to 100%.

In addition, two artificial mixtures prepared by weight using well-characterised mineral standards (i.e., quartz, albite, muscovite, biotite, hornblende and pyrite) were analysed and their mineral abundancies were quantified using the same procedures as the unknown samples for QA/QC.

3.3.3 Scanning Electron Microscopy for Mineralogy, Minor Phases

For identification and quantification of minor mineral phases, SEM was used. QEMSCAN system is an example of SEM methodology. QEMSCAN provides a surface map of the rock particles, collecting energy-dispersive X-ray spectra across a grid with user-defined resolution. X-ray spectra and backscattered electron (BSE) signals that are emitted from the sample are used to identify minerals. For each sample, a representative aliquot (usually a combination of two particle size fractions) is mounted in an epoxy resin block, which is polished on one side, imaged under reflected, plane polarised light and analysed.

4 Results

4.1 Geochemical characterisation: Snowy 2.0 Scheme Full Core (Core Scanning Workflow)

4.1.1 Core Scanning Results

Using XRF (Minalyze) data and the Tessellation (Drill Hole Domains) methodology (Section 3.3.2) combined with geological core logs, key features of each log, such as elevated S or As concentrations, have been identified (Table 2). Figures showing element concentrations and Tessellation results are contained in Appendix A. Locations of Boreholes relative to their lithological unit (geology zone) can also be found in Appendix A.

Core ID	Geology Log Summary	Summary of Geochemical Observations	Dominant Unit
BH1114	Logged as dacite	Sulphur is below detection limit for all intervals logged with the exception of three isolated 10 cm intervals that contain < 0.5%.	Kellys Plain Volcanics
BH1115	Logged as dacite	The core shows two peaks in S content that bracket an interval with increased Ca. The core photos show that this interval is paler in colour than the rocks either side of it consistent with fluid flow along a fracture around 33 m.	Kellys Plain Volcanics
BH1116	Logged as dacite	Sulphur is below detection limit for all intervals logged with the exception of two isolated 10 cm intervals that contain < 1%.	Kellys Plain Volcanics
BH1117	Logged as dacite	An interval between 25.35 and 26.3 m shows S content of approximately 0.5% and up to 2% in one 10 cm interval.	Kellys Plain Volcanics
BH2101	Logged as a dacite layer within siltstone	Sulphur occurs at contact between siltstone and dacite and within fractures in the siltstone giving locally high S values of 3-4% for the given 10 cm intervals.	Kellys Plain Volcanics+ Tantangara
BH2102	Logged as interbedded sandstone and siltstone	Sulphur occurs sporadically throughout most of the logged section. One approximate 0.5 m interval at 147 m depth contains approximately 1% S. This interval also contains As at up to 30 ppm. The core photos suggest that this interval is a poorly consolidated shale.	Tantangara
BH2103	Logged as metasandstone and metasiltstone	Sulphur is generally below detection limit but the core contains occasional localised intervals with up to 1% S and up to 30 ppm As.	Tantangara
BH3101	Logged as interbedded metasandstone and metasiltstone with a metasandstone unit	Sulphur occurs between 2 and 3 % for a 0.5 m interval around 277 m. This interval of core contains a sulphide bearing vein. There is no systematic increase of As with S.	Tantangara
BH3102	Logged as interbedded metasiltstones and metasandstones with a pyroxenite at the top of the logged section	Chromium is elevated to 400 ppm in the pyroxenite. Sulphur concentrations vary at around 0.5% within much of the metasedimentary sequence, locally reaching 1.5 % around 169 m depth.	Temperance Formation
BH3104	Logged as siltstone with an 8m interval of sandstone at the top of the analysed section	Sulphur occurs sporadically representing single pyrite grains as observed in core photos.	Tantangara
BH3106	Logged as diorite with a <1 m interval of sandstone	Sulphur is generally below detection limit in the diorite. The metasandstone layer contains up to 0.5% S. This layer also contains lower Si, and higher Ca and Mn than the diorite suggesting that the interval is dominated by calcite veins with minor sulphides as have been observed elsewhere in the core.	Boggy Plain (Temperance further up hole)

BH3107A	Logged as interbedded siltstones/sandstones with a siltstone interval, a thin (<1 m) sandstone and a thin (<1 m) breccia.	Sulphur is present throughout the logged core, rarely exceeding 1%. Between 216 m and 222 m the S concentration averages are approximately 0.5% over the 6 m interval. In one thin interval of <1 m near the top of the core S concentration is > 1.5%. This interval also contains higher K and Cr than most of the surrounding rocks consistent with is being a more shale-rich interval.	Temperance Formation
BH3108	Logged as schist	The composition of this interval is relatively consistent with minor variations in K content defining several sub-units. Sulphur content averages 0.3% over the entire core. Around 285 m a single 1 m interval contains >1000 ppm Cr and 300 ppm Ni.	Gooandra
BH3110	Logged as metasandstone with a unit of interbedded metasiltstone-metasandstone at the top.	Two distinct rock compositions are defined by combinations of K, Cr and Mn. High K, low Cr and lower Mn domains that correspond to an interbedded siltstone-sandstone, have marginally higher Si and are S-bearing. The interval between 218 and 224 m depth has a concentration of 0.3% S. Lower K, higher Mn and Cr domains are S poor. Element associations (high Al, K, Rb) suggest that the high K lithologies are more silt/shale rich since all these elements are partitioned into micaceous minerals which are more abundant in shales.	Gooandra
BH4101	Logged as interbedded metarhyolite and metavolcaniclastics.	Sulphur occurs throughout the logged interval. For the 20 m interval between 391 and 411 m depth the concentration of S is approximately 1% with individual metre composites up to 4% S. The measured Si concentrations are too low for rhyolite sensu stricto (20-25% measured vs approximately 32-35%) and the high S concentration suggests either alteration or that this lithology has been incorrectly logged. Core photos indicate a unit dark grey in colour similar to the shale in BH5102. Importantly, the rocks had been treated due to naturally occurring asbestos which might have caused a colour change. Visual inspection of the core during drilling identified fibrous material (see Section 4.3.3).	Gooandra
BH4102	Logged as gneiss and schist.	Sulphur is below detection limit for the entire interval logged.	Gooandra
BH4103	Logged as schist with interbeds of rhyodacite/rhyolite, tuffs and siltstones and basalts.	Sulphur is below detection limit for most of the core except in the interval 80-102 m depth. This does not correspond to a distinct lithological unit although it is contained within what is logged as rhyodacite. This section of the core also contains As up to approximately 100 ppm. In the core photos indicate that this interval is bleached suggesting that the S may have been added during alteration rather than being intrinsic to this lithology.	Gooandra
BH4104	Logged as siltstone with two thin fault breccia zones.	Sulphur is below detection limit for all intervals logged including the fault zone rocks.	Ravine Beds
BH4105	Logged as phyllite.	Sulphur is below detection limit for most of the intervals logged except around 396-398 m depth. In this zone individual 10 cm intervals contain between 0.5 and 0.8% S.	Ravine Beds
BH4106	Logged as interbedded gneiss and schist.	Sulphur is below detection limit for all intervals logged.	Gooandra

BH5102	Logged as siltstone with thin interbeds of sandstone, gravel and calcareous mudstone.	The top 40 m of the core is weathered and this has resulted in depletion of Ca and enrichment of K and Ba. The siltstone has a uniform composition throughout the core consistent with logging as a single lithology. Notable enrichments of S, Ca and As occur between 255 m and 285 m. Inspection of the core revealed that this delineates a zone of shale within the siltstone that has been subsampled for geochemical characterisation.	Ravine Beds/Boraig
BH5103	Logged as rhyodacite overlying conglomerates with minor schist and gravel interbeds, siltstones and sandstones.	This rhyodacite is enriched in S between 570 m and 580 m (1.5 %). Inspection of the core revealed that this is caused by sulphide minerals hosted both in fractures and as sulphide blebs within the rhyodacite. Changes in lithology correspond to changes in K concentrations. The rhyodacite, schist and siltstone have higher K concentrations whilst the conglomerates have lower K concentrations. A distinctive conglomerate occurs between 570 m and 600 m with high Mn concentration.	Boraig/Byron
BH5104A	Logged as conglomerates, interbedded siltstones and sandstones of varying proportions, a sandstone unit, and interbedded sandstones and conglomerates. A mafic intrusive occurs between 539 m and 547.5 m.	The different lithologies can be delineated using changes in Ca and K. Enrichments in S occur between 538 m and 550 m (0.15 %), 570 m and 590 m (0.2 %), and 630 m and 635 m (0.3 %). The S occurs as vein-hosted sulphide minerals. The Mn-rich conglomerate that occurred in core BH5103 occurs here between 575 m and 593 m suggesting a correlation of the conglomerate between the two drill holes.	Boraig/Byron
BH5105	Logged as interbedded sandstones and siltstones.	The rocks have a similar composition throughout the core. Sulphur enrichment occurs between 806 m and 807.5 m due to sulphide minerals hosted in calcite veins. The colour of the sulphides in the core photos and associated Cu enrichment is consistent with the presence of chalcopyrite.	Boraig/Byron
BH5107	Logged as conglomerates with interbedded sandstones and siltstones.	Sulphur is below detection limits for the entire logged interval logged.	Boraig/Byron
BH5108	Logged as siltstone.	The rocks display a uniform chemistry throughout. Sulphur is below detection limits.	Boraig/Byron

BH6101	Logged as conglomerates with interbedded sandstones and siltstones.	The conglomerates are relatively enriched in Ca and the sandstone-siltstone units are relatively enriched in K. Sulphur is generally below detection limits but is present at < 0.5% over the interval between 170.5 m and 172 m. The S is hosted in sulphide minerals that are present in the conglomerate. Arsenic is enriched up to 100 ppm between 163 m and 168 m.	Ravine Beds
BH6102	Logged as a sequence of sandstone/siltstone units interbedded with conglomerate.	Sulphur is generally below detection limit but is sporadically present at < 0.5%.	Ravine Beds
BH6103	Logged as siltstone/sandstone with two conglomerate beds.	Sulphur is below detection limit for the core section analysed.	Ravine Beds
BH6104	Logged as interbedded siltstones and sandstones with two conglomerate beds.	Sulphur is below detection limit for the core section analysed.	Ravine Beds
BH6105	Logged as siltstone with two conglomerate beds.	Sulphur is below detection limit for the core section analysed.	Ravine Beds
BH7101	Logged as ignimbrite.	Sulphur is below detection limit for the core section analysed.	Ravine Beds
BH7104	Logged as ignimbrite.	Sulphur is below detection limit for the core section analysed.	Ravine Beds
BH7105	Logged as conglomerates and siltstone.	Sulphur is below detection limit for the core section analysed.	Ravine Beds
BH7106	Logged as siltstone, conglomerate and interbedded siltstone/sandstone.	Sulphur is below detection limit for the core section analysed.	Ravine Beds
BH8106	Logged as interbedded sandstone and siltstone.	Sulphur occurs above detection limit between 652.5 m and 653.5 m (1.9%). No sulphide minerals are visible in the core photos but the increased S concentration coincides with increased Ca and Mn. The core contains calcite veins in this region. Between 658 m and 662 m S is enriched at 0.5% and As at 70 ppm in the core. Small sulphide-bearing veins are visible in the core photos.	Ravine Beds

Table 2. Summary of key findings from XRF core scanning

4.1.2 Core Scanning Results Summary

Boraig Group / Byron Group

The Boraig and Byron group (BH5103-8) siliciclastic and volcanic rocks are an interbedded sequence of conglomerates, sandstones and extrusive volcanic rocks (tuffs and ignimbrites). This zone has negligible S concentration and As up to a few tens of ppm.

Ravine Beds

The Ravine Beds (BH4104, BH4105, BH5102, bottom of BH5107 and BH5108, BH6000 and BH8000 series) are a series of siltstones interbedded with sandstones and conglomerates. Most of these lithologies have S concentrations below detection limit for the XRF except BH5102 which contains a more shale rich zone approximately of 35 m thick within a 950 m thick sequence. No other S-rich zones were recorded in the Ravine Beds.

Kelly’s Plain Volcanics

The Kelly’s Plain Volcanics (BH1114-7, parts of BH2102) are dacites with S concentrations below detection limit with the exception of isolated sulphide grains in localised 10 cm intervals with S concentrations of approximately 1%.

Peppercorn Formation

None of this lithology was provided for core scanning.

Tantangara Formation

The Tantangara Formation (BH2101-3, BH3101, BH3104) is an interbedded sequence of sandstones and siltstones. Sulphur is concentrated as isolated sulphide minerals that occur sporadically down the core unrelated to any particular lithology. Arsenic does not exceed a few tens of ppm in any 10 cm interval.

Temperance Formation

The Temperance Formation (BH3102, BH3107A) comprises a series of interbedded siltstones and sandstones with a pyroxenite layer at the top of one logged section. In the pyroxenite the Cr concentration is 400 ppm. Sulphur is present throughout the siltstones at approximately 0.5 % with localised concentrations of up to 1.5% over <1m intervals.

Boggy Plain Suite

The Boggy Plain Suite (BH3106) comprises a diorite with S below detection limits.

Gooandra Volcanics

The Gooandra Volcanics (BH3110, BH3108, BH4101-BH4103, BH4106) are a series of schistose and gneissic volcanic rocks that also contain interbedded siltstones (BH3110 and potentially BH4101). The volcanic rocks contain low concentrations of S of approximately 0.3% for some one metre composites but little As or other metals/metalloids. The interbedded siltstones in BH3101 also contain a maximum of 0.3% S but the rocks logged as rhyolites in BH4101 contain 1-4% S. The chemical logging is inconsistent with this unit being a rhyolite based on the Si concentration. This unit is likely to be a sulphidic siltstone or shale. The rocks in BH4101 are not observed in any other cores that contain Gooandra Volcanics so their relationship to the schists and gneisses, and their volumetric extent is not constrained.

Shaw Hill Gabbro

None of this lithology was provided for core scanning.

4.2 Geochemical characterisation: Snowy 2.0 Scheme Core Samples (Lab Workflow)

Quality Assurance/Quality Control of Results

The Quality Assurance/Quality Control (QA/QC) calculations performed on Certified Reference Materials (CRM) used the Half Relative Difference (HRD%) method, after Stanley and Lawie (2007). This method calculates the mean relative difference between certified values of a given CRM, against either individual or mean analyses of the CRM, expressed as a percentage, by the equation below:

$$HRD(\%) = \left(\frac{assay1 - assay2}{assay1 + assay2}\right) * 100$$

Figure 2. HRD method used for QA/QC

The results for average HRD% for each CRM are shown in in Appendix B. Errors less than 10% were considered acceptable, whereas those between 10 and 20% were queried for further investigation. Errors greater than 20% are removed from the data set or used with caution. The majority of the data are of good quality (>90%). Due to the limited set of elements certified in the chosen CRM, Au, Cd, Ge, Hg, Re, Te were not certified, and therefore have no certified QA/QC parameters for comparison. Elements with HRD% results >10% are dominated by the Rare Earth Elements (REEs: Dy, Er, Ho, Lu, Tm, Yb). This can be explained by the chosen CRM for Batches 2-4 (granodiorite [OREAS 24b]), having no certification for the four-acid digestion/ICP-MS analytical method that was used. Furthermore, Tungsten (W) returned a mean HRD value >10%, which can also be explained by the poor certification values for the 4-acid ICP-MS method for the OREAS 24b CRM. Therefore the analytical results for these elements are considered unreliable. Measurements that are below detection limit are plotted (graphically) using negative numbers as a means of identifying those in graphical format. Measurements that are below detection limit are converted to 50% of the certified detection limit and the Mean and Standard Deviation calculations incorporate this change to the data set.

Geological Zone Results

The geochemical results for lab analyses are presented per Geological Group (see Figure 1). For each Group, a summary of the geochemical results and a Tukey box plot are given. To read the Tukey plots of major elements:

- Minimum regular value is the “lower whisker”.
- Q1 (bottom of box); median (horizontal line); Q3 (top of box); maximum regular value (top of box); mean (black circle).
- The central box is the middle 50% of data from Q1 to Q3.
- Outliers (circles) are more than 1.5 times from the box (Q3-Q1).
- Far outliers (triangles) are more than 3.0 times from the box.

Complete geochemical lab results data can be found in Appendix A and summarised for each Geological Group in Appendix B.2.

4.2.1 Boraig Group

The Boraig Group siliciclastic and volcanics are an interbedded sequence of conglomerates, sandstones and extrusive volcanic rocks (tuffs and ignimbrites). This zone has locally enriched S concentrations (up to 11200 ppm, Figure 3) and Ba (10900 ppm) as reflected in Table 2 of the Appendix B.2.1. Other elements of note include Cr (up to 321 ppm); and As (up to 64.5 ppm) (Appendix B.2.1).

4.2.2 Gooandra Volcanics

The Gooandra Volcanics (BH3110, BH3108, BH4101-BH4103, BH4106) are a series of schistose and gneissic volcanic rocks that also contain interbedded siltstones (BH3110 and potentially BH4101). This zone has locally highly-enriched S concentrations (up to 3.98%) and Fe (up to 9.08%) in BH4101, which is also coincident with naturally-occurring asbestos (NOA). Other notable enrichments include Cr (up to 1070 ppm); Zn (up to 4150 ppm); and As (up to 248 ppm) (Appendix B.2.2).

4.2.3 Byron Range Group

The Byrong Range Group siliciclastic and volcanics are an interbedded sequence of conglomerates, sandstones and extrusive volcanic rocks (tuffs and ignimbrites). This zone has locally enriched S concentrations (up to 1350 ppm) and Ba (up to 7130 ppm). No other elements are notably enriched in this zone (Appendix B.2.3).

4.2.4 Temperance Formation

The Temperance Formation comprises interbedded siltstones and sandstones. In this zone there are locally-enriched S concentrations (up to 21200 ppm) (Table 5 in Appendix B.2.4). Other notable elements include Cu (up to 1446 ppm) and Cr (up to 488 ppm) (Appendix B.2.4).

4.2.5 Tantangara Formation

The Tantangara Formation comprises interbedded sandstones and siltstones. This zone has locally enriched S concentrations (up to 9860 ppm) as seen in Table 6 of Appendix B.2.5). Other elements of interest include As (up to 64 ppm) and Cr (up to 132 ppm) (Appendix B.2.5).

4.2.6 Kelly’s Plain Volcanics

The Kelly’s Plain Volcanics are comprised of dacite. This zone has localized S concentrations up to 3030 ppm. No other elements are notably enriched in this zone (Appendix B.2.6).

4.2.7 Ravine Beds

The Ravine Beds are a series of siltstones interbedded with sandstones and conglomerates. This zone has locally enriched S concentrations (up to 15700 ppm, Figure 3) and Cu (2986 ppm, Figure 12). Other elements of note include Pb (up to 750 ppm, Figure 6); As (up to 47.7 ppm, Figure 8); and Zn (up to 1850 ppm) (Appendix B.2.7).

4.2.8 Shaw Hill Gabbro

The Shaw Hill Gabbro is, comprised of a predominantly gabbroic lithology. There are no notable enrichments of any trace elements in this zone (Appendix B.2.8).

Element Group Results

Local enrichment of elements can be measured by comparing the data with the Post-Archean Australian Shale (PAAS), which is widely used as a reference standard for average crustal abundance (Taylor and McLennan, 1985). For the purposes of this data review, the elements are divided into 6 groups:

- Major Elements,
- Post-transition Metals,
- Transition Metals (Series 1,2, 3) and Metalloids,
- Light Rare Earth Elements (LREE),
- Heavy Rare Earth Elements (HREE) plus Th and U.

In each group, data distribution for each element is plotted as a normal probability plot (n-score), with data from each major geological unit indicated by colour. This method allows the distribution of concentrations for each element to be visually assessed. Where there were notable enrichments in elements that are redox-sensitive or have ecotoxicological significance, relative to PAAS, these are shown below with more detailed descriptions of their distributions relative to the PAAS reference concentration. The enrichment of elements relative to the PAAS will be discussed in detail in the P2 report.

4.2.9 Major Elements and Oxides

Of the major elements and oxides (Al_2O_3, CaO, Fe, K_2O, MgO, MnO, Na_2O, P_2O_5, S, SiO_2, TiO_2), those that are considered redox reactive (Fe, MnO, S) of biological significance (P_2O_5), are illustrated below in comparison to PAAS.

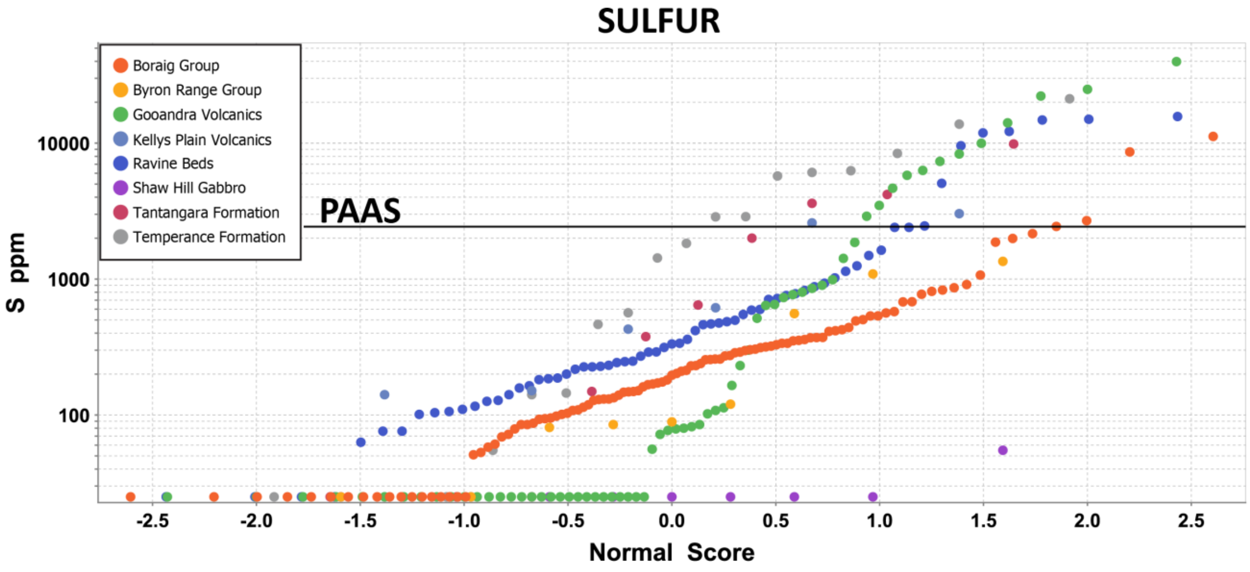


Figure 3. Sulphur (log) ppm relative to PAAS

Sulphur has a maximum concentration of 3.98% in the Gooandra Volcanics (Figure 3). Notable enrichments also occur in the Tantangara Formation, and the Ravine Beds. In the Tantangara Formation, highest concentrations are intersected in drill core BH3101, highest in meta siltstones at 61 m depth (BH3101-R-0255). In the Gooandra Volcanics the highest values are intersected in drill core BH3110 (up to 9970 ppm), with 5800 ppm being intersected in drill core BH4103 at 99 m (BH4103-R-0020). In the Ravine Beds, the highest concentrations occur in drill core BH5115 (9570 ppm) at 242 m depth (BH5115-R-0190), and BH5104 (8620 ppm) at 142 m depth (BH5104-R-0110).

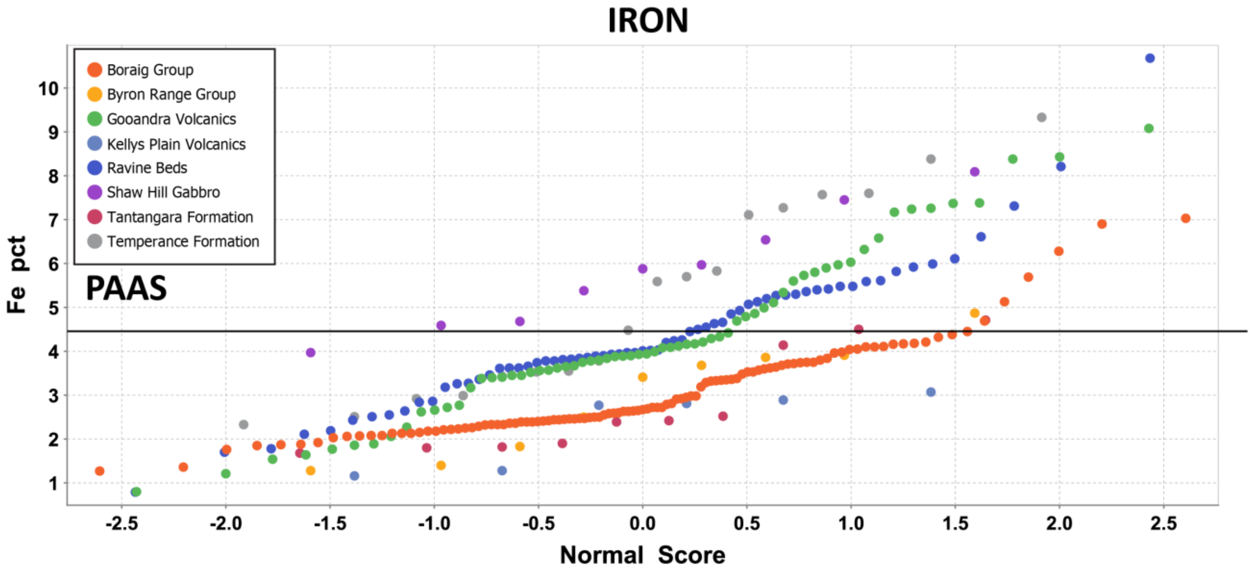


Figure 4. Iron pct relative to PAAS

Iron concentrations (Figure 4) may reach approximately twice that of PAAS concentrations in the Ravine Beds, with 10.68% in drill core BH6101 at 17 m depth (sample BH6101-R-0218). Concentrations in the Temperance Formation are up to 9.33% in drill core BH3102. The Shaw Hill Gabbro, Gooandra Volcanics, and Boraig Group have concentrations up to 8.09%, 7.38%, 7.03%, respectively.

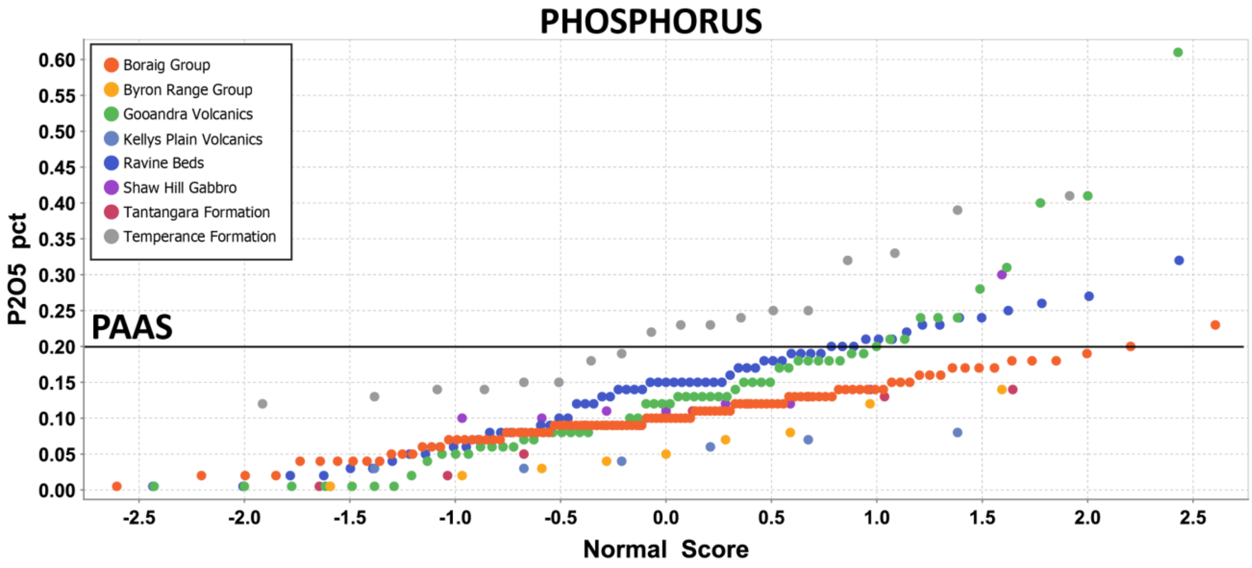


Figure 5. Sulphur ppm relative to PAAS

Phosphorus concentrations (Figure 5) up to reaching 0.61% occur in the Gooandra Volcanics in drill core BH3110. In the Temperance Formation, concentrations of 0.39% are intersected in drill core

BH3102. Concentrations elevated relative to PAAS also occur in the Ravine Beds in drill cores BH6102, BH5101 and BH7105.

4.2.10 Post-transition Metals

Of the post-transition metals (Bi, Cd, Ga, Hg, In, Pb, Sn, Tl, Zn), Pb and Tl are described in more detail below. Other elements all had concentrations that are close to those of the PAAS. On this basis, no further consideration is given here.

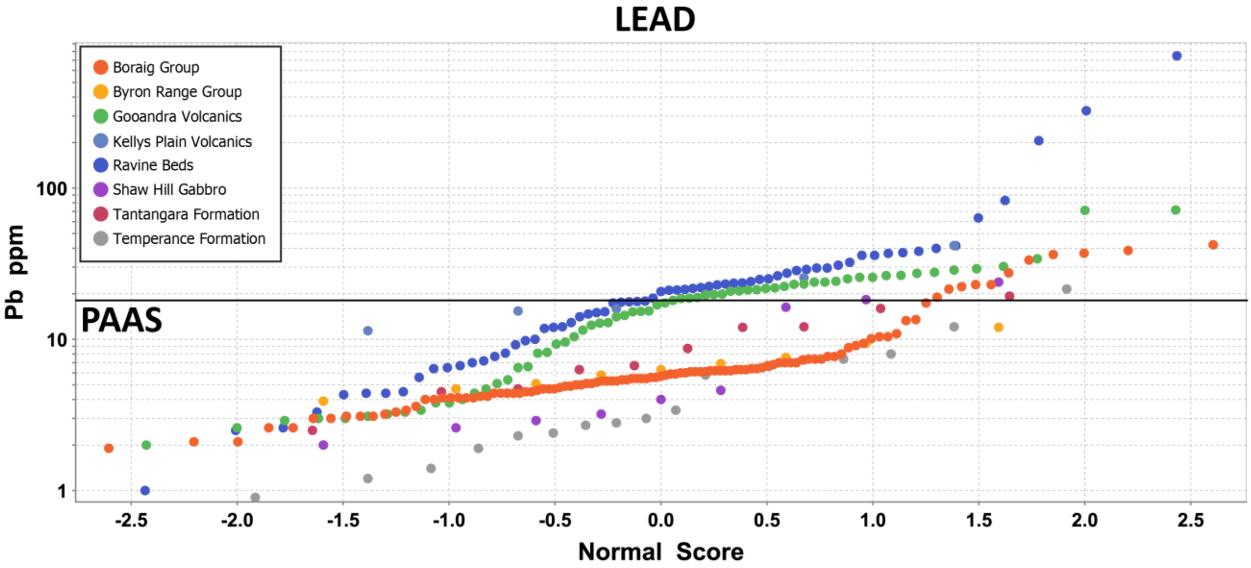


Figure 6. Lead ppm relative to PAAS (log)

Lead concentrations (Figure 6) of up to 750 ppm approximately 40 times that of the PAAS, occur in the Ravine Beds in BH7105 at 25 m depth (sample BH7105-R-0038). Concentrations up to 71.7 ppm Pb occur in the Gooandra Volcanics in BH4103; and 42.2 ppm Pb in the Boraig Group.

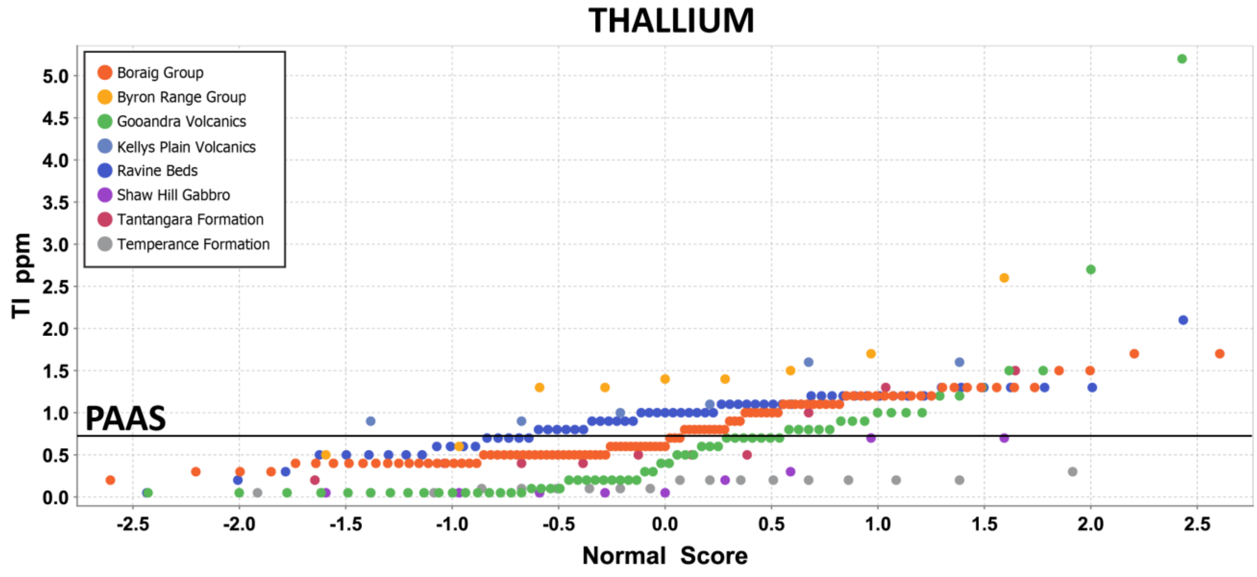


Figure 7. Thallium ppm relative to PAAS

Thallium concentrations (Figure 7) up to 5.2 ppm occur in the Gooandra Volcanics in drill core BH4103. Concentrations up to 2.6 ppm occur in the Byron Range Group, 2.1 ppm in the Ravine Beds, and 1.7 ppm in the Boraig Group.

4.2.11 Metalloids

Of the metalloids (As, Ge, Sb, Se, Te), there are enrichments in As, Sb, Se relative to PAAS. Germanium and tellurium had concentrations that are close to those of the PAAS. On this basis, no further consideration is given here.

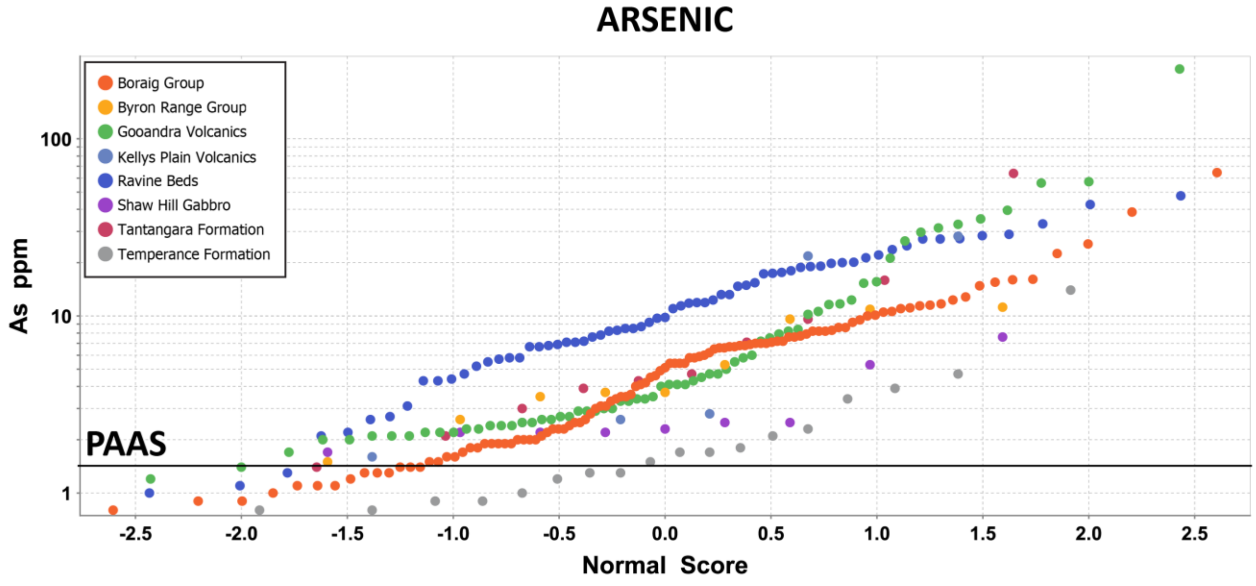


Figure 8. Arsenic ppm relative to PAAS

Arsenic is highest in concentration (Figure 8) in the Gooandra Volcanics in BH4103, with up to 243 ppm at 82 m depth (sample BH4103-R-0017). Concentrations up to 65 ppm occur in the Boraig

Group, 64 ppm in the Tantagara Formation, and 47.7 ppm in the Ravine Beds. Lower maximum concentrations of 14 ppm and 11 ppm occur in the Temperance Formation and Byron Range Group, respectively.

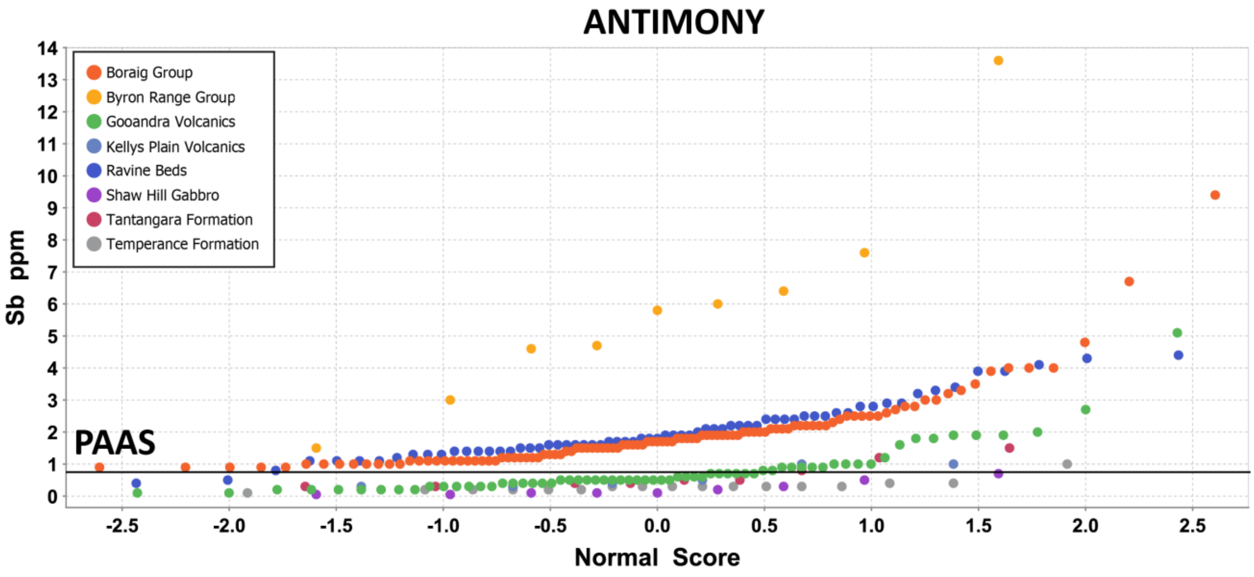


Figure 9. Antimony ppm relative to PAAS

The highest concentrations of Antimony (Sb) (shown in Figure 9) occur in the Byron Range Group, up to 14 ppm. Concentrations of Sb of up to 9 ppm occur in the Boraig Group, 5 ppm in the Gooandra Volcanics, 4 ppm in the Ravine Beds.

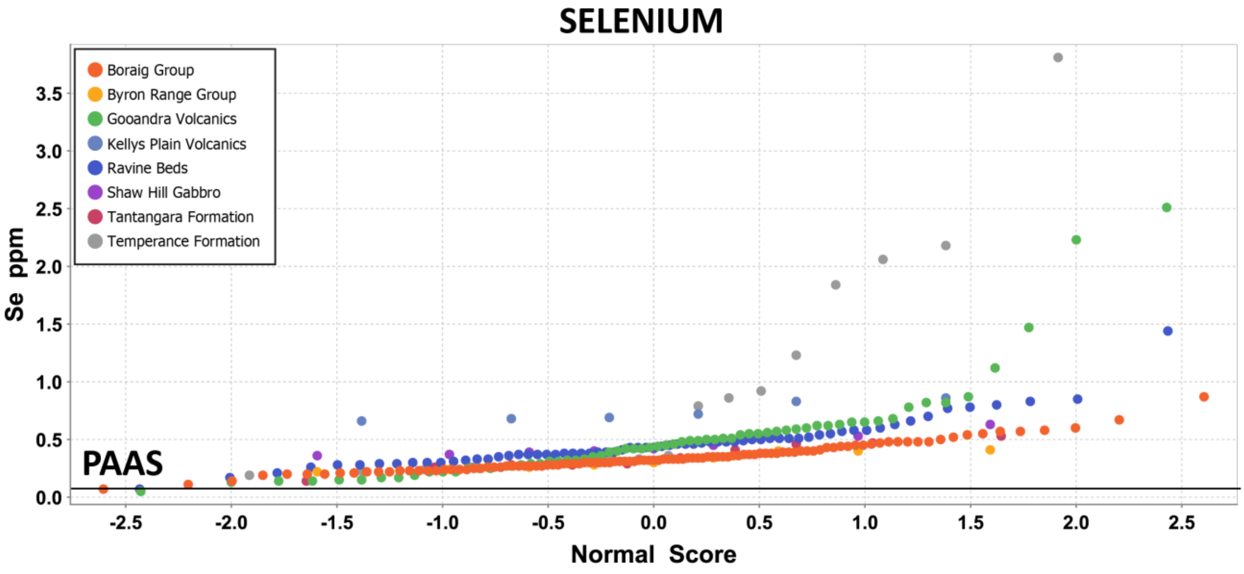


Figure 10. Selenium ppm relative to PAAS

The highest concentrations of Se (Figure 10) occur in the Temperance Formation, up to 4 ppm. Concentrations of Se of up to 1 ppm occur in the Ravine Beds, 1 ppm in the Gooandra Volcanics, and 1 ppm in the Boraig Group.

4.2.12 1st Series Transition Metals

Of the 1st Series Transition metals (Co, Cr, Cu, Ni, Sc, V), Cr and Cu are enriched relative to PAAS, and are considered in more detail below.

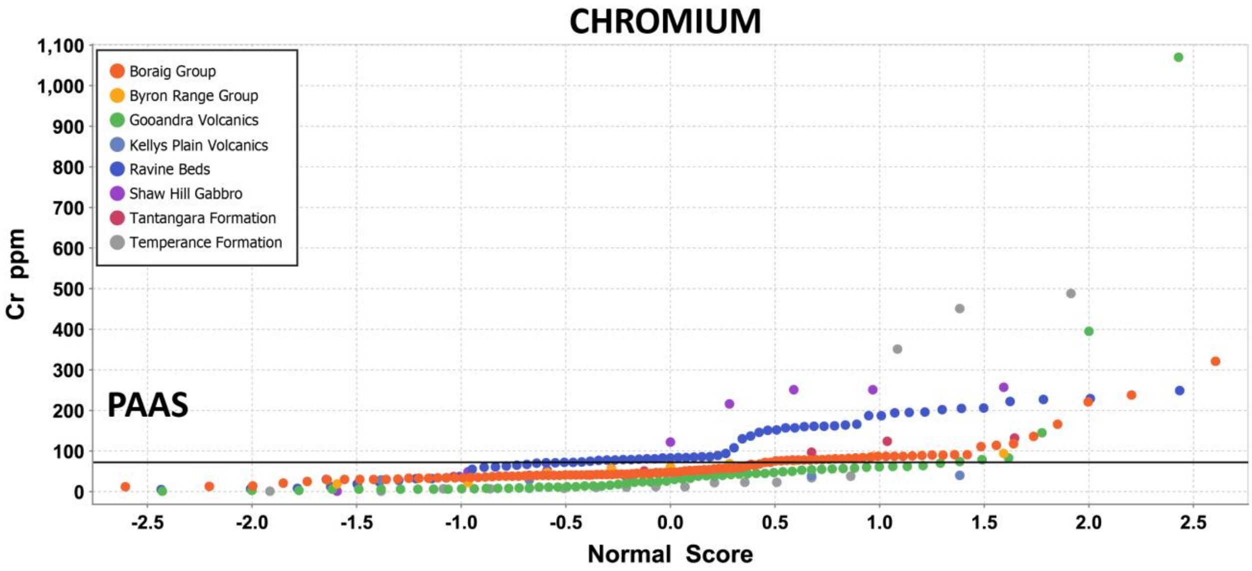


Figure 11. Chromium ppm relative to PAAS

The highest concentrations of Cr (Figure 11) occur in the Gooandra Volcanics, up to 1070 ppm. Concentrations of Cr of up to 488 ppm occur in the Temperance Formation, 321 ppm in the Boraig Group, 257 ppm in the Shaw Hill Gabbro, and 249 ppm in the Ravine Beds.

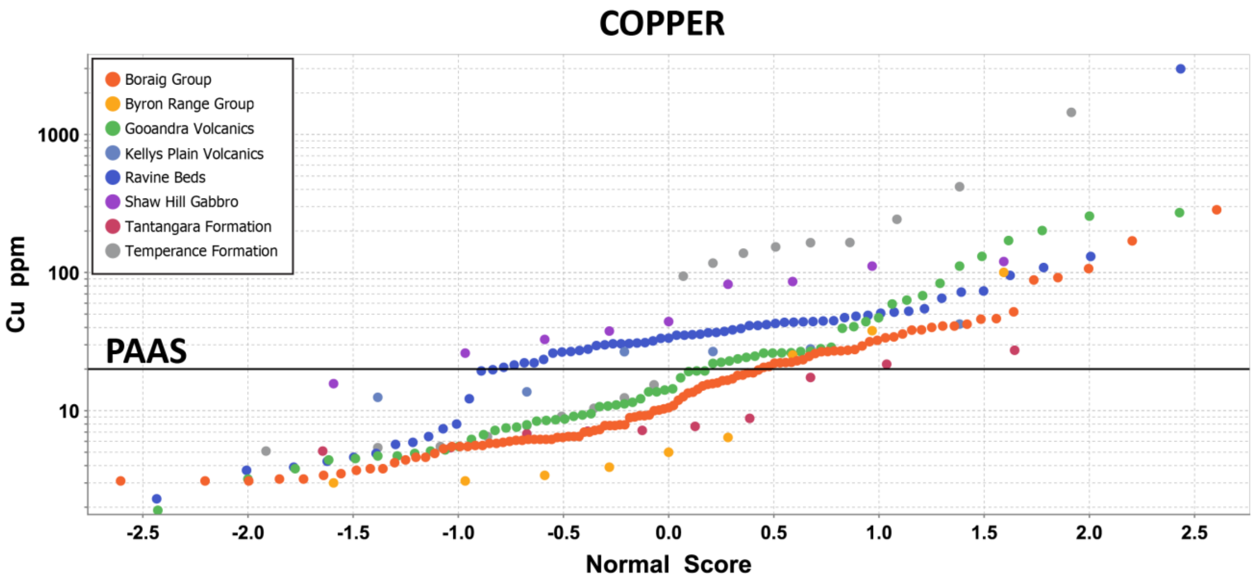


Figure 12. Copper ppm relative to PAAS

The highest concentrations of Cu (Figure 12) occur in the Ravine Beds, up to 2986 ppm. Concentrations of Cu of up to 1446 ppm occur in the Temperance Formation, 285 ppm in the Boraig Group, 272 ppm in the Gooandra Volcanics, 120 ppm in the Shaw Hill Gabbro, and 100 ppm in the Byron Range Group.

4.2.13 2nd Series Transition Metals

The 2nd Series Transition Metals (Ag, Cd, Mo, Nb, Y, Zr) all had concentrations that are close to that of the PAAS. On this basis, no further consideration is given here.

4.2.14 3rd Series Transition metals

The 3rd Series Transition Metals (Au, Hf, La, Pt, Re, Ta, W) all had concentrations that are similar to PAAS, other than Re and W which are detailed below. The highest concentrations of Re (Figure 13) of up to 17 ppm occur in the Temperance Formation. Concentrations up to 8 ppm occur in the Gooandra Volcanics, 1 ppm in the Tantangara Formation, 1 ppm in the Boraig Group, and 1 ppm in the Ravine Beds.

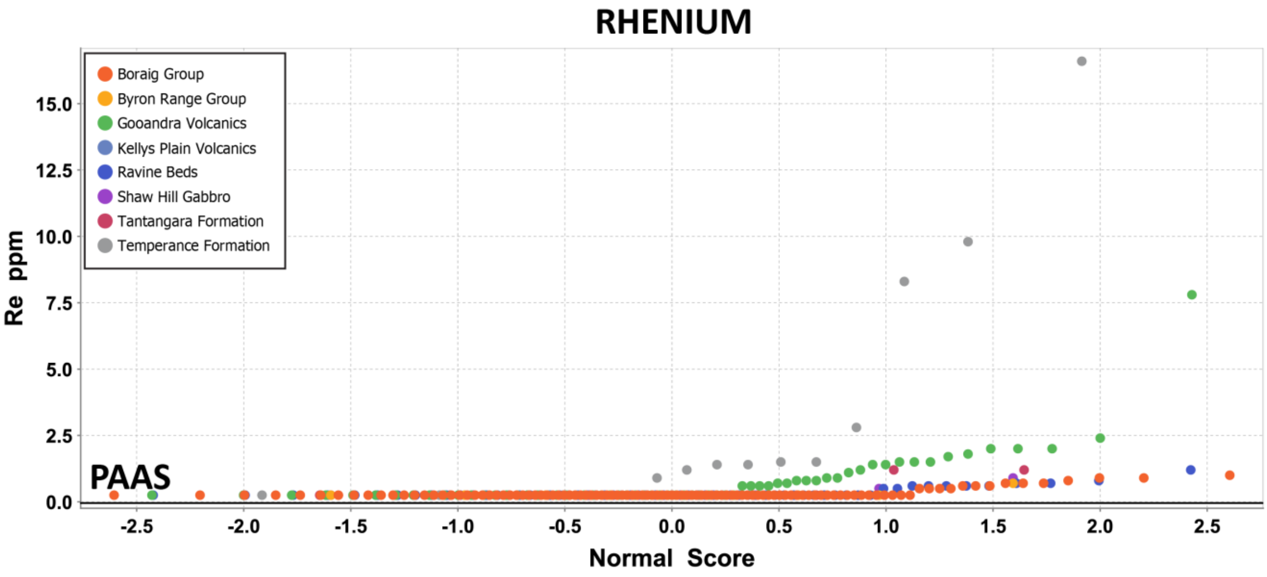


Figure 13. Rhenium ppm relative to PAAS

The highest concentrations of W (Figure 14) of up to 14 ppm occur in the Byron Range Group. Concentrations up to 12 ppm occur in the Gooandra Volcanics, 11 ppm in the Ravine Beds, 9 ppm in the Boraig Group.

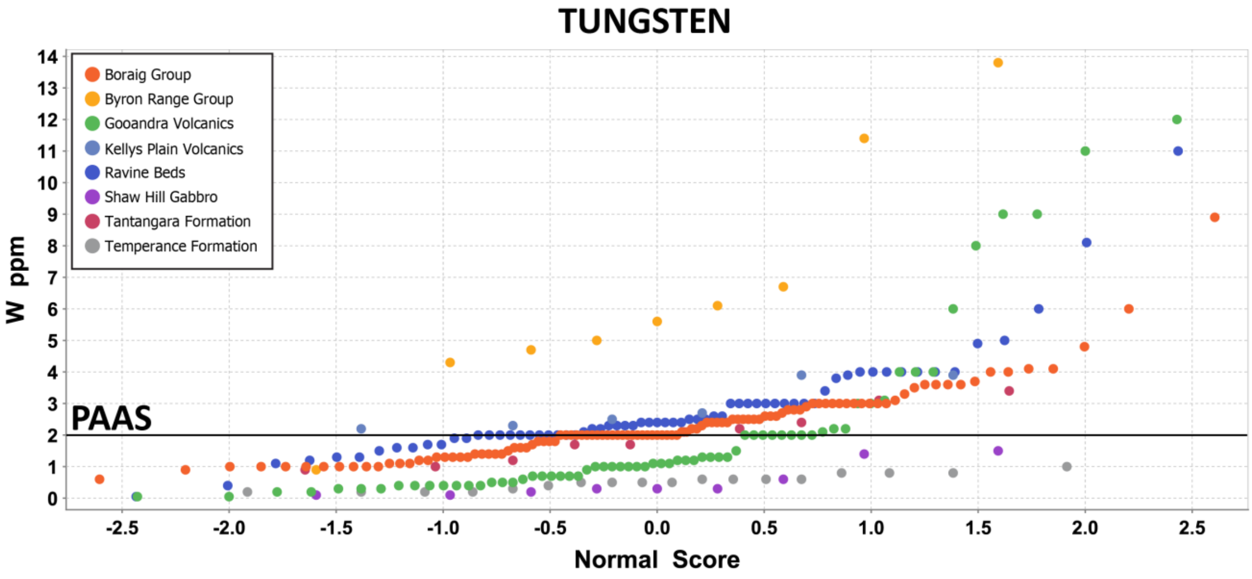


Figure 14. Tungsten ppm relative to PAAS

4.2.15 Light Rare Earth Elements

The Light Rare Earth Elements (La, Ce, Pr, Nd, Sm, Eu) all are present in concentrations similar to PAAS (Table 3), and are not considered further here.

	La_ppm	Ce_ppm	Pr_ppm	Nd_ppm	Sm_ppm	Eu_ppm
PAAS	30.0	64.0	7.1	26.0	4.5	0.9
Snowy	29.3	59.5	6.7	24.9	5.2	1.0

Table 3. Light Rare Earth Elements Concentrations

4.2.16 Heavy Rare Earth Elements (plus Th, U)

The Heavy Rare Earth Elements (Gd, Tb, Dy Ho, Er, Yb, Lu, Th) have concentrations similar to or are only slightly elevated compared to PAAS. There are numerous U concentrations elevated relative to PAAS values.

The highest concentrations of U (Figure 15) occur in the Ravine Beds, up to 8 ppm. Concentrations up to 8 ppm occur in the Boraig Group, 5 ppm in the Gooandra Volcanics, 5 ppm in the Ravine Beds, and 5 ppm in the Byron Range Group.

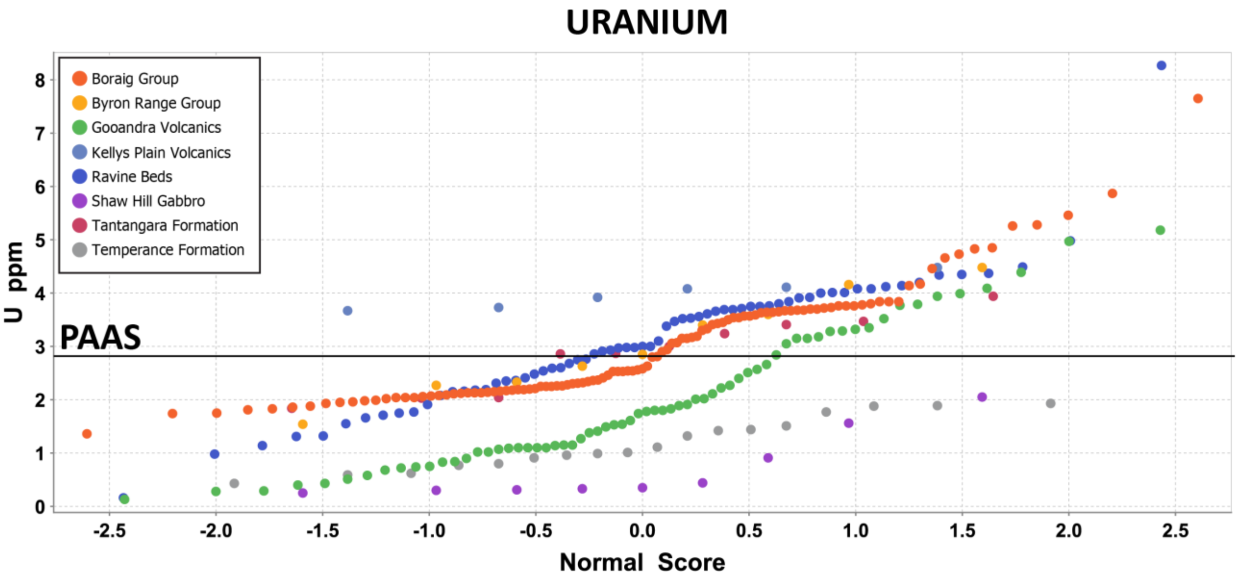


Figure 15. Sulphur ppm relative to PAAS

4.3 Mineralogical characterisation: Snowy 2.0 Scheme Core Samples (Lab Workflow)

4.3.1. Bulk mineralogy

X-Ray Diffraction (XRD) analysis was used to identify mineral phases in the samples and estimate their abundances. The detection limit for the technique is from 1 to 3 wt. % of a mineral depending on the mineral phase. Results for samples from the following drill holes are reported here: BH1115, BH1116, BH1117, BH2102, BH3101, BH3102, BH3104, BH3106, BH3110, BH4102, BH4104, BH4105, BH4106, BH5101, BH5102, BH5103, BH5104, BH5105, BH5107, BH5108, BH5115, BH6101, BH6102, BH6105, BH7104, BH7105, and BH8106. The results of the quantitative XRD analysis for the studied samples are given in Appendix A.3.

The following minerals were identified by XRD in the core samples from the Snowy 2.0 project drill holes:

- quartz - SiO_2;
- albite - $NaAlSi_3O_8$ [feldspar group];
- orthoclase - $KAlSi_3O_8$ [feldspar group];
- muscovite - $KAl_2[AlSi_3O_{10}(OH)_2$ [white mica group];
- chamosite - $(Fe,Mg)_5Al[AlSi_3O_{10}](OH)_8$ [chlorite group];
- scapolite - $(Na,Ca)_4[Al_3Si_9O_{24}]Cl$;
- calcite - $CaCO_3$;
- dolomite - $CaMg(CO_3)_2$;
- hematite - Fe_2O_3;
- pyrite - FeS_2;
- actinolite - $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$ [amphibole group];
- kaolinite - $Al_2Si_2O_5(OH)_4$ [kaolin group];
- diopside - $CaMgSi_2O_6$ (pyroxene group); and
- epidote - $Ca_2Al_2(Fe^{3+},Al)Si_3O_{12}(OH)$ (epidote group).

The aforementioned drill holes intersected the following major lithological units of interest:

- Byron Range Group (upper parts of BH5107 and BH8106);
- Boraig Group (BH5103, BH5104, BH5105, BH5107, BH5108, middle part of BH8106);
- Kellys Plain Volcanics (BH1115, BH1116 and BH1117);

- Ravine Beds (BH4104, BH5101, BH5102, BH5115, BH6101, BH6102, BH6105, BH7104, BH7105 and lower part of BH8106);
- Tantangara Formation (BH2102, BH3101, BH3104);
- Temperance Formation (BH3102 and BH3106);
- Shaw Hill Gabbro (BH4106); and
- Gooandra Volcanics (BH3110, BH4102, BH4103, BH4105).

The drill holes studied here and their corresponding geologic zones are given in Appendix D.1. Average mineralogical abundances for each individual drill hole are given in Appendix E2 (Figures E1-E5).

Byron Range Group

The rocks of the Byron Range Group were only observed in the upper part of the BH5107 and BH8106 drill holes. These rocks are mainly composed of the following minerals with their average values given in parentheses: quartz (71%), albite (16%), orthoclase (10%), muscovite (9%), chamosite (9%), calcite (4%) and hematite (1%). The ranges and averages of the observed mineral abundances are given in Appendix D.1. The averaged mineralogical composition of the Byron Range Group rocks is shown in Figure 16 a.

Boraig Group

The rocks of Boraig Group mainly comprise quartz (64%), albite (12%), orthoclase (10%), muscovite (9%), chamosite (9%) and calcite (4%). Minor dolomite, hematite, pyrite, scapolite, kaolinite, and actinolite were observed mainly in drill holes BH5104 and BH5105 (see Appendix D.2). The ranges and averages of the observed mineral abundances are given in Appendix D.1. The averaged mineralogical composition of the Boraig Group rocks is shown in Figure 16 b.

Ravine Beds

The rocks of Ravine Beds comprise a similar mineral assemblage to the Boraig Group rocks: quartz (50%), albite (20%), orthoclase (10%), muscovite (11%), and chamosite (16%). Calcite (up to 10%) and dolomite (up to 11%) are quite common the Ravine Beds rocks. Minor pyrite (up to 3%), hematite (up to 2%) and scapolite (up to 3%) also occur in the Ravine Beds. The ranges and averages of the observed mineral abundances are given in Appendix D.1. The averaged mineralogical composition of the Ravine Beds rocks is shown in Figure 16 c.

Kellys Plain Volcanics

The rocks of Kellys Plain Volcanics are composed of quartz (34%), albite (26%), orthoclase (18%), muscovite (8) and chamosite (20%). Minor kaolinite (up to 5%) was only observed in the drill hole BH1115 (see Appendix D.2). The ranges and averages of the observed mineral abundances are given in Appendix D.1. The averaged mineralogical composition of the Kellys Plain Volcanics rocks is shown in Figure 16 d.

Tantangara Formation

The rocks of Tantangara Formation mainly comprise quartz (58%), albite (14%), orthoclase (8%), muscovite (11%), and chamosite (12%). Minor dolomite (3%) and pyrite (1%) were observed only in the drill hole BH3101 (see Appendix D.2). The ranges and averages of the observed mineral abundances are given in Appendix D.1. The averaged mineralogical composition of the Tantangara Formation rocks is shown in Figure 16 e.

Temperance Formation

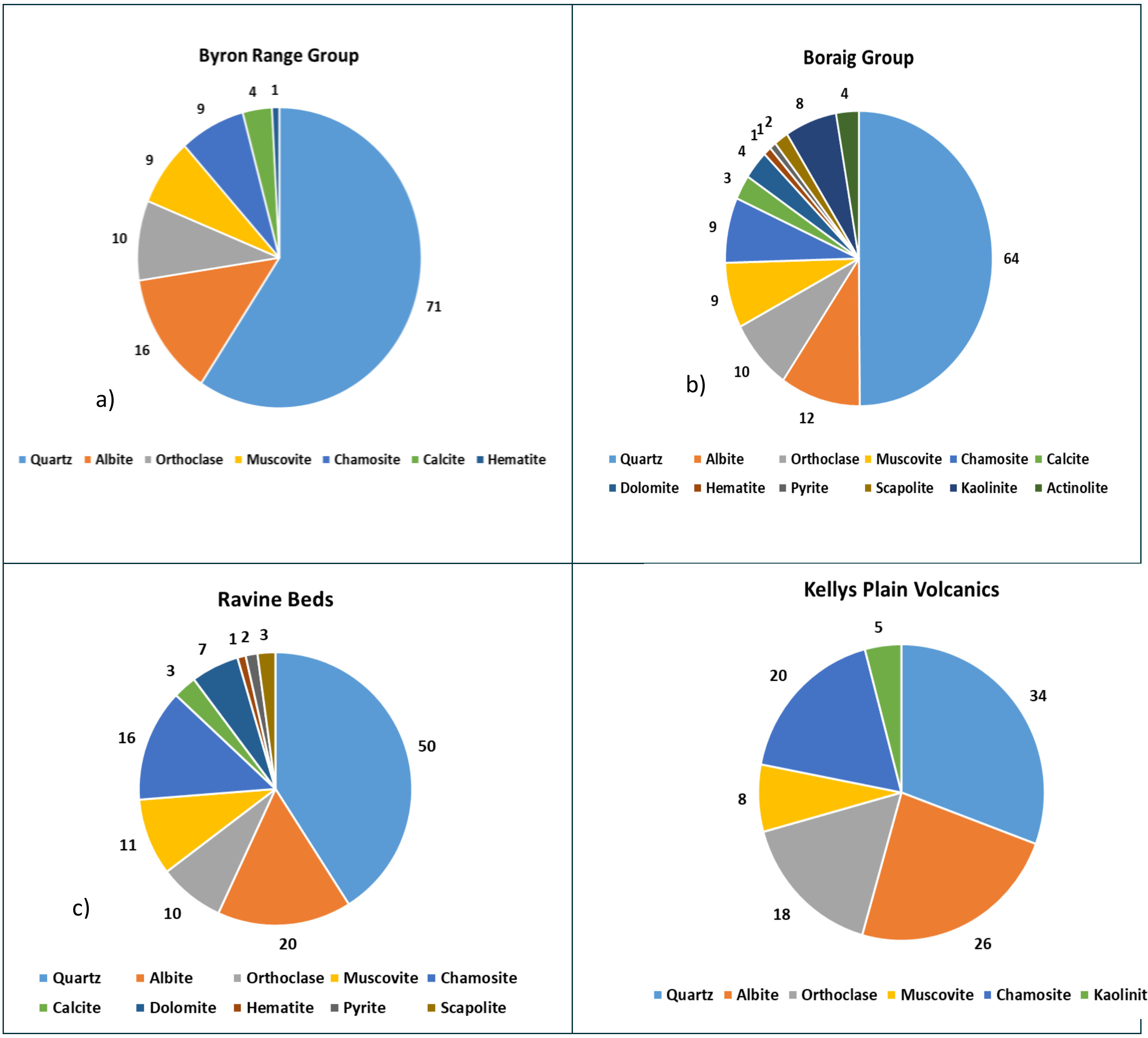
The rocks of Temperance Formation mainly comprise quartz (24%), albite (35%), orthoclase (11%), muscovite (7%), and chamosite (13%), actinolite (9%), epidote (20%) and diopside (29%). Minor calcite (up to 2%) was observed in both drill holes intersected this formation, i.e. BH3102 (see Appendix D.2) and BH3106 (see Appendix D.2). The ranges and averages of the observed mineral abundances are given in Appendix D.1. The averaged mineralogical composition of the Temperance Formation rocks is shown in Figure 16 f.

Shaw Gabbro

The rocks of Shaw Hill Gabbro mainly comprise quartz (19%), albite (29%), orthoclase (8%), muscovite (9%), chamosite (19%), actinolite (7%), and epidote (20%). No diopside was observed due to alteration to actinolite and epidote. Minor calcite (up to 2%) and hematite (up to 4%) were also observed (see Appendix D.2). The ranges and averages of the observed mineral abundances are given in Appendix D.1. The averaged mineralogical composition of the Shaw Hill Gabbro rocks is shown in Figure 16 g.

Gooandra Volcanics

The rocks of Gooandra Volcanics mainly comprise quartz (45%), albite (20%), orthoclase (7%), muscovite (15%), chamosite (19%), and epidote (15%). Minor calcite (up to 2%), dolomite (up to 7%) and hematite (up to 2%) were also observed (see Appendix D.2). The ranges and averages of the observed mineral abundances are given in Appendix D.1. The averaged mineralogical composition of the Gooandra Volcanics rocks is shown in Figure 16 h. Naturally occurring asbestos was found within this unit and is detailed within Section 4.3.3


Byron Range Group
4
1
9
9
10
71
16
a)
■ Quartz ■ Albite ■ Orthoclase ■ Muscovite ■ Chamosite ■ Calcite ■ Hematite
Boraig Group
8
4
1
1
2
4
3
9
64
9
10
b)
12
■ Quartz ■ Albite ■ Orthoclase ■ Muscovite ■ Chamosite ■ Calcite
■ Dolomite ■ Hematite ■ Pyrite ■ Scapolite ■ Kaolinite ■ Actinolite
Ravine Beds
7
1
2
3
3
16
50
11
c)
10
20
■ Quartz ■ Albite ■ Orthoclase ■ Muscovite ■ Chamosite
■ Calcite ■ Dolomite ■ Hematite ■ Pyrite ■ Scapolite
Kellys Plain Volcanics
5
20
34
8
18
26
■ Quartz ■ Albite ■ Orthoclase ■ Muscovite ■ Chamosite ■ Kaolinite

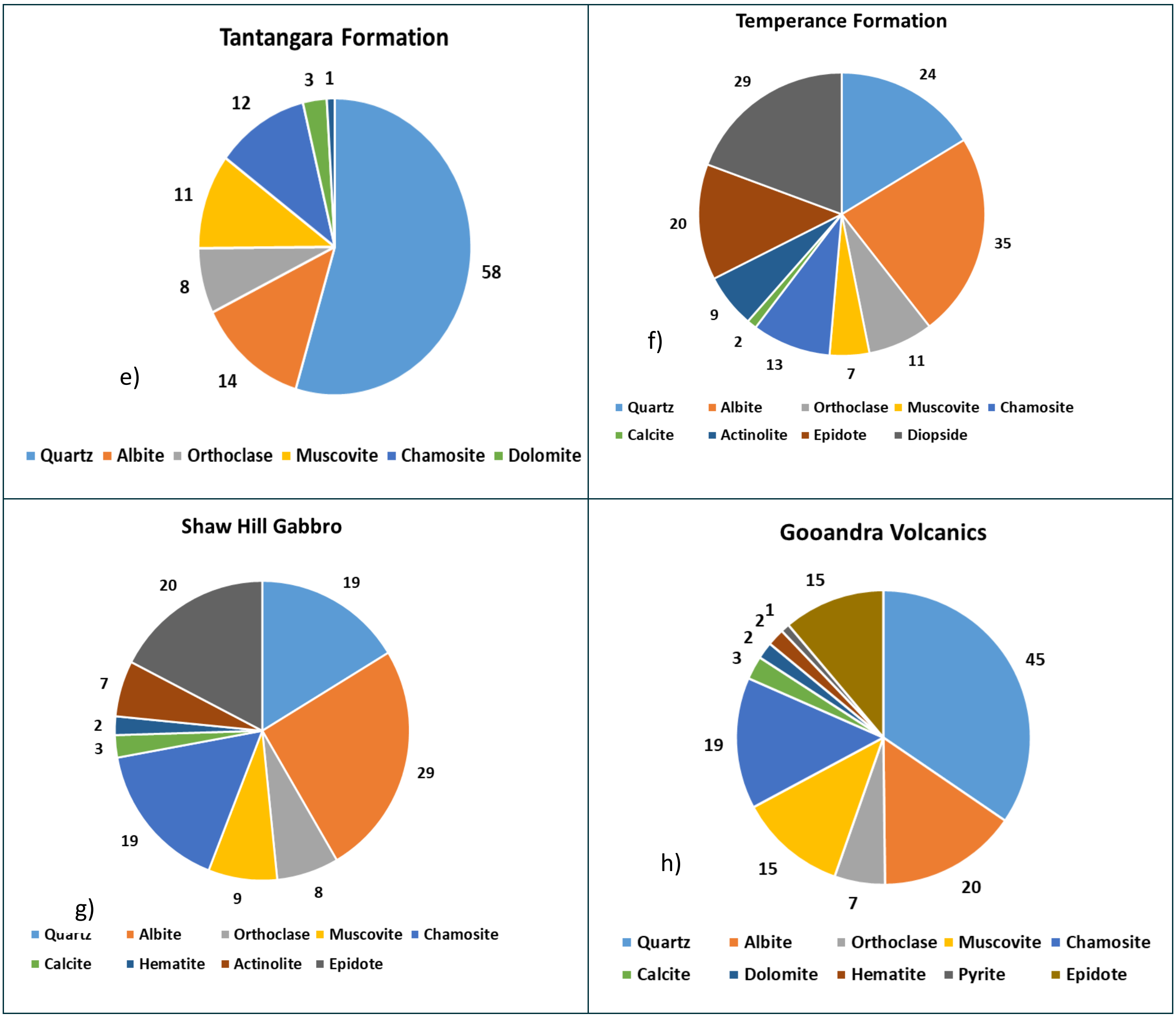


Figure 16. Averaged mineralogical abundances for the rocks of the following main geologic zones: (a) Byron Range Group; (b) Boraig Group; (c) Kellys Plain Volcanics; (d) Ravine Beds; (e) Tantangara Formation; (f) Temperance Formation; (g) Shaw Hill Gabbro, and (h) Gooandra Volcanics.

4.3.2. Minor and accessory mineralogy

A number of samples of core were selected for detailed petrographic analysis to identify minor and accessory mineral phases that could not be identified by quantitative X-ray Diffraction analysis.

The list of samples is given in Table 4. The outputs of the mineral mapping analyses as well as back-scattered electron images are given in Appendix A.4. The mineral mapping results confirmed the presence of major minerals, such as quartz, feldspars, chlorite, micas, amphibole, epidote, pyrite, calcite, dolomite and hematite. Among accessory phases rare rutile, titanite, apatite, allanite, pyrrhotite, arsenopyrite, chalcopyrite, and sphalerite were identified in small quantities.

Drill hole	Depth (m)	Rock type
BH4103	347.35-347.53	Hematite breccia with quartz veins
BH4103	82.37-82.68	Schist
BH6102	233.13-233.54	Sandy conglomerate
BH5101	528.1-528.52	Siltstone
BH5104	142.17-142.43	Conglomerate
BH5104	239.15-239.4	Sandstone
BH5104	441.1-441.4	Conglomerate
BH5108	600-600.3	Siltstone
BH5108	661-661.3	Siltstone
BH3102	35.25-35.55	Metasiltstone
BH3102	268-268.3	Metasiltstone/metasandstone
BH3110	92-92.25	Metasiltstone
BH3110	172.75-173	Metasiltstone

Table 4. Selected samples for detailed characterisation of minor and accessary minerals, their corresponding drill holes, depths and logged rock types

4.3.3. Identification of naturally-occurring asbestos

A subset of core samples was selected from visual inspection for quantification of the modal abundance of amphibole and detailed characterisation of the amphibole to determine if it was naturally occurring asbestos.

These samples were selected upon visual investigation of the core material specifically targeting areas of potential naturally occurring asbestos. Hence, the results of the quantitative X-ray Diffraction analysis are not included in Section 4.3.1, as their bulk mineralogy may not be representative of the bulk mineralogy of the drill holes BH4101 and BH3108.

In general, the mineral assemblage in selected samples from BH4101 and BH3108 (both within the Gooandra Volcanics) is similar to the drill holes described in Section 4.3.1. The main minerals are: quartz, feldspars (albite and orthoclase), chlorite, micas (biotite and muscovite), calcite, amphibole (actinolite) and pyrite.

A study was undertaken to characterise the nature of amphibole in the selected samples from BH4101 and BH3108 and determine if any of the naturally occurring amphibole is asbestos. The outcomes of this study are provided in Appendix A.5, however, to summarise the findings: ***two of the thirteen samples received by CSIRO for assessment met the Australian Standard (AS4964-2004) for asbestos, others had fibrous materials (not meeting the definition) but can be classified as being potentially hazardous to human health.***

An additional study assessed amphibole within BH3106 (Boggy Plain/Temperance) and BH4106 (Gooandra Volcanics). Of the three samples analysed, which contained elongated amphibole fragments, none met the Australian Standard (AS4964-2004) for asbestos. ***As with the BH4101 and BH3108 results, fibrous materials pose potential hazard for human health.*** Outcomes of this study are provided in Appendix A.6.

With all fibrous materials, it is recommended that suitable handling practices are employed for the Snowy 2.0 purpose. This should include (but not limited to), placing the materials in a wet condition for handling and submersion in the subaqueous environment in such to reduce airborne exposure to humans.

5 Summary

The P1 Assignment completed a geochemistry examination on core extracted from the proposed Snowy 2.0 tunnel alignment. Three main analytical techniques were applied to characterise the drill core, these were:

a) High resolution geochemical scanning to understand the geochemical composition of the rock. Full drill cores were scanned where they intersected the volumes of the proposed surge, pressure and power caverns; elsewhere, core that intersected the head and tailrace, were scanned only along the tunnel alignment

b) Laboratory analysis on selected samples for high precision geochemical characterisation

c) Mineralogical analysis of samples analysed in (b)

These three techniques have resulted in a detailed understanding of the geochemical and mineralogical composition of the rocks that are potentially to be excavated as part of the Snowy 2.0 scheme.

The results from the investigation indicated that that **two lithological units contained elevated sulphur concentrations: Ravine Beds and Gooandra Volcanics. The Ravine Beds contained a 35m apparent thickness shale unit containing approximately 1.5% S. The Gooandra Volcanics contain a unit of unconstrained thickness with up to 4% S and naturally occurring asbestos**. The geochemistry and mineralogy of the main lithological units can be summarised as:

Byron Range Group

- Siliciclasic rocks, mostly siltstones, shales, sansdtones and conglomerates.
- Mineralogy dominated by quartz and feldspars, with lesser amounts of muscovite, chamosite, calcite and hematite.

Boraig Group

- Sedimentary and volcanic rocks, characterised by high quartz and feldspar content, with small amounts of muscovite, chamosite, and calcite.
- Minor dolomite, hematite, pyrite, scapolite, kaolinite and actinolite are also observed in a few drill holes.

Kellys Plain Volcanics

- Volcaniclastic rocks composed of quartz, feldspars, muscovite and chamosite.
- Minor kaolinite (up to 5%) was only observed in the drill hole BH1115.

Ravine Beds

- Interlaminated shales, siltstones, and conglomerates, composed of quartz, feldspars, muscovite and chamosite. Calcite (up to 10%) and dolomite (up to 11%) may occur.

- Minor pyrite, hematite and scapolite.

Tantangara Formation

- Siliciclastic rocks, mainly composed of quartz, feldspars, muscovite and chamosite.
- Minor dolomite and pyrite only observed in the drill hole BH3101.

Temperance Formation

- Volcaniclastic rocks comprised of quartz, feldspars, muscovite, chamosite, actinolite, epidote and diopside, and minor calcite.

Shaw Hill Gabbro

- Intrusive gabbro composed of quartz, feldspars, muscovite, chamosite, actinolite, and epidote, with minor calcite and hematite.

Gooandra Volcanics

- Volcanics comprised of quartz, feldspars, muscovite, chamosite, and epidote, with minor calcite, dolomite, and hematite.

6 Recommendations

The results from this examination would suggest:

1) The sulphide zone in BH5102 has an apparent thickness of approximately 35 m. Due to the angle between the drill hole and the bedding in BH5102, the actual thickness is more likely to be 10-15m. The rocks in this region are folded therefore there may be repetition of the sulphide zones within this rock package. The maximum S content (from lab analyses) of the samples from BH5102 that were available to the project is 1.5%. If these samples are identified as having high S contents in subsequent studies/examination (for example Assignments mentioned in Section 2 or other Snowy 2.0 work packages) then it is encouraged that additional holes are drilled in the neighbourhood of BH5102.

2) BH4101 core has a very different character to the cores either side of it (i.e. BH3108 and BH4106). Both the intervals from which the lab cores were taken (around 50 – 225 m) and the Minalyze intervals, contain up to 4% S. Given the unknown extent of this unit and the high S content, it is recommended that further holes are drilled, preferably perpendicular to stratigraphy between BH3108, BH4101, and BH4106. Given that this section is the head-race tunnel, several shallower holes to approximately 400 m could be drilled. This would aid in characterising the extents of this S mass.

3) BH4101 contains asbestiform minerals. Further drilling within the volcanic part of the Gooandra Volcanics would allow further sampling to determine not only the extent of the sulphidic material but also the asbestos.

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Snowy 2.0 P1: Comprehensive Geochemistry Examination

Final Report APPENDICES

Ryan Fraser, Yulia Uvarova, Mark Pearce, Sam Spinks, June Hill, Grant Douglas and Monica leGras
2 Nov 2018

For Snowy 2.0 Scheme, Snowy Hydro Limited
Commercial-in-confidence

Citation

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Contents

Figures

Tables

Appendix A Supporting Materials

The following results are provided in digital format:

A.1 Geochemistry Examination: Core Scanning Schedule – “P1-CSIRO-Core-ScanningSch.xlsx”

A.2 Borehole Reports – downhole logs and tessellation for each drill core analysed, see “Borehole Reports” folder for each individual drill core report

A.3 Mineralogy Results – P1-CSIRO-MineralogyAllFinal.xlsx”

A.4 Minor and Accessory Mineralogy – “P1-CSIRO-MinorAccessMineralogy.pdf”

A.5 Amphibole Mineralogy – “NOA-SEM-tests-BH3106BH4106-Sept2018.pdf”

A.6 Amphibole Mineralogy - “NOA-tests-BH3108BH4101-Oct2018.pdf”

A.7 Geochemistry Results – “P1-CSIRO-GeochemLabAllFinal.xlsx” and “P1-CSIRO-GeochemLabQAQC-Final.xlsx”

A.8 Snowy 2.0 Drilling Program – Locations on Boreholes as part of the Feasibility Study (2018)

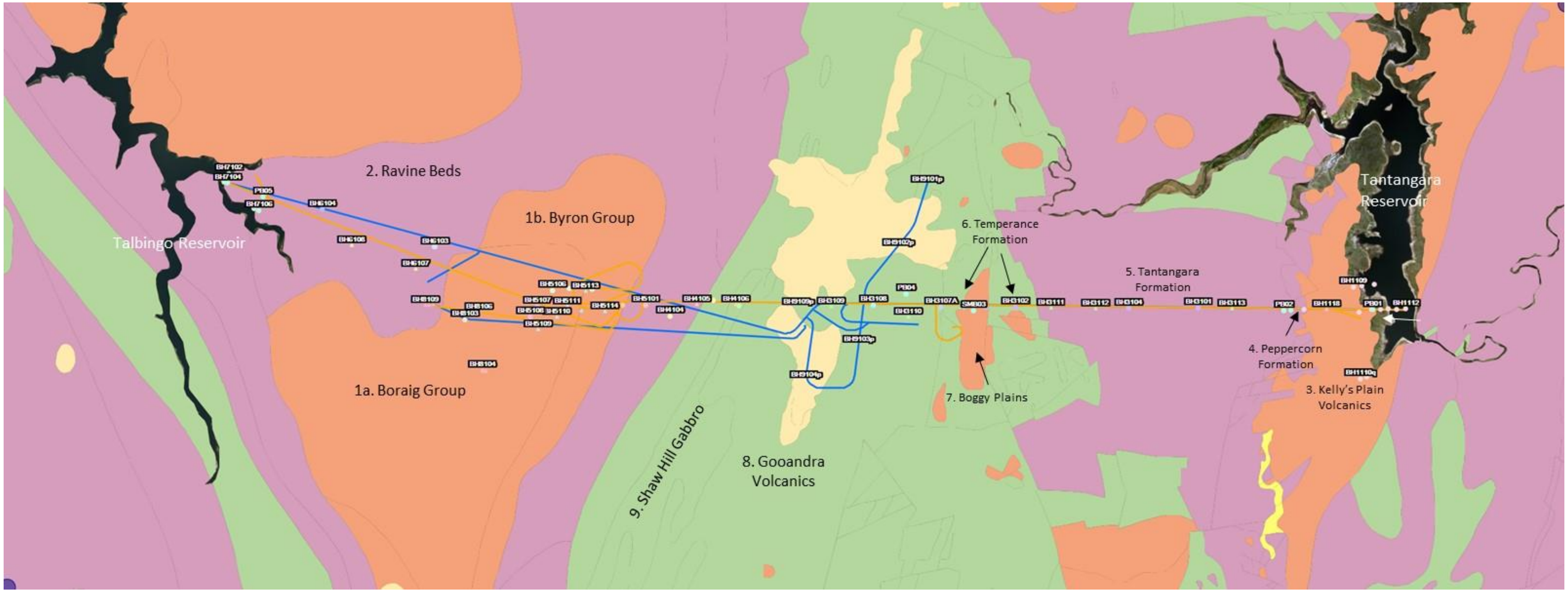
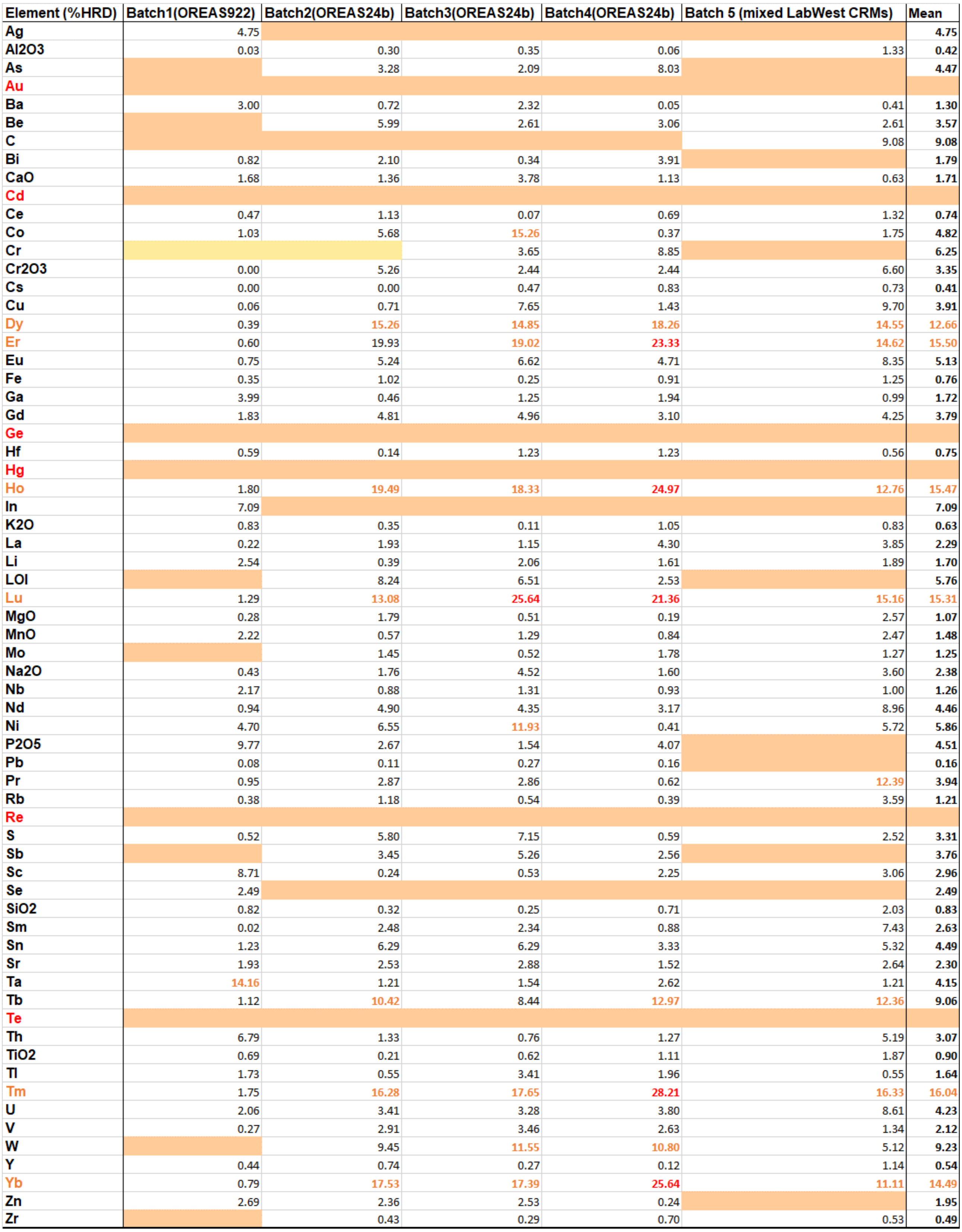


Figure 1. Borehole Locations relevant to surface Lithologic Units (geology zones)

Appendix B Geochemical Characterisation: Lab Samples

B.1 HRD values for Lab Samples



Element (%HRD)	Batch1(OREAS922)	Batch2(OREAS24b)	Batch3(OREAS24b)	Batch4(OREAS24b)	Batch 5 (mixed LabWest CRMs)	Mean
Ag	4.75					4.75
Al2O3	0.03	0.30	0.35	0.06	1.33	0.42
As		3.28	2.09	8.03		4.47
Au						
Ba	3.00	0.72	2.32	0.05	0.41	1.30
Be		5.99	2.61	3.06	2.61	3.57
C					9.08	9.08
Bi	0.82	2.10	0.34	3.91		1.79
CaO	1.68	1.36	3.78	1.13	0.63	1.71
Cd						
Ce	0.47	1.13	0.07	0.69	1.32	0.74
Co	1.03	5.68	15.26	0.37	1.75	4.82
Cr			3.65	8.85		6.25
Cr2O3	0.00	5.26	2.44	2.44	6.60	3.35
Cs	0.00	0.00	0.47	0.83	0.73	0.41
Cu	0.06	0.71	7.65	1.43	9.70	3.91
Dy	0.39	15.26	14.85	18.26	14.55	12.66
Er	0.60	19.93	19.02	23.33	14.62	15.50
Eu	0.75	5.24	6.62	4.71	8.35	5.13
Fe	0.35	1.02	0.25	0.91	1.25	0.76
Ga	3.99	0.46	1.25	1.94	0.99	1.72
Gd	1.83	4.81	4.96	3.10	4.25	3.79
Ge						
Hf	0.59	0.14	1.23	1.23	0.56	0.75
Hg						
Ho	1.80	19.49	18.33	24.97	12.76	15.47
In	7.09					7.09
K2O	0.83	0.35	0.11	1.05	0.83	0.63
La	0.22	1.93	1.15	4.30	3.85	2.29
Li	2.54	0.39	2.06	1.61	1.89	1.70
LOI		8.24	6.51	2.53		5.76
Lu	1.29	13.08	25.64	21.36	15.16	15.31
MgO	0.28	1.79	0.51	0.19	2.57	1.07
MnO	2.22	0.57	1.29	0.84	2.47	1.48
Mo		1.45	0.52	1.78	1.27	1.25
Na2O	0.43	1.76	4.52	1.60	3.60	2.38
Nb	2.17	0.88	1.31	0.93	1.00	1.26
Nd	0.94	4.90	4.35	3.17	8.96	4.46
Ni	4.70	6.55	11.93	0.41	5.72	5.86
P2O5	9.77	2.67	1.54	4.07		4.51
Pb	0.08	0.11	0.27	0.16		0.16
Pr	0.95	2.87	2.86	0.62	12.39	3.94
Rb	0.38	1.18	0.54	0.39	3.59	1.21
Re						
S	0.52	5.80	7.15	0.59	2.52	3.31
Sb		3.45	5.26	2.56		3.76
Sc	8.71	0.24	0.53	2.25	3.06	2.96
Se	2.49					2.49
SiO2	0.82	0.32	0.25	0.71	2.03	0.83
Sm	0.02	2.48	2.34	0.88	7.43	2.63
Sn	1.23	6.29	6.29	3.33	5.32	4.49
Sr	1.93	2.53	2.88	1.52	2.64	2.30
Ta	14.16	1.21	1.54	2.62	1.21	4.15
Tb	1.12	10.42	8.44	12.97	12.36	9.06
Te						
Th	6.79	1.33	0.76	1.27	5.19	3.07
TiO2	0.69	0.21	0.62	1.11	1.87	0.90
Tl	1.73	0.55	3.41	1.96	0.55	1.64
Tm	1.75	16.28	17.65	28.21	16.33	16.04
U	2.06	3.41	3.28	3.80	8.61	4.23
V	0.27	2.91	3.46	2.63	1.34	2.12
W		9.45	11.55	10.80	5.12	9.23
Y	0.44	0.74	0.27	0.12	1.14	0.54
Yb	0.79	17.53	17.39	25.64	11.11	14.49
Zn	2.69	2.36	2.53	0.24		1.95
Zr		0.43	0.29	0.70	0.53	0.49

Table 1. Compiled QA/QC (%HRD) results for each element from Batches 1-5. Different CRMs were used throughout the project, resulting in inconsistent returns for individual elements. Those elements highlighted in have no QA/QC

constraints from the CRMs, and those highlighted in orange have mean %HRD scores >10 from the CRM results, and must be considered with caution.

B.2 Geological Zone Results

B.2.1 Boraig Group

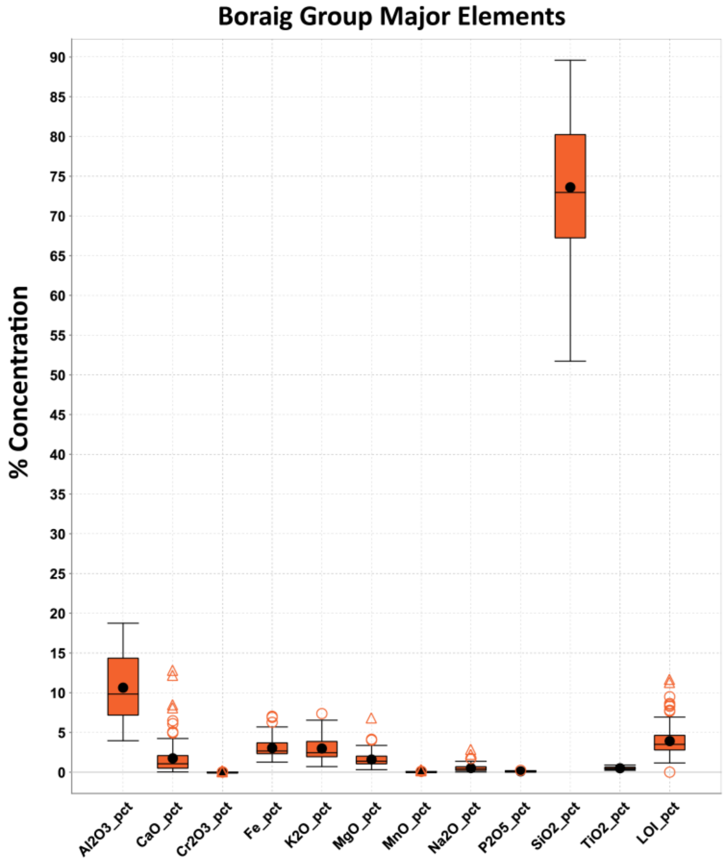


Figure 2. Tukey box plot of the major elements for the Boraig Group. Minimum regular value (lower whisker); Q1 (bottom of box); median (horizontal line); Q3 (top of box); maximum regular value (top of box); mean (black circle); The central box is the middle 50% of data from Q1 to Q3. Outliers (circles) are more than 1.5 times from the box (Q3-Q1). Far outliers (triangles) are more than 3.0 times from the box.

	Minimum	Maximum	Mean	Std. Dev.
Al2O3_pct	3.96	18.75	10.63	3.77
CaO_pct	0.03	12.73	1.75	2.18
Cr2O3_pct	0.01	0.18	0.01	0.02
Fe_pct	1.27	7.03	3.04	1.04
Hf_ppm	3.00	10.00	6.19	1.30
K2O_pct	0.70	7.37	2.98	1.38
MgO_pct	0.32	6.73	1.59	0.83
MnO_pct	0.01	0.31	0.06	0.05
Na2O_pct	0.02	2.81	0.52	0.46
Nb_ppm	4.10	16.50	10.34	3.40

P2O5_pct	0.01	0.23	0.10	0.04
SiO2_pct	51.72	89.58	73.60	7.92
Ta_ppm	0.37	1.50	0.85	0.32
TiO2_pct	0.23	0.89	0.50	0.16
Y_ppm	14.40	41.90	25.33	5.61
Zr_ppm	89.00	357.00	221.07	46.99
LOIPct	0.01	11.55	3.91	1.96
Ag_ppm	0.01	0.96	0.10	0.12
As_ppm	0.80	64.50	6.52	7.86
Au_ppb	0.25	15.00	0.69	2.01
Ba_ppm	145.00	10900.00	539.69	1027.56
Be_ppm	0.70	3.90	1.95	0.88
Bi_ppm	0.05	9.90	0.45	0.96
Cd_ppm	0.03	0.13	0.03	0.02
Ce_ppm	33.50	104.00	65.02	19.46
Co_ppm	2.30	44.00	10.07	5.47
Cr_ppm	12.00	321.00	62.17	43.00
Cs_ppm	2.50	27.40	9.33	6.09
Cu_ppm	3.10	284.70	21.47	34.29
Dy_ppm	1.90	7.20	3.97	0.97
Er_ppm	0.98	5.02	2.28	0.63
Eu_ppm	0.42	1.64	0.95	0.24
Ga_ppm	5.40	24.70	14.01	5.12
Gd_ppm	2.62	7.75	4.74	1.11
Ge_ppm	0.41	1.59	0.93	0.31
Hg_ppm	0.03	0.10	0.03	0.01
Ho_ppm	0.35	1.55	0.77	0.21
In_ppm	0.02	0.49	0.05	0.05
La_ppm	15.50	50.90	31.93	9.52
Li_ppm	4.10	159.00	25.41	19.67
Lu_ppm	0.17	0.85	0.35	0.10
Mo_ppm	0.05	3.70	0.31	0.37
Nd_ppm	14.10	42.70	27.06	7.45
Ni_ppm	6.00	165.00	30.94	17.96
Pb_ppm	1.90	42.20	8.19	7.93
Pr_ppm	3.85	11.70	7.42	2.14
Pt_ppb	0.50	11.00	1.70	2.53
Rb_ppm	32.20	436.00	155.31	73.11
Re_ppm	0.25	1.00	0.31	0.16
S_ppm	25.00	11200.00	511.85	1386.69
Sb_ppm	0.90	9.40	1.93	1.16
Sc_ppm	3.00	45.00	9.94	5.58
Se_ppm	0.07	0.87	0.34	0.12
Sm_ppm	3.00	8.45	5.33	1.35
Sn_ppm	1.20	23.10	3.68	2.38
Sr_ppm	7.90	269.00	47.11	47.83
Tb_ppm	0.35	1.16	0.69	0.16
Te_ppm	0.03	0.09	0.03	0.01
Th_ppm	6.12	31.80	13.83	5.13
Tl_ppm	0.20	1.70	0.78	0.35

Tm_ppm	0.14	0.80	0.34	0.10
U_ppm	1.36	7.65	2.99	1.05
V_ppm	21.00	227.00	75.20	33.92
W_ppm	0.60	8.90	2.29	1.12
Yb_ppm	1.03	5.11	2.19	0.62
Zn_ppm	8.00	184.00	49.29	24.62

Table 2. Boraig Group multi-element geochemical results

B.2.2 Gooandra Volcanics

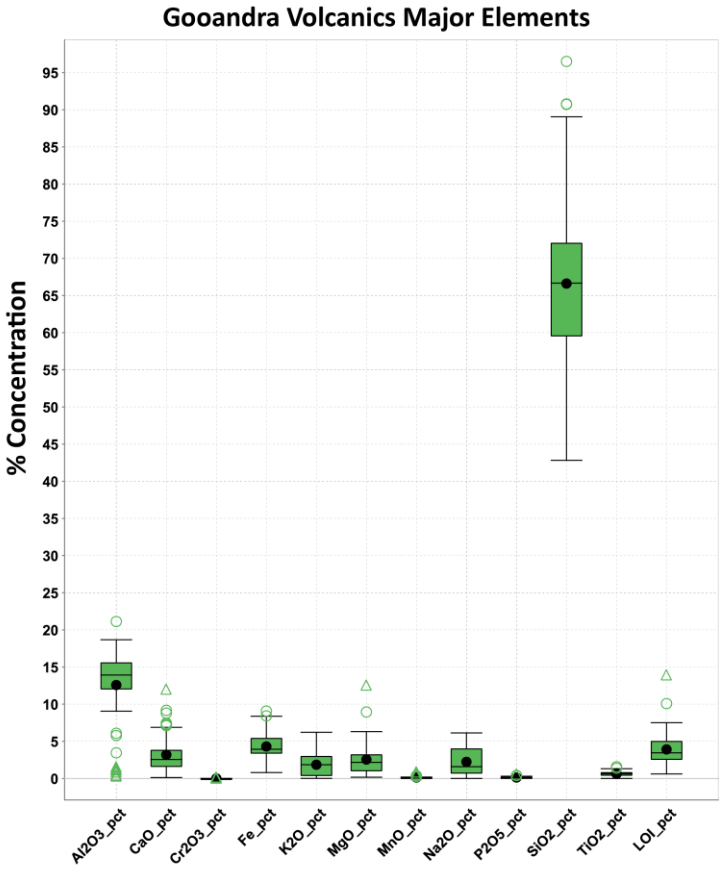


Figure 3. Tukey box plot of the major elements for the Gooandra Volcanics. Minimum regular value (lower whisker); Q1 (bottom of box); median (horizontal line); Q3 (top of box); maximum regular value (top of box); mean (black circle); The central box is the middle 50% of data from Q1 to Q3. Outliers (circles) are more than 1.5 times from the box (Q3-Q1). Far outliers (triangles) are more than 3.0 times from the box.

	Minimum	Maximum	Mean	Std. Dev.
Al2O3_pct	0.28	21.13	12.58	4.95
CaO_pct	0.13	12.01	3.20	2.44
Cr2O3_pct	0.005	0.16	0.01	0.02
Fe_pct	0.8	9.08	4.31	1.81
Hf_ppm	0.05	11.00	4.34	2.36
K2O_pct	0.02	6.23	1.85	1.54

MgO_pct	0.17	12.46	2.55	2.07
MnO_pct	0.01	0.88	0.14	0.16
Na2O_pct	0.005	6.14	2.24	1.88
Nb_ppm	0.25	16.70	7.90	4.48
P2O5_pct	0.005	0.61	0.13	0.10
SiO2_pct	42.82	96.50	66.61	10.98
Ta_ppm	0.08	1.41	0.63	0.33
TiO2_pct	0.005	1.58	0.61	0.35
Y_ppm	2.9	59.90	26.70	11.42
Zr_ppm	0.25	396.00	153.69	79.57
LOIPct	0.62	13.92	3.91	2.09
Ag_ppm	0.005	1.50	0.08	0.20
As_ppm	1.2	248.00	12.75	31.88
Au_ppb	0.25	8.00	0.47	1.26
Ba_ppm	9.7	1820.00	398.00	344.38
Be_ppm	0.1	3.00	1.55	0.86
Bi_ppm	0.05	5.20	0.53	0.97
Cd_ppm	0.025	6.64	0.35	1.19
Ce_ppm	2.48	106.00	53.77	28.22
Co_ppm	1.1	191.00	18.38	24.39
Cr_ppm	1	1070.00	53.83	137.19
Cs_ppm	0.05	11.30	3.99	3.82
Cu_ppm	1.9	271.50	34.77	55.26
Dy_ppm	0.48	10.00	4.62	2.10
Er_ppm	0.27	6.82	2.83	1.34
Eu_ppm	0.09	2.17	1.03	0.45
Ga_ppm	0.69	28.90	15.71	6.41
Gd_ppm	0.46	9.89	4.98	2.11
Ge_ppm	0.22	1.18	0.56	0.19
Hg_ppm	0.025	0.06	0.03	0.00
Ho_ppm	0.09	2.14	0.94	0.44
In_ppm	0.005	0.12	0.06	0.02
La_ppm	1.16	54.10	25.47	13.67
Li_ppm	0.25	83.60	18.92	16.06
Lu_ppm	0.03	0.88	0.39	0.17
Mo_ppm	0.05	7.30	0.64	1.27
Nd_ppm	1.19	46.00	23.77	11.53
Ni_ppm	1	427.00	25.52	52.37
Pb_ppm	2	71.70	17.07	13.14
Pr_ppm	0.28	14.80	6.30	3.26
Pt_ppb	0.5	10.00	1.50	2.09
Rb_ppm	0.3	232.00	75.12	65.33
Re_ppm	0.25	7.80	0.72	1.05
S_ppm	25	39800.00	2457.56	6617.31
Sb_ppm	0.1	5.10	0.78	0.76
Sc_ppm	0.5	35.00	14.23	8.79
Se_ppm	0.05	2.51	0.51	0.41
Sm_ppm	0.31	9.67	5.05	2.24
Sn_ppm	0.1	6.40	2.65	1.67
Sr_ppm	7.8	650.00	150.36	118.55

Tb_ppm	0.07	1.66	0.79	0.35
Te_ppm	0.025	0.29	0.04	0.05
Th_ppm	0.26	29.00	10.14	7.02
Tl_ppm	0.05	5.20	0.58	0.76
Tm_ppm	0.025	0.97	0.41	0.19
U_ppm	0.13	5.18	1.97	1.24
V_ppm	5	364.00	112.02	87.67
W_ppm	0.05	12.00	1.98	2.54
Yb_ppm	0.26	6.44	2.63	1.22
Zn_ppm	5.1	4150.00	248.38	751.17

Table 3. Gooandra Volcanics multi-element geochemical results

B.2.3 Byron Range Group

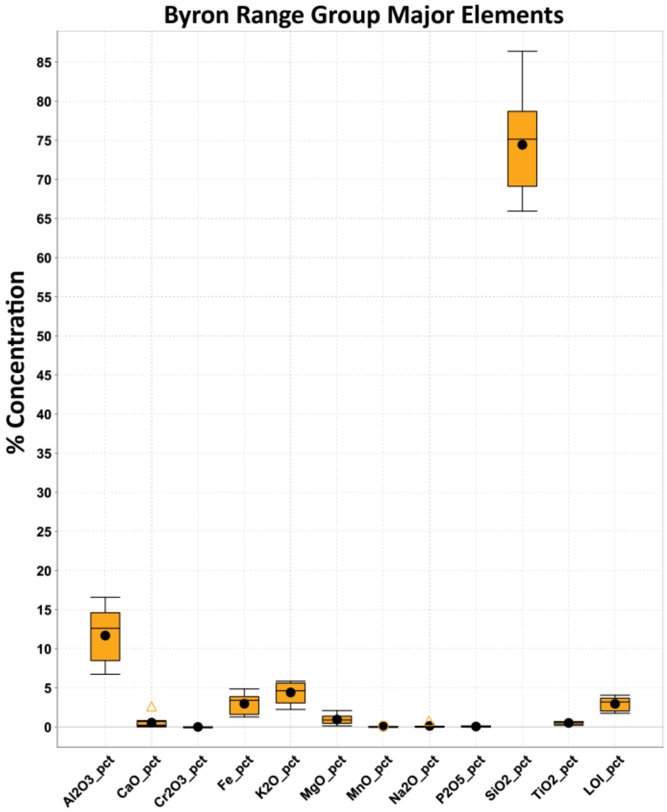


Figure 4. Tukey box plot of the major elements for the Byron Range Group. Minimum regular value (lower whisker); Q1 (bottom of box); median (horizontal line); Q3 (top of box); maximum regular value (top of box); mean (black circle); The central box is the middle 50% of data from Q1 to Q3. Outliers (circles) are more than 1.5 times from the box (Q3-Q1). Far outliers (triangles) are more than 3.0 times from the box.

	Minimum	Maximum	Mean	Std. Dev.
Al2O3_pct	6.740	16.58	11.69	3.39
CaO_pct	0.010	2.63	0.56	0.82
Cr2O3_pct	0.005	0.01	0.01	0.00
Fe_pct	1.280	4.87	2.97	1.27
Hf_ppm	3.000	8.00	6.00	1.66
K2O_pct	2.240	5.86	4.41	1.34

MgO_pct	0.150	2.09	0.95	0.61
MnO_pct	0.005	0.14	0.04	0.04
Na2O_pct	0.030	0.72	0.14	0.22
Nb_ppm	5.000	15.10	11.09	3.37
P2O5_pct	0.005	0.14	0.06	0.05
SiO2_pct	65.950	86.38	74.42	6.39
Ta_ppm	0.430	1.22	0.94	0.26
TiO2_pct	0.210	0.69	0.52	0.17
Y_ppm	16.300	31.00	26.53	5.12
Zr_ppm	111.000	276.00	210.44	56.05
LOIPct	1.750	4.07	2.95	0.88
Ag_ppm	0.005	0.12	0.06	0.04
As_ppm	1.500	11.20	5.78	3.75
Au_ppb	0.250	0.25	0.25	0.00
Ba_ppm	366.000	7130.00	1550.11	2359.83
Be_ppm	0.900	4.30	2.71	1.40
Bi_ppm	0.100	3.30	0.67	1.02
Cd_ppm	0.025	0.03	0.03	0.00
Ce_ppm	42.400	94.50	70.49	18.48
Co_ppm	1.500	13.10	7.52	3.93
Cr_ppm	19.000	94.00	59.00	26.28
Cs_ppm	6.600	633.00	110.66	199.85
Cu_ppm	3.000	100.30	20.92	32.23
Dy_ppm	2.660	4.61	3.85	0.70
Er_ppm	1.410	2.83	2.25	0.47
Eu_ppm	0.690	1.52	1.17	0.22
Ga_ppm	6.080	22.90	14.84	5.75
Gd_ppm	3.540	5.80	4.90	0.72
Ge_ppm	0.610	1.83	1.36	0.42
Hg_ppm	0.025	0.03	0.03	0.00
Ho_ppm	0.510	0.96	0.76	0.16
In_ppm	0.030	0.15	0.08	0.03
La_ppm	20.800	50.80	37.26	9.40
Li_ppm	8.600	31.50	15.63	7.27
Lu_ppm	0.210	0.44	0.34	0.08
Mo_ppm	0.050	0.40	0.24	0.10
Nd_ppm	18.300	37.40	28.48	6.44
Ni_ppm	4.000	42.00	22.67	12.36
Pb_ppm	3.900	12.00	6.86	2.53
Pr_ppm	4.960	10.20	7.76	1.84
Pt_ppb	0.500	8.00	3.06	2.76
Rb_ppm	98.900	604.00	297.66	149.05
Re_ppm	0.250	0.70	0.30	0.15
S_ppm	25.000	1350.00	380.22	507.09
Sb_ppm	1.500	13.60	5.91	3.42
Sc_ppm	4.000	15.00	9.56	3.91
Se_ppm	0.220	0.41	0.32	0.07
Sm_ppm	3.820	7.30	5.86	1.08
Sn_ppm	1.800	5.10	3.50	1.08
Sr_ppm	13.500	231.00	56.59	75.77

Tb_ppm	0.490	0.85	0.73	0.12
Te_ppm	0.025	0.08	0.05	0.02
Th_ppm	7.030	18.80	14.24	3.76
Tl_ppm	0.500	2.60	1.37	0.61
Tm_ppm	0.220	0.46	0.35	0.08
U_ppm	1.540	4.48	3.03	0.96
V_ppm	34.000	111.00	78.67	26.69
W_ppm	0.900	13.80	6.50	3.87
Yb_ppm	1.450	2.89	2.26	0.48
Zn_ppm	11.300	71.00	33.70	19.77

Table 4. Byron Range Group multi-element geochemical results

B.2.4 Temperance Formation

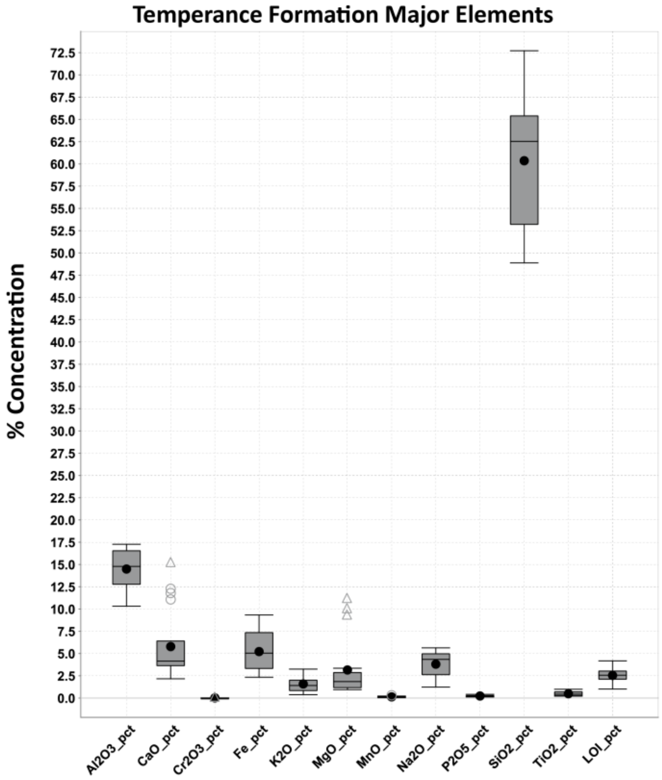


Figure 5. Tukey box plot of the major elements for the Temperance Formation. Minimum regular value (lower whisker); Q1 (bottom of box); median (horizontal line); Q3 (top of box); maximum regular value (top of box); mean (black circle); The central box is the middle 50% of data from Q1 to Q3. Outliers (circles) are more than 1.5 times from the box (Q3-Q1). Far outliers (triangles) are more than 3.0 times from the box.

	Minimum	Maximum	Mean	Std. Dev.
Al2O3_pct	10.320	17.27	14.49	2.30
CaO_pct	2.160	15.26	5.78	3.88
Cr2O3_pct	0.005	0.08	0.02	0.02
Fe_pct	2.330	9.33	5.22	2.22
Hf_ppm	0.050	4.00	1.79	1.15
K2O_pct	0.380	3.25	1.58	0.90
MgO_pct	0.940	11.16	3.15	3.31
MnO_pct	0.040	0.31	0.13	0.07

Na2O_pct	1.230	5.63	3.80	1.44
Nb_ppm	2.200	14.30	6.39	3.52
P2O5_pct	0.120	0.41	0.23	0.09
SiO2_pct	48.880	72.71	60.36	7.29
Ta_ppm	0.120	0.75	0.37	0.18
TiO2_pct	0.210	0.98	0.48	0.23
Y_ppm	9.100	25.50	15.15	5.76
Zr_ppm	15.000	140.00	67.67	39.31
LOIPct	1.010	4.17	2.54	0.73
Ag_ppm	0.005	0.45	0.06	0.10
As_ppm	0.800	14.00	2.52	3.07
Au_ppb	0.250	7.00	0.63	1.59
Ba_ppm	56.300	1170.00	520.13	330.05
Be_ppm	0.600	1.60	1.02	0.24
Bi_ppm	0.050	0.40	0.12	0.12
Cd_ppm	0.025	0.30	0.07	0.07
Ce_ppm	10.400	52.40	30.46	12.28
Co_ppm	6.500	48.00	19.20	13.57
Cr_ppm	1.000	488.00	83.72	161.51
Cs_ppm	0.050	2.10	1.06	0.51
Cu_ppm	5.100	1446.00	167.65	337.77
Dy_ppm	1.430	4.48	2.67	1.06
Er_ppm	0.980	2.77	1.68	0.61
Eu_ppm	0.440	1.69	0.88	0.42
Ga_ppm	10.600	27.40	15.82	4.08
Gd_ppm	1.440	5.59	3.04	1.44
Ge_ppm	0.390	1.95	0.67	0.35
Hg_ppm	0.025	0.03	0.03	0.00
Ho_ppm	0.310	0.94	0.55	0.22
In_ppm	0.010	0.43	0.07	0.09
La_ppm	5.410	24.70	15.96	5.84
Li_ppm	1.900	11.80	6.86	3.24
Lu_ppm	0.140	0.34	0.23	0.07
Mo_ppm	0.050	6.60	0.90	1.54
Nd_ppm	6.050	29.10	14.70	7.69
Ni_ppm	1.000	110.00	21.89	32.42
Pb_ppm	0.900	21.50	5.39	5.03
Pr_ppm	1.410	6.82	3.64	1.70
Pt_ppb	0.500	22.00	3.06	5.12
Rb_ppm	4.800	85.70	36.06	19.24
Re_ppm	0.250	16.60	2.63	4.44
S_ppm	25.000	21200.00	3996.94	5711.80
Sb_ppm	0.100	1.00	0.31	0.19
Sc_ppm	4.000	45.00	17.06	13.55
Se_ppm	0.190	3.81	0.92	0.98
Sm_ppm	1.450	6.40	3.21	1.72
Sn_ppm	0.400	5.70	1.28	1.18
Sr_ppm	273.000	1140.00	595.83	245.00
Tb_ppm	0.250	0.83	0.47	0.20
Te_ppm	0.025	0.36	0.08	0.09

Th_ppm	1.140	3.61	2.57	0.62
Tl_ppm	0.050	0.30	0.15	0.07
Tm_ppm	0.150	0.42	0.26	0.09
U_ppm	0.430	1.93	1.19	0.48
V_ppm	76.000	328.00	158.33	73.38
W_ppm	0.200	1.00	0.52	0.24
Yb_ppm	1.080	2.64	1.65	0.55
Zn_ppm	4.000	154.00	53.14	44.03

Table 5. Temperance Formation multi-element geochemical results.

B.2.5 Tantangara Formation

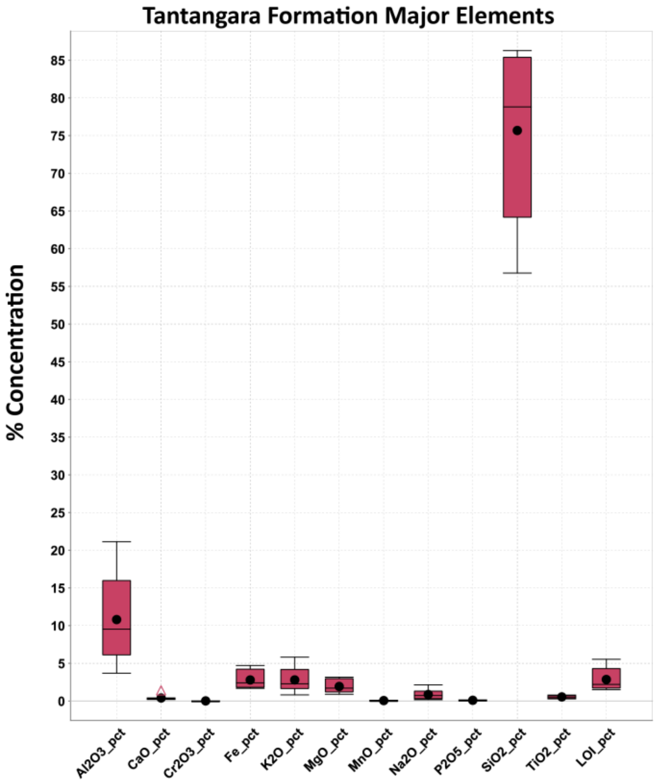


Figure 6. Tukey box plot of the major elements for the Tantangara Formation. Minimum regular value (lower whisker); Q1 (bottom of box); median (horizontal line); Q3 (top of box); maximum regular value (top of box); mean (black circle); The central box is the middle 50% of data from Q1 to Q3. Outliers (circles) are more than 1.5 times from the box (Q3-Q1). Far outliers (triangles) are more than 3.0 times from the box.

	Minimum	Maximum	Mean	Std. Dev.
Al2O3_pct	3.680	21.13	10.80	5.59
CaO_pct	0.200	1.33	0.40	0.33
Cr2O3_pct	0.005	0.02	0.01	0.01
Fe_pct	1.680	4.71	2.79	1.19
Hf_ppm	3.000	12.00	7.70	3.37
K2O_pct	0.810	5.82	2.80	1.64
MgO_pct	0.890	3.16	1.93	0.83
MnO_pct	0.020	0.10	0.05	0.02
Na2O_pct	0.170	2.14	0.87	0.62
Nb_ppm	4.700	16.90	11.50	4.40

P2O5_pct	0.005	0.14	0.09	0.05
SiO2_pct	56.760	86.28	75.68	10.72
Ta_ppm	0.460	1.39	0.97	0.33
TiO2_pct	0.280	0.78	0.54	0.19
Y_ppm	13.600	38.70	25.46	8.08
Zr_ppm	111.000	439.00	272.00	121.19
LOI_pct	1.510	5.53	2.85	1.47
Ag_ppm	0.005	0.23	0.06	0.08
As_ppm	1.400	63.80	11.58	18.84
Au_ppb	0.250	0.25	0.25	0.00
Ba_ppm	151.000	767.00	402.20	196.68
Be_ppm	0.600	6.20	2.31	1.91
Bi_ppm	0.050	0.80	0.28	0.28
Cd_ppm	0.025	0.11	0.03	0.03
Ce_ppm	37.500	118.00	70.90	27.71
Co_ppm	3.900	20.20	9.77	5.74
Cr_ppm	30.000	132.00	67.10	37.31
Cs_ppm	1.200	15.30	5.18	4.91
Cu_ppm	5.100	27.40	11.46	7.83
Dy_ppm	1.830	5.40	3.75	1.25
Er_ppm	0.990	3.31	2.16	0.74
Eu_ppm	0.560	1.58	0.93	0.33
Ga_ppm	5.030	30.70	14.70	8.72
Gd_ppm	2.640	7.11	4.69	1.58
Ge_ppm	0.460	0.75	0.58	0.11
Hg_ppm	0.025	0.03	0.03	0.00
Ho_ppm	0.320	1.11	0.73	0.26
In_ppm	0.010	0.07	0.04	0.02
La_ppm	17.100	55.70	33.56	13.57
Li_ppm	4.900	26.60	10.68	6.33
Lu_ppm	0.160	0.39	0.27	0.08
Mo_ppm	0.050	14.20	1.70	4.41
Nd_ppm	14.900	48.40	28.54	11.13
Ni_ppm	13.000	67.00	30.90	18.10
Pb_ppm	2.500	19.30	9.28	5.44
Pr_ppm	3.970	14.00	7.89	3.21
Pt_ppb	0.500	8.00	2.05	2.69
Rb_ppm	40.500	269.00	130.61	84.16
Re_ppm	0.250	1.20	0.44	0.40
S_ppm	25.000	9860.00	2090.50	3139.12
Sb_ppm	0.300	1.50	0.62	0.42
Sc_ppm	4.000	21.00	8.60	6.04
Se_ppm	0.140	0.53	0.35	0.12
Sm_ppm	3.050	8.93	5.53	1.99
Sn_ppm	1.100	6.20	3.20	1.79
Sr_ppm	13.100	60.40	30.51	14.42
Tb_ppm	0.330	0.99	0.68	0.23
Te_ppm	0.025	0.06	0.03	0.01
Th_ppm	8.300	26.70	15.31	6.34
Tl_ppm	0.200	1.50	0.67	0.44

Tm_ppm	0.140	0.46	0.30	0.11
U_ppm	1.840	3.94	2.87	0.70
V_ppm	22.000	134.00	62.30	42.24
W_ppm	0.900	3.40	1.97	0.84
Yb_ppm	0.930	2.98	1.98	0.66
Zn_ppm	15.300	112.00	44.48	30.49

Table 6. Tantangara Formation multi-element geochemical results

B.2.6 Kelly's Plain Volcanics

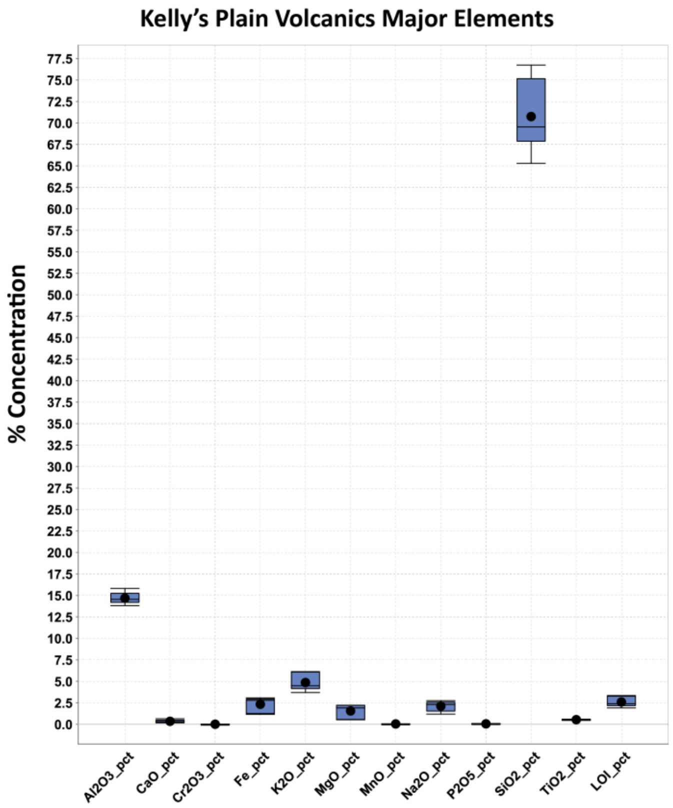


Figure 7. Tukey box plot of the major elements for the Kelly's Plain Volcanics. Minimum regular value (lower whisker); Q1 (bottom of box); median (horizontal line); Q3 (top of box); maximum regular value (top of box); mean (black circle); The central box is the middle 50% of data from Q1 to Q3. Outliers (circles) are more than 1.5 times from the box (Q3-Q1). Far outliers (triangles) are more than 3.0 times from the box.

	Minimum	Maximum	Mean	Std. Dev.
Al2O3_pct	13.810	15.81	14.68	0.68
CaO_pct	0.170	0.64	0.34	0.17
Cr2O3_pct	0.005	0.01	0.01	0.00
Fe_pct	1.160	3.07	2.33	0.87
Hf_ppm	5.000	6.00	5.50	0.55
K2O_pct	3.690	6.13	4.86	1.00
MgO_pct	0.530	2.21	1.56	0.79
MnO_pct	0.010	0.05	0.04	0.02
Na2O_pct	1.180	2.75	2.12	0.60
Nb_ppm	10.200	12.00	11.37	0.77
P2O5_pct	0.030	0.08	0.05	0.02

SiO2_pct	65.300	76.74	70.75	4.19
Ta_ppm	0.970	1.03	1.01	0.02
TiO2_pct	0.460	0.59	0.54	0.06
Y_ppm	29.800	37.10	32.37	2.74
Zr_ppm	174.000	206.00	192.67	11.81
LOI_pct	1.910	3.34	2.59	0.57
Ag_ppm	0.100	0.17	0.13	0.03
As_ppm	1.600	28.20	9.92	11.86
Au_ppb	0.250	0.25	0.25	0.00
Ba_ppm	494.000	567.00	534.50	27.56
Be_ppm	1.900	2.40	2.20	0.24
Bi_ppm	0.050	0.40	0.15	0.16
Cd_ppm	0.025	0.03	0.03	0.00
Ce_ppm	61.000	73.40	66.65	5.13
Co_ppm	8.000	9.70	8.90	0.81
Cr_ppm	29.000	40.00	34.83	4.96
Cs_ppm	2.700	3.70	3.28	0.41
Cu_ppm	12.500	42.40	25.02	10.97
Dy_ppm	4.820	5.22	5.12	0.15
Er_ppm	2.850	3.14	3.03	0.10
Eu_ppm	0.830	1.06	0.93	0.09
Ga_ppm	16.500	17.40	16.80	0.39
Gd_ppm	5.400	6.00	5.64	0.25
Ge_ppm	0.390	0.55	0.47	0.07
Hg_ppm	0.025	0.03	0.03	0.00
Ho_ppm	0.990	1.09	1.06	0.04
In_ppm	0.040	0.06	0.05	0.01
La_ppm	29.800	36.40	32.67	2.74
Li_ppm	6.900	21.40	14.72	6.04
Lu_ppm	0.350	0.40	0.38	0.02
Mo_ppm	0.300	1.00	0.48	0.26
Nd_ppm	23.700	28.30	25.92	1.98
Ni_ppm	13.000	21.00	16.33	3.08
Pb_ppm	11.400	41.70	21.63	10.93
Pr_ppm	6.500	7.81	7.08	0.54
Pt_ppb	0.500	0.50	0.50	0.00
Rb_ppm	147.000	218.00	178.00	30.68
Re_ppm	BDL	BDL	N/A	N/A
S_ppm	141.000	3030.00	1159.17	1298.54
Sb_ppm	0.300	1.00	0.58	0.33
Sc_ppm	9.000	12.00	10.67	1.03
Se_ppm	0.660	0.86	0.74	0.08
Sm_ppm	5.270	5.99	5.64	0.30
Sn_ppm	3.700	7.30	4.73	1.42
Sr_ppm	39.100	69.80	58.00	14.46
Tb_ppm	0.810	0.90	0.88	0.04
Te_ppm	0.025	0.03	0.03	0.00
Th_ppm	14.900	18.40	16.15	1.33
Tl_ppm	0.900	1.60	1.18	0.33
Tm_ppm	0.390	0.43	0.42	0.02

U_ppm	3.670	4.48	4.00	0.30
V_ppm	55.000	76.00	66.17	8.84
W_ppm	2.200	3.90	2.92	0.78
Yb_ppm	2.580	2.96	2.80	0.13
Zn_ppm	20.200	53.70	42.40	13.87

Table 7. Kelly's Plain Volcanics multi-element geochemical results

B.2.7 Ravine Beds

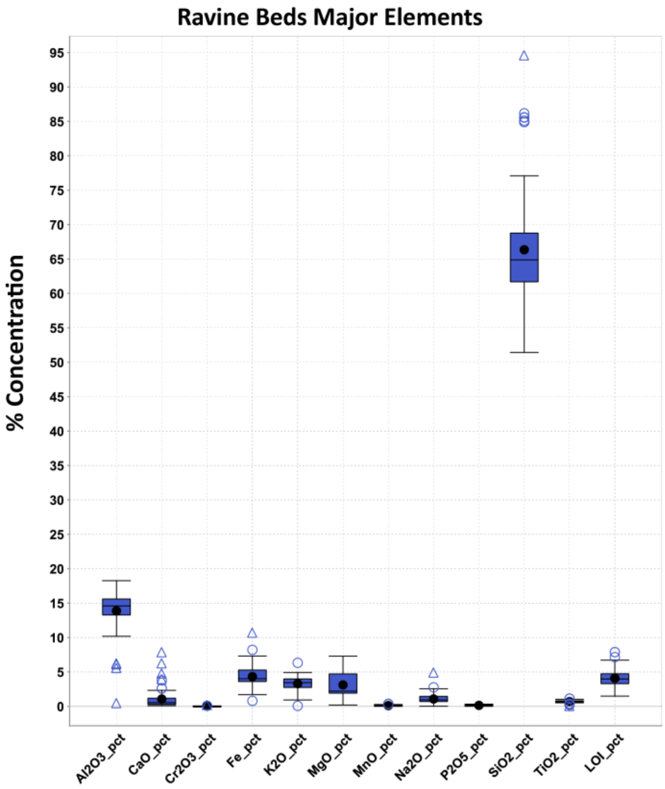


Figure 8. Tukey box plot of the major elements for the Ravine Beds. Minimum regular value (lower whisker); Q1 (bottom of box); median (horizontal line); Q3 (top of box); maximum regular value (top of box); mean (black circle); The central box is the middle 50% of data from Q1 to Q3. Outliers (circles) are more than 1.5 times from the box (Q3-Q1). Far outliers (triangles) are more than 3.0 times from the box.

	Minimum	Maximum	Mean	Std. Dev.
Al2O3_pct	0.360	18.26	13.87	3.28
CaO_pct	0.090	7.83	1.06	1.41
Cr2O3_pct	0.005	0.12	0.02	0.02
Fe_pct	0.790	10.68	4.32	1.55
Hf_ppm	0.050	8.00	5.02	1.43
K_2O_pct	0.070	6.32	3.29	1.06
MgO_pct	0.190	7.30	3.11	1.92
MnO_pct	0.020	0.37	0.11	0.08
Na2O_pct	0.020	4.86	1.07	0.82
Nb_ppm	0.250	16.10	12.91	3.04
P2O5_pct	0.005	0.32	0.14	0.07

SiO2_pct	51.420	94.51	66.35	8.24
Ta_ppm	0.050	1.63	0.98	0.31
TiO2_pct	0.010	1.13	0.69	0.21
Y_ppm	4.000	45.10	28.34	6.38
Zr_ppm	9.000	284.00	177.90	48.55
LOI_pct	1.480	7.88	4.08	1.35
Ag_ppm	0.005	1.60	0.16	0.22
As_ppm	1.000	47.70	13.13	9.80
Au_ppb	0.250	16.00	0.74	2.25
Ba_ppm	16.900	998.00	593.13	197.22
Be_ppm	0.100	4.20	2.51	0.96
Bi_ppm	0.050	2.30	0.54	0.38
Cd_ppm	0.025	3.93	0.14	0.49
Ce_ppm	2.100	104.00	75.19	20.77
Co_ppm	1.000	53.10	17.82	9.31
Cr_ppm	5.000	249.00	106.43	63.99
Cs_ppm	0.500	24.00	11.03	4.89
Cu_ppm	2.300	2986.00	79.32	361.26
Dy_ppm	0.780	7.83	4.54	1.22
Er_ppm	0.490	4.37	2.62	0.72
Eu_ppm	0.280	1.86	1.19	0.30
Ga_ppm	0.770	25.50	18.19	4.47
Gd_ppm	0.780	9.47	5.42	1.28
Ge_ppm	0.370	1.45	0.83	0.28
Hg_ppm	0.025	0.65	0.07	0.14
Ho_ppm	0.150	1.52	0.89	0.25
In_ppm	0.010	0.34	0.08	0.05
La_ppm	1.000	52.40	37.96	10.68
Li_ppm	2.300	94.40	48.33	22.77
Lu_ppm	0.080	0.58	0.38	0.10
Mo_ppm	0.050	1.80	0.37	0.29
Nd_ppm	1.290	43.60	31.33	7.83
Ni_ppm	1.000	215.00	81.03	70.76
Pb_ppm	1.000	750.00	38.37	99.33
Pr_ppm	0.290	11.60	8.45	2.19
Pt_ppb	0.500	17.00	1.85	3.04
Rb_ppm	4.400	323.00	165.21	60.18
Re_ppm	0.250	1.20	0.32	0.18
S_ppm	25.000	15700.00	1709.73	3767.82
Sb_ppm	0.400	4.40	2.04	0.86
Sc_ppm	0.500	24.00	13.19	4.58
Se_ppm	0.070	1.44	0.46	0.19
Sm_ppm	0.470	9.40	6.15	1.41
Sn_ppm	0.100	10.10	3.96	1.42
Sr_ppm	7.800	584.00	84.22	76.49
Tb_ppm	0.150	1.42	0.80	0.20
Te_ppm	0.025	0.11	0.04	0.02
Th_ppm	0.600	24.60	14.45	5.21
Tl_ppm	0.050	2.10	0.93	0.32
Tm_ppm	0.080	0.65	0.38	0.11

U_ppm	0.160	8.27	3.08	1.19
V_ppm	3.000	169.00	106.85	39.99
W_ppm	0.050	11.00	2.78	1.61
Yb_ppm	0.550	3.79	2.49	0.64
Zn_ppm	2.400	1850.00	147.37	231.96
C_pct	0.180	0.72	0.53	0.24

Table 8. Ravine Beds multi-element geochemical results

B.2.8 Shaw Hill Gabbro

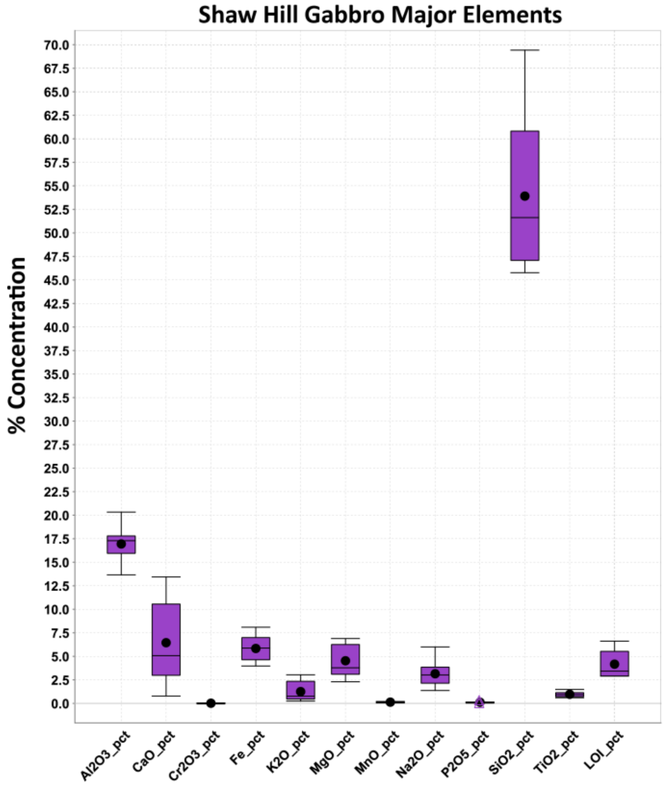


Figure 9. Tukey box plot of the major elements for the Shaw Hill Gabbro. Minimum regular value (lower whisker); Q1 (bottom of box); median (horizontal line); Q3 (top of box); maximum regular value (top of box); mean (black circle); The central box is the middle 50% of data from Q1 to Q3. Outliers (circles) are more than 1.5 times from the box (Q3-Q1). Far outliers (triangles) are more than 3.0 times from the box.

	Minimum	Maximum	Mean	Std. Dev.
Al2O3_pct	13.660	20.33	16.95	1.81
CaO_pct	0.780	13.44	6.45	4.31
Cr2O3_pct	0.005	0.04	0.02	0.02
Fe_pct	3.970	8.09	5.84	1.36
Hf_ppm	2.000	7.00	4.00	1.58
K2O_pct	0.250	3.04	1.25	1.04
MgO_pct	2.300	6.89	4.53	1.75
MnO_pct	0.050	0.21	0.14	0.05
Na2O_pct	1.370	6.00	3.15	1.35
Nb_ppm	1.800	12.60	6.57	4.10
P2O5_pct	0.005	0.30	0.12	0.08
SiO2_pct	45.770	69.42	53.91	8.08

Ta_ppm	0.170	1.11	0.52	0.37
TiO2_pct	0.600	1.48	0.96	0.28
Y_ppm	18.500	38.30	28.06	6.84
Zr_ppm	49.000	226.00	141.89	54.88
LOIPct	2.900	6.62	4.17	1.44
Ag_ppm	0.005	0.07	0.02	0.02
As_ppm	1.700	7.60	3.17	1.96
Au_ppb	0.250	0.25	0.25	0.00
Ba_ppm	32.500	471.00	186.09	168.03
Be_ppm	0.400	2.60	1.28	0.86
Bi_ppm	0.050	0.50	0.18	0.19
Cd_ppm	0.025	0.09	0.06	0.02
Ce_ppm	11.300	96.20	43.68	29.82
Co_ppm	12.600	41.70	27.82	11.25
Cr_ppm	1.000	257.00	139.67	103.98
Cs_ppm	0.200	8.90	2.74	3.10
Cu_ppm	15.700	120.20	61.83	38.75
Dy_ppm	3.030	6.25	4.87	1.17
Er_ppm	1.970	3.98	2.95	0.65
Eu_ppm	0.710	1.42	1.10	0.24
Ga_ppm	13.700	21.70	17.68	2.59
Gd_ppm	2.670	7.03	4.79	1.36
Ge_ppm	0.430	0.93	0.56	0.16
Hg_ppm	0.025	0.03	0.03	0.00
Ho_ppm	0.660	1.35	1.01	0.24
In_ppm	0.050	0.08	0.07	0.01
La_ppm	5.160	47.70	19.51	15.35
Li_ppm	6.900	71.20	26.98	19.97
Lu_ppm	0.200	0.38	0.30	0.06
Mo_ppm	0.050	0.05	0.05	0.00
Nd_ppm	7.940	37.10	19.80	10.05
Ni_ppm	5.000	89.00	42.78	28.80
Pb_ppm	2.000	23.90	8.64	8.41
Pr_ppm	1.740	10.00	4.97	2.94
Pt_ppb	0.500	2.00	1.00	0.75
Rb_ppm	4.400	148.00	46.74	55.21
Re_ppm	0.250	0.90	0.35	0.22
S_ppm	25.000	55.00	28.33	10.00
Sb_ppm	0.050	0.70	0.23	0.23
Sc_ppm	12.000	37.00	25.89	9.01
Se_ppm	0.360	0.63	0.45	0.09
Sm_ppm	2.170	7.49	4.51	1.73
Sn_ppm	0.600	4.70	1.97	1.64
Sr_ppm	89.600	353.00	209.84	85.69
Tb_ppm	0.500	1.13	0.84	0.21
Te_ppm	0.025	0.08	0.03	0.02
Th_ppm	1.450	17.80	6.97	6.69
Tl_ppm	0.050	0.70	0.24	0.28
Tm_ppm	0.270	0.54	0.40	0.09
U_ppm	0.250	2.05	0.72	0.66

V_ppm	92.000	216.00	151.33	46.82
W_ppm	0.100	1.50	0.53	0.54
Yb_ppm	1.600	3.34	2.47	0.52
Zn_ppm	52.700	110.00	82.73	17.69

Table 9. Shaw Hill Gabbro multi-element geochemical results

	Minimum	Maximum	Mean	Std. Dev.
Al2O3_pct	3.680	21.13	13.17	4.12
CaO_pct	0.200	15.26	3.86	4.05
Cr2O3_pct	0.005	0.08	0.01	0.02
Fe_pct	1.680	9.33	4.35	2.23
Hf_ppm	0.500	12.00	3.90	3.60
K2O_pct	0.380	5.82	2.01	1.33
MgO_pct	0.890	11.16	2.71	2.74
MnO_pct	0.020	0.31	0.10	0.07
Na2O_pct	0.170	5.63	2.75	1.87
Nb_ppm	2.200	16.90	8.22	4.52
P2O5_pct	0.005	0.41	0.18	0.10
SiO2_pct	48.880	86.28	65.83	11.30
Ta_ppm	0.120	1.39	0.59	0.38
TiO2_pct	0.210	0.98	0.50	0.22
Y_ppm	9.100	38.70	18.83	8.25
Zr_ppm	15.000	439.00	140.64	125.74
LOI_pct	1.010	5.53	2.65	1.04
Ag_ppm	0.005	0.45	0.06	0.09
As_ppm	0.800	63.80	5.75	11.99
Au_ppb	0.250	7.00	0.49	1.28
Ba_ppm	56.300	1170.00	478.01	291.19
Be_ppm	0.600	6.20	1.48	1.28
Bi_ppm	0.050	0.80	0.18	0.20
Cd_ppm	0.025	0.30	0.05	0.06
Ce_ppm	10.400	118.00	44.90	27.21
Co_ppm	3.900	48.00	15.83	12.17
Cr_ppm	1.000	488.00	77.79	130.21
Cs_ppm	0.050	15.30	2.53	3.50
Cu_ppm	5.100	1446.00	111.87	278.68
Dy_ppm	1.430	5.40	3.06	1.23
Er_ppm	0.980	3.31	1.85	0.69
Eu_ppm	0.440	1.69	0.90	0.39
Ga_ppm	5.030	30.70	15.42	6.01
Gd_ppm	1.440	7.11	3.63	1.67
Ge_ppm	0.390	1.95	0.64	0.29
Hg_ppm	0.025	0.03	0.03	0.00
Ho_ppm	0.310	1.11	0.62	0.24
In_ppm	0.010	0.43	0.06	0.08
La_ppm	5.410	55.70	22.24	12.52
Li_ppm	1.900	26.60	8.22	4.84
Lu_ppm	0.140	0.39	0.24	0.07
Mo_ppm	0.050	14.20	1.18	2.85
Nd_ppm	6.050	48.40	19.64	11.14

Ni_ppm	1.000	110.00	25.11	28.11
Pb_ppm	0.900	21.50	6.78	5.42
Pr_ppm	1.410	14.00	5.16	3.09
Pt_ppb	0.500	22.00	2.70	4.38
Rb_ppm	4.800	269.00	69.83	68.72
Re_ppm	0.250	16.60	1.85	3.69
S_ppm	0.014	9860.00	2066.07	2822.96
Sb_ppm	0.100	1.50	0.42	0.32
Sc_ppm	4.000	45.00	14.04	12.03
Se_ppm	0.140	3.81	0.71	0.83
Sm_ppm	1.450	8.93	4.04	2.12
Sn_ppm	0.400	6.20	1.96	1.68
Sr_ppm	13.100	1140.00	393.93	337.58
Tb_ppm	0.250	0.99	0.55	0.23
Te_ppm	0.025	0.36	0.06	0.08
Th_ppm	1.140	26.70	7.12	7.23
Tl_ppm	0.050	1.50	0.33	0.36
Tm_ppm	0.140	0.46	0.27	0.10
U_ppm	0.430	3.94	1.79	0.99
V_ppm	22.000	328.00	124.04	78.62
W_ppm	0.200	3.40	1.04	0.88
Yb_ppm	0.930	2.98	1.77	0.60
Zn_ppm	4.000	154.00	50.05	39.35

Appendix C Comparison between Lab and Core Scanning Results

Compositional trends and geological boundaries have been successfully defined using the Minalyze datasets, however, absolute element concentrations are subject to calibration with appropriate standards. For example, the differences in K concentration between the sandstone/siltstone and conglomerates are real but the magnitude of these differences may change. The Minalyze data presented above has been validated using the laboratory data as described below.

The laboratory (UCS) samples were taken prior to the Minalyze analysis so it was not possible to directly compare the Minalyze measurements with laboratory measurements on the same rock samples. To address this issue, element concentrations from 30 cm above and below the laboratory sample have been extracted from the Minalyze datasets. A mean concentration for each element was calculated from these results and compared to the laboratory data. The results are compared using the HRD methods that was used above to QA/QC the laboratory data. A plot of HRD for all the intervals analysed shows that for many elements the HRD values are < 20% and therefore the match between the Minalyze data and the laboratory data is acceptable for the purposes of this study where the primary aim is to identify rock types and anomalous element concentrations in inform sample selection in project P2.

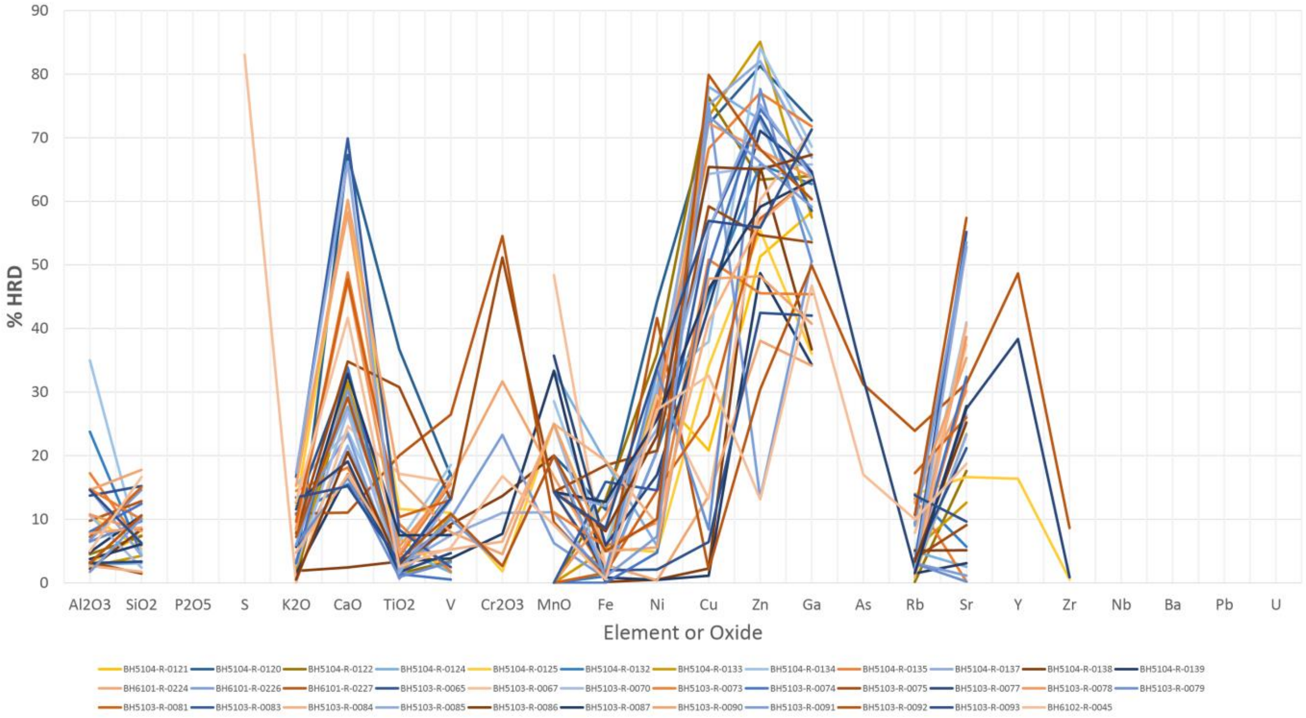


Figure 10. HRD Element Comparisons

Elements with y high HRD values are Zn, Cu, Sr and CaO and Mn. Zinc is unreliable since many of the cores were contaminated with drilling mud that contains ZnO. Cu shows a strong correlation between concentration measured in the laboratory samples and the HRD between the lab and Minalyze datasets. The HRD value is minimised for samples at around 40 ppm Cu. This can be explained because the standard that was used to calibrate the Minalyze data was OREAS25b which contains 36 ppm Cu. Therefore the accuracy of Cu values below this concentration is low even though the trends will still be valid.

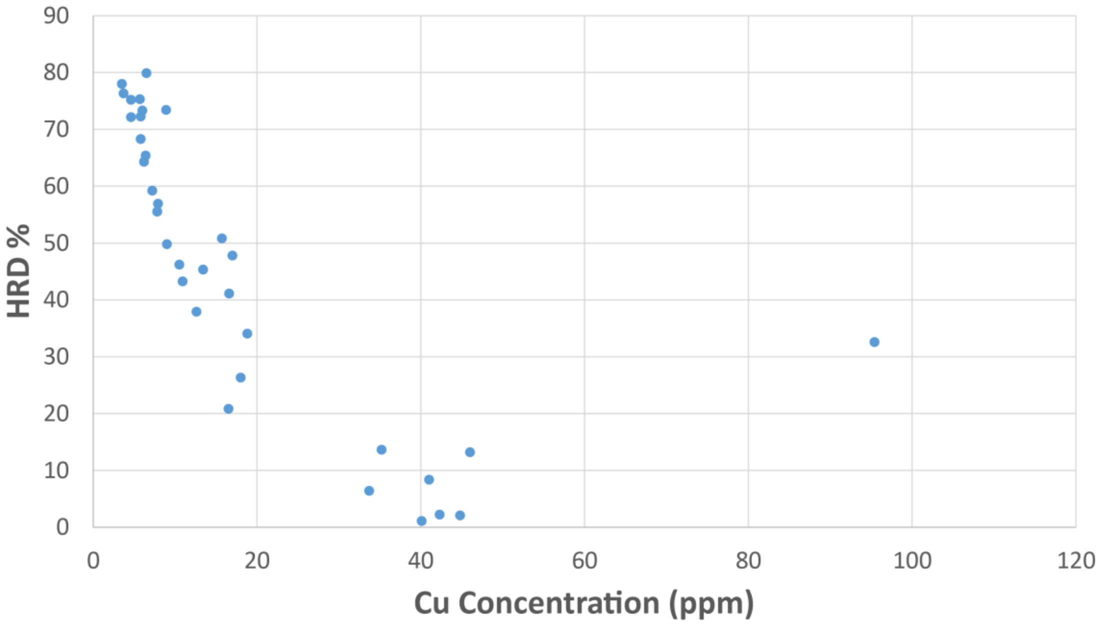


Figure 11. Scatter plot showing the effect of Cu concentration on the HRD % value calculated between the laboratory analysis concentration and equivalent Minalyze concentration.

Ca, Sr and Mn are elements that are all present in carbonate minerals (calcite and dolomite). These minerals often form veins in deformed rocks, especially in BH5102. The differences between the laboratory and Minalyze data can be explained by vein intensity between the two samples.

Apart from these elements highlighted the Minalyze data are a good representation of the rock chemistry. They can be used reliably to split the rocks into domains for volume average estimates of bulk composition for each geological zone and to extrapolate the presence of any deleterious elements identified using the laboratory whole rock analyses.

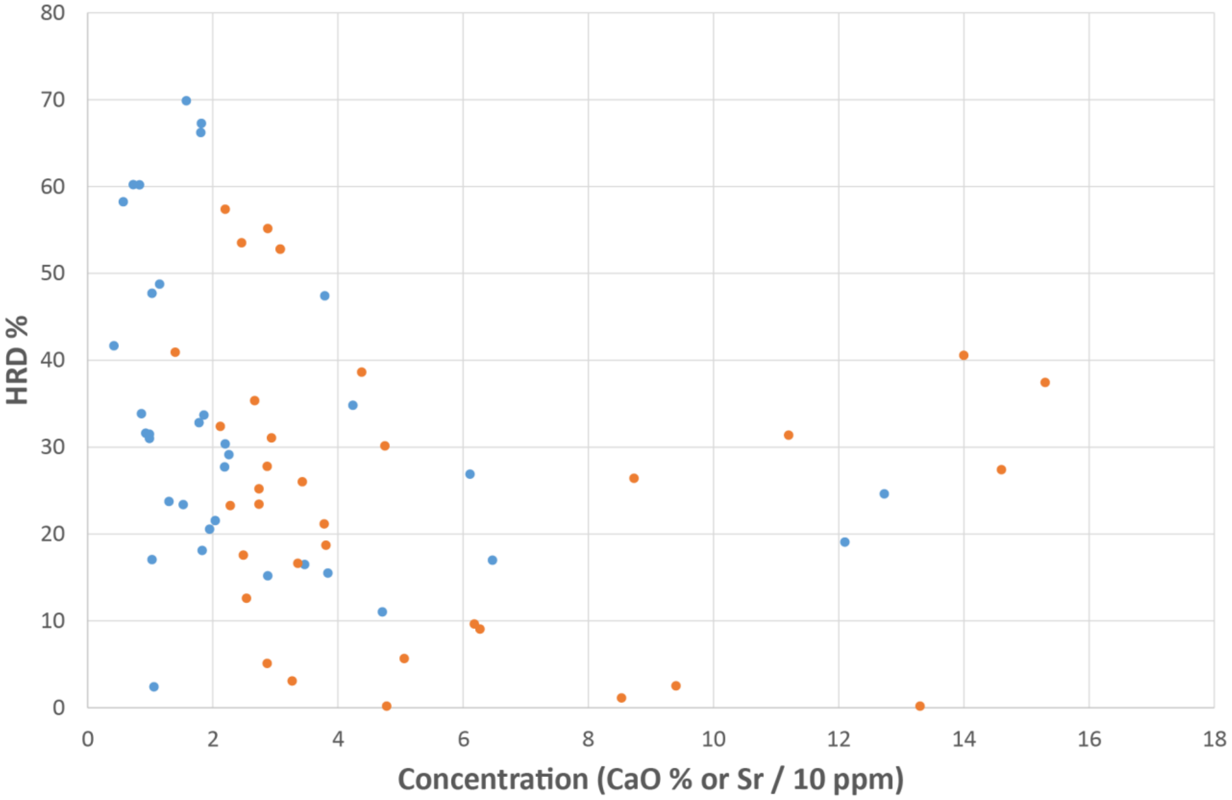


Figure 12. Scatter plot showing the effect of CaO and Sr concentration on the HRD % value calculated between the laboratory analysis concentration and equivalent Minalyze concentration.

Appendix D Mineralogical Characterisation: Lab Workflow

D.1 Mineralogical associations and abundances for main geologic zones: minimum, maximum and average values for mineral percentages are given

Geologic zone	Drill holes	Minerals identified	Min (%)	Max (%)	Average (%)
Byron Range Group	Upper BH5107, upper BH8106	Quartz	60	91	71
		Albite	16	16	16
		Orthoclase	6	18	10
		Muscovite	2	21	9
		Chamosite	9	9	9
		Calcite	4	4	4
		Hematite	1	1	1
Boraig Group	BH5103, BH5104, BH5105, BH5107, BH5108	Quartz	8	93	64
		Albite	2	50	12
		Orthoclase	2	30	10
		Muscovite	2	36	9
		Chamosite	1	28	9
		Calcite	1	20	3
		Dolomite	4	4	4
		Hematite	1	2	1
		Pyrite	1	1	1
		Scapolite	1	3	2
		Kaolinite	6	10	8
		Actinolite	2	5	4
Kellys Plain Volcanics	BH1115, BH1116, BH1117	Quartz	31	38	34
		Albite	22	28	26
		Orthoclase	11	30	18
		Muscovite	5	11	8
		Chamosite	18	22	20
		Kaolinite	4	5	5
Ravine Beds	BH4104, BH5101, BH5102, BH5115,	Quartz	23	98	50

	BH6101, BH6102, BH6104, BH6105, BH7104, BH7105, lower BH8106				
		Albite	3	55	20
		Orthoclase	2	24	10
		Muscovite	2	45	11
		Chamosite	4	31	16
		Calcite	1	10	3
		Dolomite	4	11	7
		Hematite	1	2	1
		Pyrite	1	3	2
		Scapolite	2	3	3
Tantangara Formation	BH2102, BH3101, BH3104	Quartz	35	83	58
		Albite	2	27	14
		Orthoclase	6	9	8
		Muscovite	6	19	11
		Chamosite	4	29	12
		Dolomite	3	3	3
		Pyrite	1	1	1
Temperance Formation	BH3102, BH3106	Quartz	4	44	24
		Albite	15	55	35
		Orthoclase	6	19	11
		Muscovite	3	12	7
		Chamosite	2	21	13
		Calcite	1	2	2
		Actinolite	5	15	9
		Epidote	6	46	20
		Diopside	25	33	29
Shaw Hill Gabbro	BH4106	Quartz	5	41	19
		Albite	12	58	29
		Orthoclase	6	13	8
		Muscovite	4	21	9
		Chamosite	14	29	19
		Calcite	1	4	3
		Hematite	1	4	2
		Actinolite	3	11	7
		Epidote	9	28	20
Gooandra Volcanics	BH3110, BH4102, BH4103, BH4105	Quartz	12	93	45
		Albite	2	43	20
		Orthoclase	2	25	7
		Muscovite	2	30	15

		Chamosite	2	64	19
		Calcite	1	15	3
		Dolomite	1	7	3
		Hematite	1	5	2
		Pyrite	1	2	1
		Epidote	7	24	15

Table 10. Mineralogical associations and abundances for main geologic zones: minimum, maximum and average values for mineral percentages are given

D.2 Average Mineralogical Abundances for each individual drill hole (with available core) within the Snowy 2.0 Tunnel Alignment

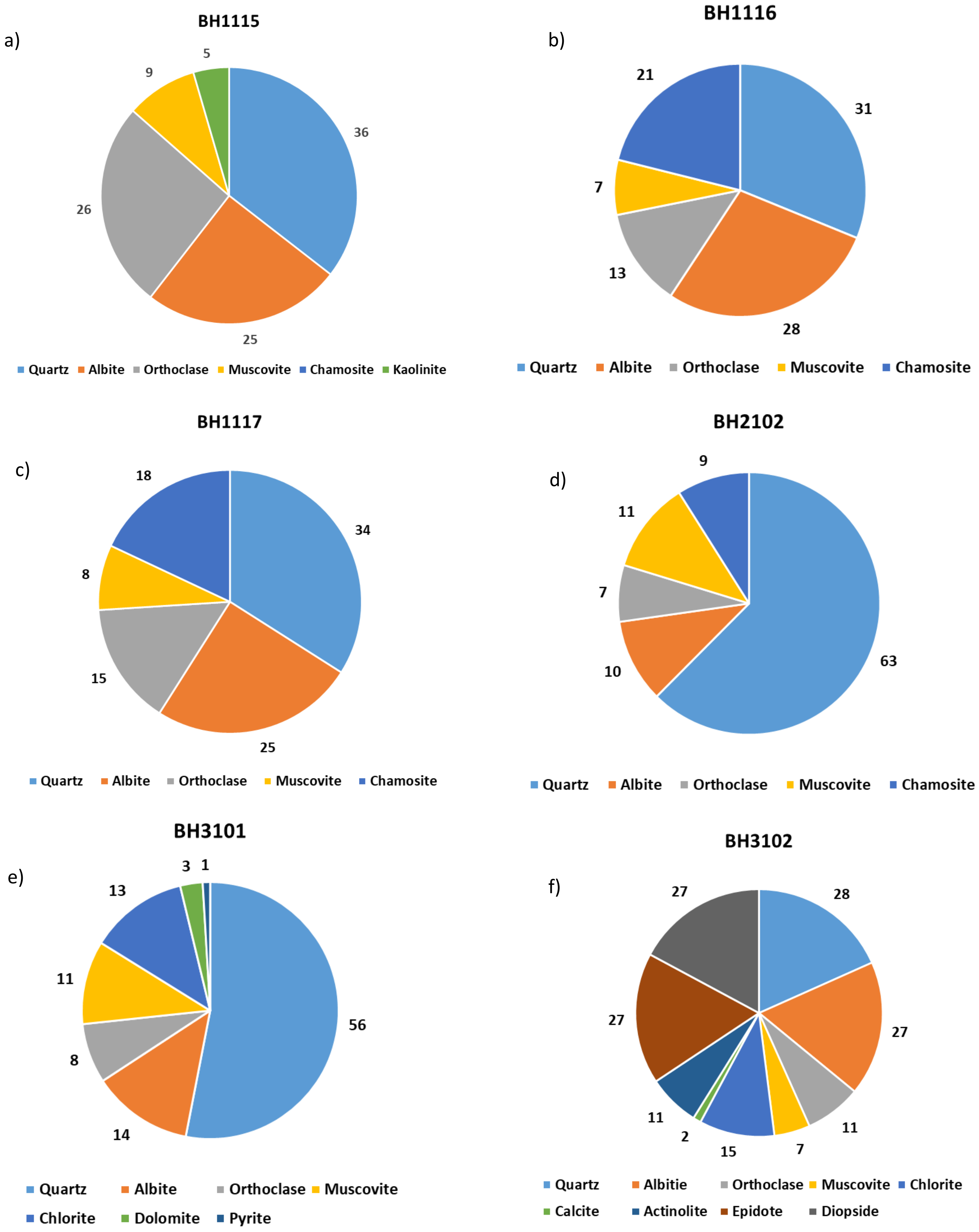


Figure 13. Averaged mineralogical abundances for the rocks intersected by selected diamond drill holes of the Snowy 2.0 project.

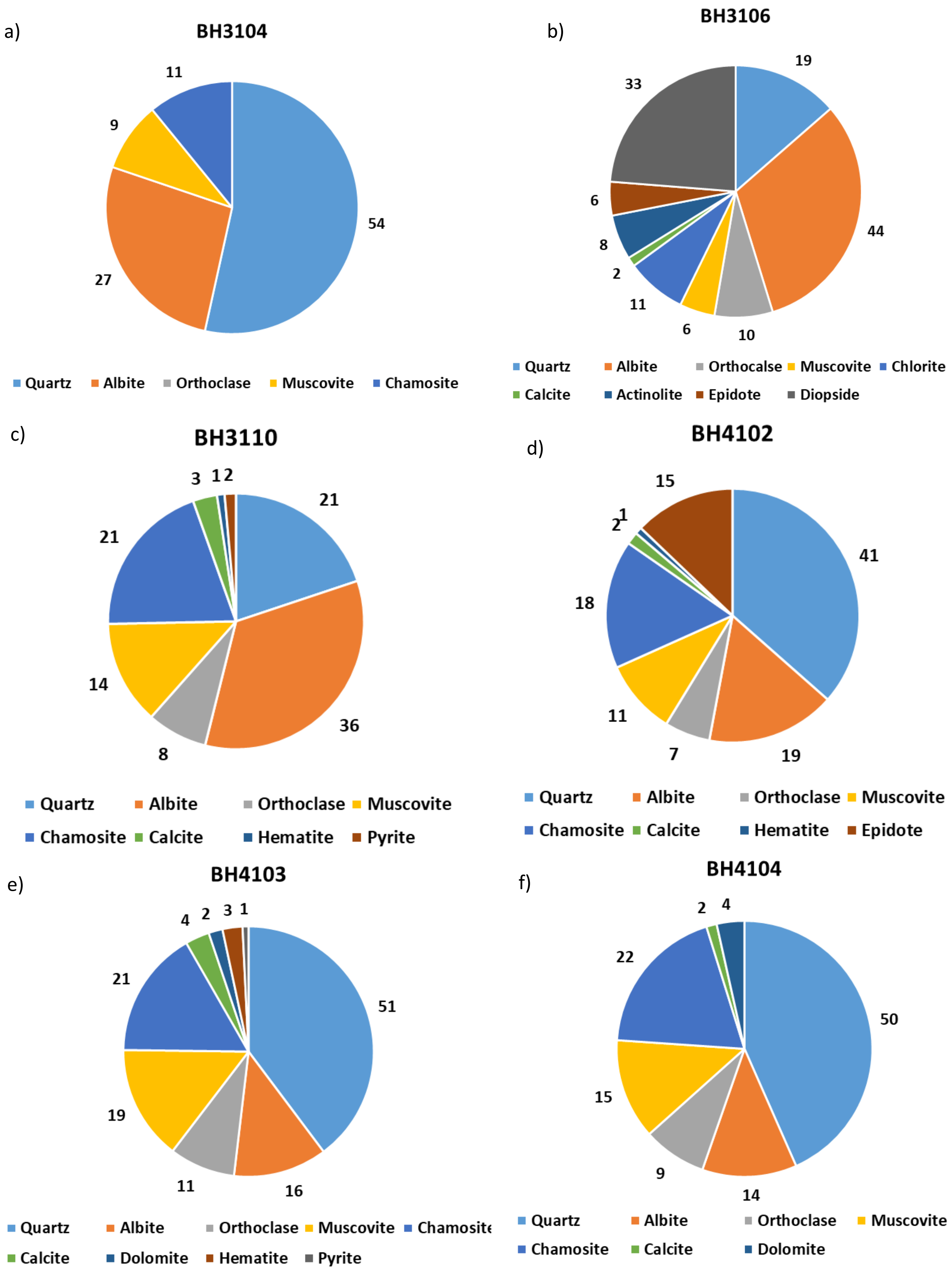


Figure 14. Averaged mineralogical abundances for the rocks intersected by selected diamond drill holes of the Snowy 2.0 project.

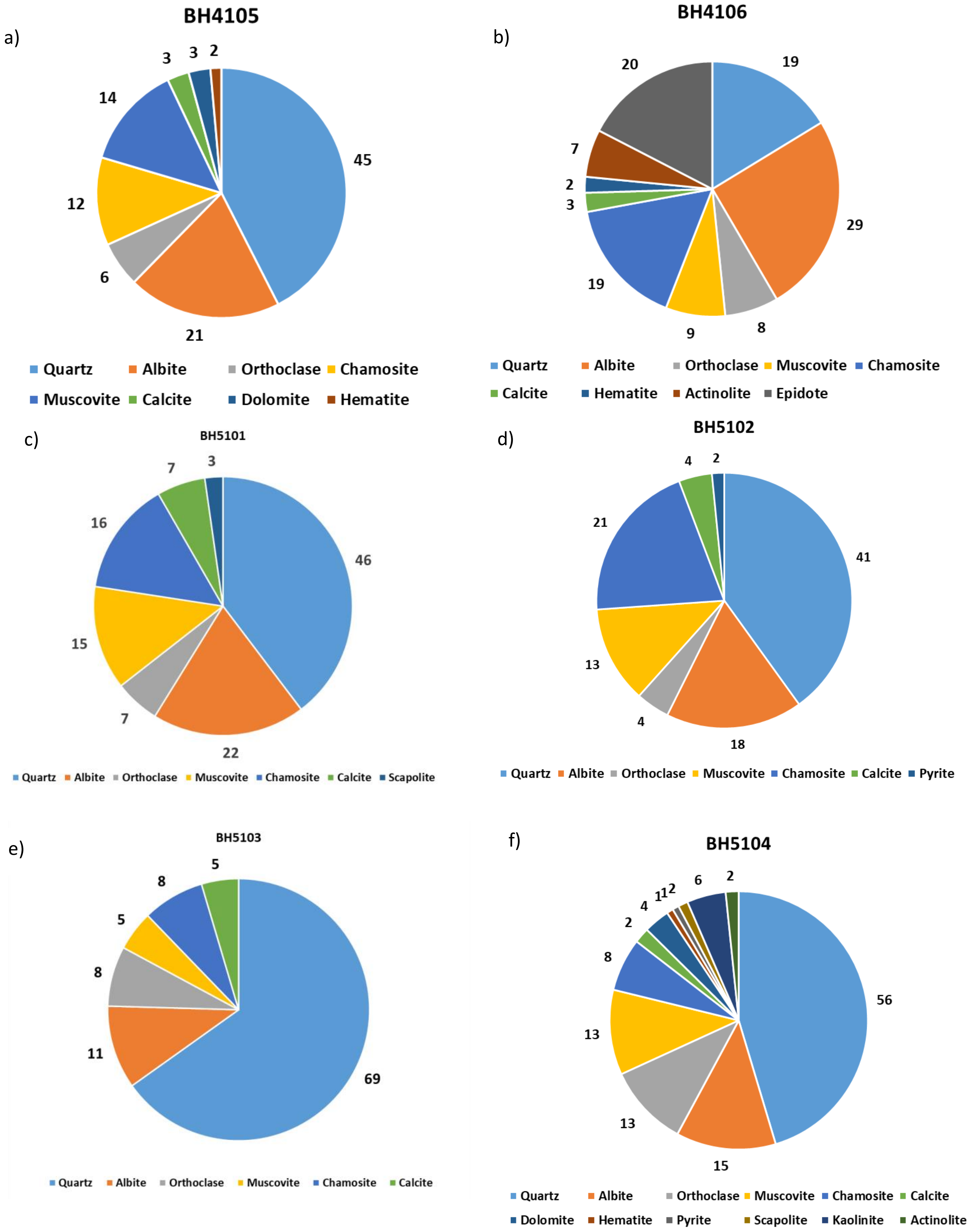


Figure 15. Averaged mineralogical abundances for the rocks intersected by selected diamond drill holes of the Snowy 2.0 project.

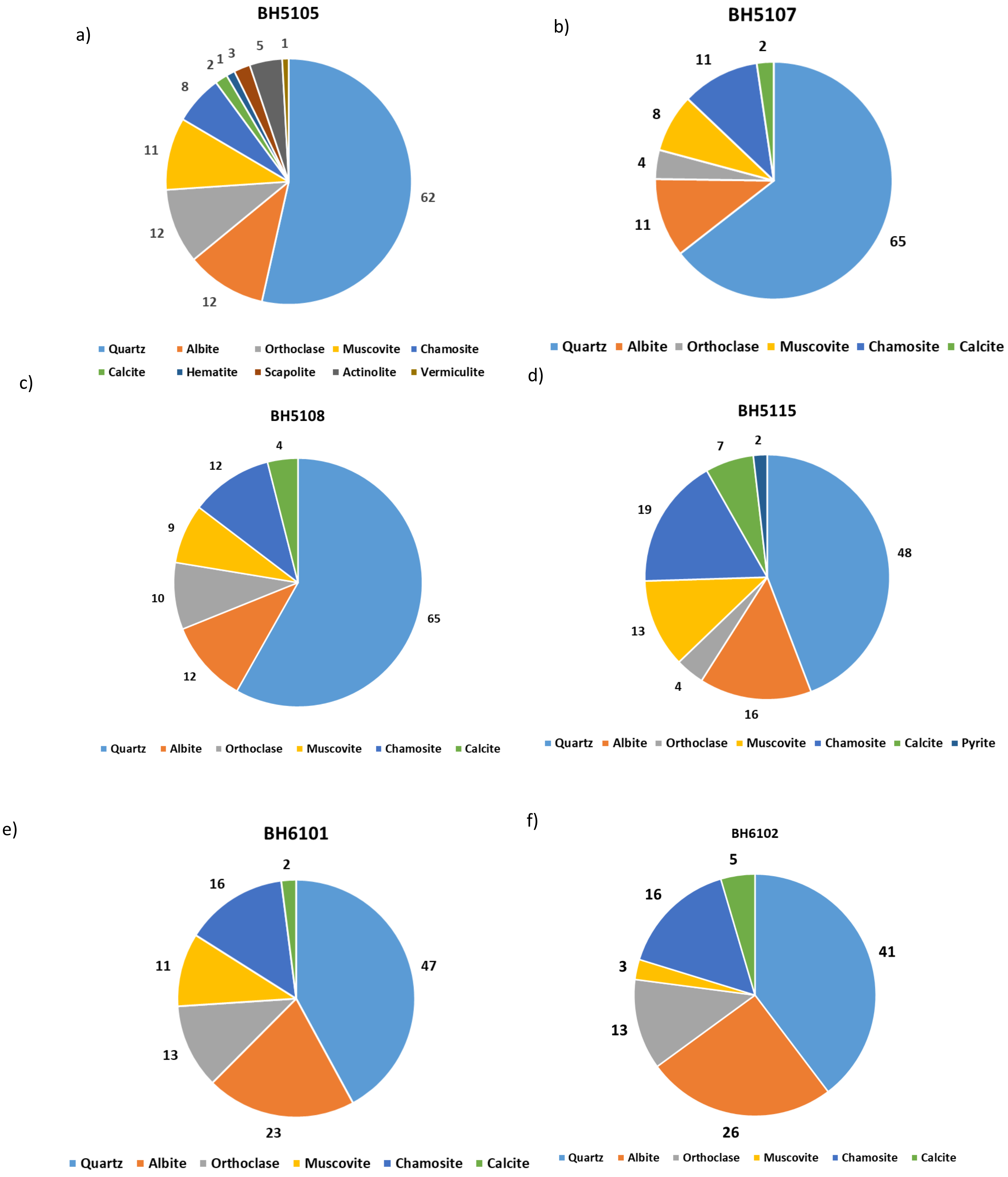


Figure 16. Averaged mineralogical abundances for the rocks intersected by selected diamond drill holes of the Snowy 2.0 project.

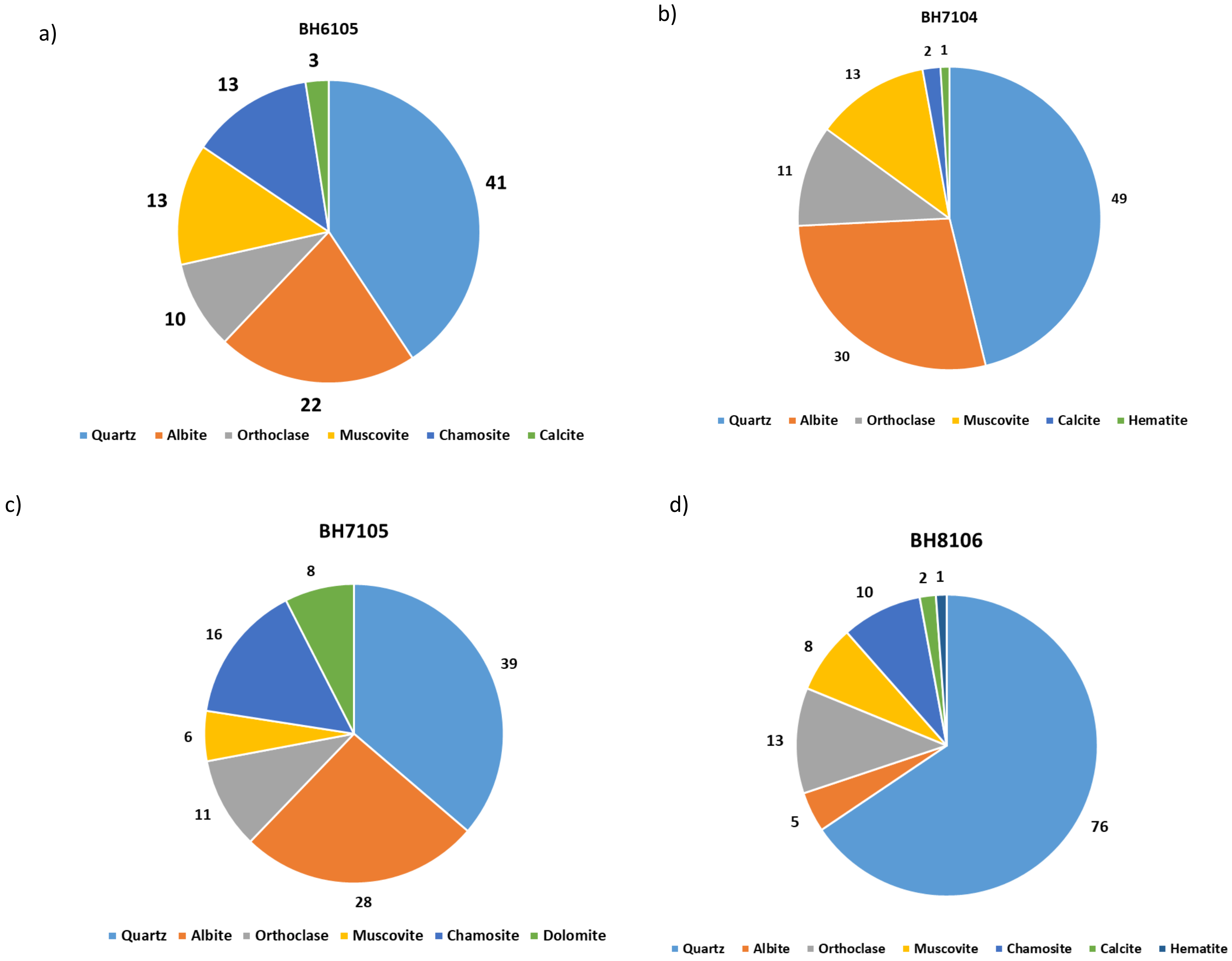


Figure 17. Averaged mineralogical abundances for the rocks intersected by selected diamond drill holes of the Snowy 2.0 project.

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Annexure B Environmental Risk Categorisation of Rock Materials

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Snowy 2.0 P2:

Environmental Risk Categorisation of Rock Materials

Final Report

Grant Douglas, Ryan Fraser, John Gouzos, Jason Kirby, Louise Schoneveld
January 2019

For Snowy 2.0 Scheme, Snowy Hydro
Commercial-in-confidence

Citation

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Important disclaimer

Foreword and Assignment Summary

CSIRO was requested by Snowy Hydro Limited (SHL) in November 2017 to provide scientific expertise and capability in relation to identifying and assessing the environmental risks associated with the placement of excavated rocks from the development and operations of the proposed Snowy 2.0 scheme. EMM Consulting (EMM) had been selected to prepare the Environmental Impact Statement (EIS) on behalf of SHL, and CSIRO's role is to develop and undertake a series of assignments to provide information for environmental risk assessment associated with handling of excavated rock materials from the proposed works. In December 2017, CSIRO worked with EMM to develop conceptual models to provide information to the environmental risk assessment (ERA). As a result CSIRO agreed to undertake an initial series of five assignments.

In March 2018, Haskoning Australia (HKA) was engaged to provide additional capability, specifically to take the role of leading the project entitled: "Engineering Option for placement of Excavated Rocks". The draft work assignments CSIRO had previously provided to SHL and EMM (in late January 2018) were subsequently updated to ensure they would fulfil the needs of EIS requirements and HKA's "Engineering Option for placement of Excavated Rocks" project. These updated assignments have been executed and are providing relevant input into the ERA. This report details the results of one of the Assignments, P2: Environmental Risk Categorisation of Rock Materials.

Disclaimer

This Assignment Subcontract and all documents and information provided by CSIRO to HKA under this Assignment Subcontract are prepared (i) as inputs for further scientific services to be performed for HKA by CSIRO under separate Assignment Subcontracts that has been agreed; and (ii) to assist HKA in its development of an excavated rock disposal and management plan as part of the environmental impact assessment process for the proposed Snowy 2.0 Pumped Hydro Electric Scheme("Purpose"), and for no other purpose. This Assignment Subcontract does not involve the provision of advice or recommendations in relation to specific risks or mitigations associated with Excavated Rock disposal and management or design and construction of the Snowy 2.0 project however it is understood that the inputs provided by CSIRO are for the Purpose and are based on CSIRO's professional skill, care and~~,~~ diligence in performing this Assignment Subcontract. In the course of performing this Assignment Subcontract, CSIRO may rely on stated assumptions and/or information provided by HKA or third parties which is not within the control of CSIRO, and this Assignment does not involve CSIRO verifying such assumptions or information except to the extent expressly stated herein. If CSIRO provides any forecasts or projections, CSIRO does not represent that they will be realised as forecast or projected and actual outcomes may vary materially from forecast or projected outcomes. Documents and information provided to HKA under this Assignment Subcontract are to be read as a whole, and if reproduced must be reproduced in full and no part should be read or relied upon out of context. CSIRO does not accept responsibility for, or liability arising from, any error in, or omission in connection with, stated assumptions or third party-supplied information, or reliance on documents or information provided under this Assignment by HKA other than for the Purpose, or by any other person.

Contents

Figures

Tables

Acknowledgments

CSIRO would like to acknowledge the support from Haskoning Australia Pty Ltd for their assistance in acquiring information for this report.

Executive summary

Assignment P2 - *Environmental Risk Categorisation of Rock Materials* sought to assess reactivity, leachability, and potential environmental consequences of excavated rock placement on land and in reservoirs. The outcomes of this study inform the "Engineering Option" prepared by Haskoning Australia Pty Ltd (HKA), and excavated rock management options in the Environmental Impact Statement (EIS). The outputs of Assignment P2 will also be used in CSIRO Assignment P4: *Environmental Categorisation of Rock Interactions with and Potential Impacts on Reservoir Waters and Sediments*, and Assignment P5: *Ecotoxicology Assessment of Excavated Rock Leachates in Water and Excavated Rock-Sediment Mixtures*.

A first principles approach based on the geochemical composition, hand specimen analysis from Assignment P1: *Comprehensive Geochemistry Examination*, and examination of the regional geology between Tantangara Reservoir and Talbingo Reservoir, was used to define seven geological zones as a basis for the work conducted in Assignment P2:

> *(1) Ravine Group* and (2) *Byron/Boraig Group*, around the western portion of approximately 13 km of the tunnel transect and surge shaft;
>
> *(3) Shaw Hill Gabbro,* which is the only gabbro in the tunnel transect and constitutes approximately 1 km tunnel transect intersection;
>
> *(4) Gooandra Volcanics,* that comprises around 5 km of tunnel transect;
>
> *(5) Peppercorn/Tantangara/Temperance Formations* that constitute around 9 km of the tunnel transect of a mostly similar geology;
>
> *(6) Kellys Plain Volcanics,* which are in the intake area at the Tantangara Reservoir and constitute around 2 km of the tunnel: and
>
> *(7) Felsic/Granite/Gneiss/Ignimbrite* which is a compilation of granitic/extrusive equivalents present at various places along the tunnel transect.

A further classification based on a comparison with the Post-Archean Australian Shale, which is considered a average upper crustal composition (reference), was used to assist in the selection of a Baseline Group and an Enriched Group for each of the seven geological zones. The most common attribute of the Enriched Group being elevated Sulphur (S) and trace element concentrations (including metals and metalloids) compared to the Baseline Group.

Following this classification, a total of 115 samples, encompassing Baseline and Enriched Groups for each geological zone were selected for acid-base accounting and leachate analysis. Major outcomes of these studies are summarised below:

Acid-Base Accounting

- Total sulphur (S), and hence Maximum Potential Acidity (MPA) varied by a factor of 15 between Baseline and Enriched Groups, respectively.

- Water-rock leaching tests indicate no samples had acidic pH and all samples had low leachable salts.
- Only 23% of samples could be classified as having a Net Acid Generation (NAG) capacity. Mean Acid Neutralisation Capacity (ANC) was similar in both Baseline and Enriched Groups.
- The ANC is in excess of MPA for all samples with 93% nominally classified as very low risk.
- A relative risk ranking based on mean ANC and MPA suggests the greatest potential for generation of acidity from the Gooandra Volcanics, Byron/Boraig Groups and Peppercorn/Tantangara/Temperance Groups.

Leachate testing

- Talbingo Reservoir water used in the leachate studies had a circumneutral pH and low dissolved salts and nutrient concentrations similar to that of modified rainwater.
- The leaching ratio used (1:20) is similar to the projected volume of rock to solute (5%) to be deposited in Talbingo Reservoir and Tantangara Reservoir.
- Under oxic, anoxic and acidic conditions, major and trace element leachate compositions can at times be substantially different between Baseline and Enriched Groups.
- A comparison of aggregated Baseline to Enriched Groups in oxic leachates reveals that despite there being similar mean pH of ca. 9 and low Electrical Conductivity (EC), there are substantial differences in the means and/or minima and maxima for a range of elements. In particular, there are substantially higher mean concentrations of Ca, S, Sb and Se in the Enriched leachates.
- A comparison of aggregated Baseline to Enriched Groups in anoxic leachates reveals that despite similar mean EC and pH approximately two =units lower than in oxic leachates, there are substantial differences in the means and/or minima and maxima for a range of elements. In particular, there are higher mean concentrations of Ba and S in the Enriched leachates.
- A comparison of aggregated Baseline to Enriched Groups in dilute acid leachates reveals a higher EC but similar mean pH to the oxic leachates, despite the dilute acidity being present (initial pH 4.9), indicating a substantial buffering capacity. There are substantial differences in the means and/or minima and maxima for a range of elements. In particular there are substantially higher mean concentrations in the Enriched leachates of a more numerous and diverse array of elements including Al, As, Ba, Cd, Mn, S, Sb, Se, Total Nitrogen (TN) and Cl.
- A comparison of anoxic to oxic leachate ratios in the Baseline and Enriched Groups reveals substantially higher Mn, in addition to the alkaline earths: Ca, Mg, Sr and Ba, and Total Carbon (TC). The alkalis, K and Na, are also relatively enriched in the anoxic relative to oxic leachates. Some trace elements can also be elevated, in particular Co, Ni and Mo.
- For dilute acid to oxic leachate ratios, in both the Baseline and Enriched Groups, substantially higher Cr, Ca, TC, Sr, Mo, NO_3, and TN are present in the dilute acid leachates.

Spillway rock analysis

- A study was undertaken on 12 rock specimens immersed in the Talbingo Reservoir spillway for approximately 50 years. Distinct weathering rinds were present on some of the rocks. A geochemical traverse across the rinds indicated elevated Fe and Mn with concurrent enrichment in Ca, Sc, V, As and the Light Rare Earth Elements suggesting that at least some rock types may, via surface reaction following immersion, have the capacity to act as a sink for a range of trace elements.

1 Introduction

1.1 Background and Proposal Summary

Snowy Hydro Limited (SHL) are embarking on the development of the landmark Snowy 2.0 expansion. There are several challenges that are associated with this expansion and a suitable extensive, but ultimately urgent, environmental assessment is necessary. To accomplish Snowy 2.0, SHL will require to “drill-out” between the two reservoirs Talbingo and Tantangara and in the process 10 million m^3 of excavated rock will need to be disposed of primarily within these two reservoirs as land-based disposal of significant quantities of excavated rock is unlikely to be possible within the National Park, nor is it practical to remove it from site. Options are being sort for the management and ultimate disposal of excavated rock as part of an Environmental Impact Statement (EIS) and practical engineering options for its management.

Haskoning Australia Pty Ltd (HKA) have been appointed to manage and deliver an Engineering Option for subaqueous excavated rock placement for Snowy 2.0. CSIRO has been requested to provide scientific insight into the environmental impacts associated with the excavated rock placement options.

1.2 Project Opportunity: Assignment P2: Environmental Rock Risk Categorisation

As the subsurface geology at a localised scale is largely unknown, a geological study (performed by GHD & SMEC) complemented by a geochemical (Assignment P1- *Geochemistry Examination* [P1]) and mineralogical characterisation (this Assignment P2 - *Environmental Risk Categorisation of Rock Materials [P2]*) was required to determine the composition of the materials to be extracted in the construction phase. The majority of the excavated rock will eventually be disposed of within the reservoirs, however, initially the excavated rock will likely be temporarily stockpiled on land and then relocated to the reservoirs. It is a requirement for subaqueous placement that the excavated rock is chemically stable now and into the future so the ecological state of the environment is not compromised. Further the disposal of the excavated rock must:

- not compromise existing operations during the expansion construction;
- not compromise existing environmental flows;
- seek to ensure extreme and “1 in a 100” year weather events do not impact the long-term stability of the excavated rock placed within either Talbingo or Tantangara Reservoirs;
- remain stable under pumping loads of 350 cumecs during expanded hydro operations (intake outflow); and
- not adversely impact threatened species (both terrestrial and aquatic).

Finally, ensuring all of the above, a social licence to operate must be maintained.

P2 acted as an input to the requirement imposed by SHL upon HKA to assess the reactivity, leachability, and potential environmental consequence of excavated rock temporary placement on land and ultimate placement in the reservoirs. P2 categorised rock samples collected during the bore hole drilling program in a Risk Ranking through multiple lines of evidence examining the mineralogy/geochemistry (e.g. chemical composition and reactivity), potential acid generation, and leachability of pollutants (e.g. metals and nutrients) under oxic and anoxic conditions.

The information may be used as an input for further work that considers:

- the potential environmental risk of rock materials when added to land or reservoirs; and
- management and mitigation strategies (e.g. separation of reactive phases, excavated rock placement, and containment) to reduce environmental impacts.

The P2 "Risk Ranking" is based on categorisation studies only and does not take into account complimentary studies to be undertaken in Assignments P4 and P5, nor a formal assessment of impact pathways or receptors that is required to define broader environmental risk. The P2 work focuses on determining risk at the "Stressors" point, whilst Assignments P4: *Environmental Characterisation of Spoil Interactions with and Potential Impacts on Reservoir Waters and Sediments* and P5: *Ecotoxicology Assessment of Spoil Leachates in Water and Spoil Sediment Mixtures* explore through to receptors/endpoints (Figure 1).

For the avoidance of doubt, the work delivered under this Assignment does not consider risk beyond the samples received, the broader potential environmental risk, or strategies to reduce such risk, of the rock materials.

An opportunity arose to analyse rock deposited on the "spillway" some 50 years ago from previous expansions. This affords also a rare advantage to assess rock-water interaction for an extended period.

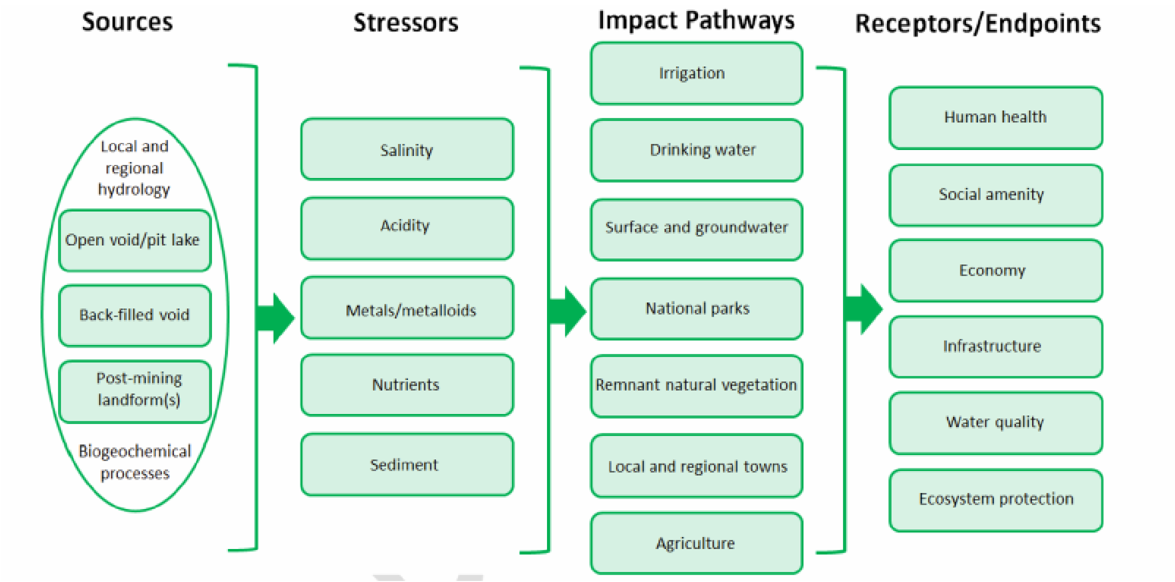


Figure 1. Demonstration of Source impact to Receptors.

Assignment P2 focuses on providing information/Risk Ranking to "Stressors". Subsequent Assignments P4 & P5 explore receptors.

2 Assignment Work Plan

2.1 Materials

In order to carry out the proposed Environmental Risk Categorisation of Rock materials (Risk Ranking) SHL provided the following (1 to 4 as supplied for P1):

1. Hole survey data (collars, orientations, deviations etc.), Digital Elevation Model (DEM) for area around project site, results of GHD characterisation including XRD.
2. Geological logging and all GHD assessments/results associated with the GHD drilling/logging program (GIP).
3. Access to Core shed at Cooma facility for data collection campaigns.
4. Core samples (previously subjected to Uniaxial Compression Strength [UCS]) following testing and all pulverised material from samples analysed for core characterisation. Any thin sections and off-cuts used by GHD for characterisation. Samples and associated metadata were sent to CSIRO as soon as GHD had finished analysing them.
5. Representative historical materials deposited in Talbingo Reservoir spillway (sample numbers dependent on the number of rock types deposited).

2.2 Aims of Assignment

P2 acted as an input to the assessment the reactivity, leachability, and potential environmental consequence of excavated rock placement on land and in reservoirs.

P2 categorised potential environmental risk of rock materials collected during the bore hole drilling program through multiple lines of evidence that examines the mineralogy/geochemistry (e.g. chemical composition, structure and reactivity), potential acid generation, and leachability of pollutant (e.g. metals and nutrients) under oxic and anoxic conditions.

The Risk Ranking information will be used as an input to further work that seeks to categorise the potential environmental risk of rock materials temporarily stored on land before emplacement in the reservoirs for better management and mitigation strategies (e.g. separation of reactive phases, excavated rock placement, and containment) to reduce environmental impacts. In effect this work will categorise risk of rock samples received from a variety of geological zones.

P2 work was staged (i.e. sample numbers) dependant on findings from mineralogy, potential acid generation and leachability tests.

The initial test plan (Table 1) included:

- Up to approximately 400 rock samples (dependent on the range of geology/mineralogy zones) collected during the bore hole drilling program were categorised based on mineral and chemical composition (presence of major and minor elements) using X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) collected in Assignment P1 (Comprehensive Geochemistry Examination).
- Approximately 150 rock samples were assessed for potential acid generation using Acid-Base Accounting (ABA) and Net Acid Generation (NAG) Tests.

- Approximately 150 rock samples were assessed for reservoir water (oxic and anoxic) and weak acid leachability of pollutants using the Australian Standards Leaching Procedure (ASLP).
- Representative rock types were collected from the Talbingo Reservoir spillway for characterisation using methods described above as required.

P2 built on work delivered within P1 by providing a risk categorisation for each geological zone for which samples are provided. This information may provide a basis for further work on the management and most appropriate methods of emplacement. The outcomes of this study (potential for element leachability and acid generation) will feed directly into the Engineering Option being prepared by HKA, and as information on the potential reactivity of the geological zones and waste rock management options in the EIS's being submitted.

Table 1 Summary of Relations between Tests and other Assignments.

Test	Input required	Results	Related studies	Impact questions
Mineralogy. Geochemistry Characterisation.	Information from P1 and additional analyses as required.	Mineralogy and geochemical composition of samples with potentially problematic/reactive samples selected for subsequent analyses.	Ecotoxicology.	Potential for reactivity of rock materials.
Potential Acid Generation: Acid-Base Accounting (ABA), Net Acid Generation (NAG), pH and Electrical Conductivity (EC) tests.	Information from P1 and additional analyses as required.	Information on potential longer-term impacts of placement of rock material on land and in reservoirs e.g. release of stored acidity and pollutants, formation of secondary minerals, etc.	Ecotoxicology.	Potential for reactivity of rock materials.
Potential Leachability of Pollutants from Rocks: Water Leachability (Oxic and Anoxic Conditions), Dilute Acid Leachability.	Information from P1 and additional analyses as required.	Information on potential longer-term impacts of rock placement on land or in reservoirs e.g. release of acidity and pollutants, formation of secondary minerals.	Ecotoxicology.	Potential for reactivity of rock materials.
Characterisation of Talbingo Reservoir spillway samples.	Representative spillway samples.	Unique insight into the sustained reactivity of rocks types.	Ecotoxicology.	Potential for rock reactivity.

3 Analytical methods

3.1 Mineralogy/Geochemical Characterisation

The reactivity and leachability of pollutants from rock samples collected during the bore hole drilling program depends on the mineral (e.g. presence of sulphides, oxides and carbonate phases) and chemical (e.g. arsenic, copper and nickel) composition of the rock material and properties of the receiving environment (e.g. redox state).

The mineral phases (e.g. iron sulphides, and carbonates) will be examined and categorised based on their potential reactivity and release of pollutants into the environment (e.g. acidity, metals, and nutrients) under oxic and anoxic conditions. For example, the presence of significant framboidal or fine grained pyrite in a sample would imply pyrite oxidation and acid production rates from materials represented by this sample. Not all sulphur (S) species produce acid (e.g. galena, sphalerite, covellite, bornite and chalcocite do not release acid when oxidised), and determining the relative proportion of these sulphides (and neutralising species) in a sample provides more detail on the acid potential (e.g. potential acid forming [PAF]) of samples.

Quantification of the mineral and elemental composition of rock samples also provides information on potential longer-term impacts of placement of rock material on land and in reservoirs, e.g. release of stored acidity and pollutants, formation of secondary minerals.

The rock samples collected during the bore hole drilling program (GHD) were examined/categorised based on their identified mineral and chemical composition based on XRD and XRF analysis conducted in P1 and predicted reactivity under oxic and anoxic conditions (i.e. leachability of pollutants).

3.2 Potential Acid Generation

Acid rock drainage (ARD) is produced by the exposure of sulphide minerals such as pyrite to atmospheric oxygen and water. The ability to identify in advance any rock material that could potentially produce ARD is essential for timely implementation of mine waste management strategies for ARD control and land and reservoir placement.

A number of test procedures have been developed to determine the acid forming characteristics of mine waste materials. The most widely used assessment methods for ARD characterisation are the ABA and the NAG tests. These methods are referred to as static tests because each involves a single measurement in time.

The data gained from the mineralogy and chemical composition analysis, ABA and NAG tests has been used to categorise the rock material based on the Australian Government's Guidelines on Managing Acidic and Metalliferous Drainage (DITR, 2016), which is based on an earlier classification system included within the AMIRA ARD Test Handbook (AMIRA, 2002).

3.2.1 Acid-Base Account (ABA) Test

The parameters arising from the acid-base accounting are referred to as the maximum potential acidity (MPA) and the Acid Neutralising Capacity (ANC). The difference between the MPA and ANC is referred to as the Net Acid Producing Potential (NAPP).

The MPA can be calculated using the total S content of rock samples and assumes that the measured S content occurs as pyrite (FeS_2) (kg sulphuric acid (H_2SO_4)/t). The total S content of samples is commonly determined by high temperature combustion methods or inductively coupled plasma-mass spectrometry following strong acid digestion.

If S species can be identified during XRD analysis this information can be used to provide a better estimate of the MPA, for example the potential for overestimating acid-generation potential if a sample contains forms of S other than pyrite, such as commonly occurring sulphate minerals (e.g., anhydrite, gypsum, barite, jarosite, alunite, schwertmannite), non-acid-forming sulphides (e.g., sphalerite, galena, covellite) or weakly acid-generating organic S-bearing compounds.

The ANC is commonly determined using the Sobek method. This method involves the addition of a known amount of standardised hydrochloric acid (HCl) to an accurately weighed sample, allowing the sample time to react (with heating), then back-titrating the mixture with standardised sodium hydroxide to determine the amount of unreacted HCl. The amount of acid consumed by reaction with the sample is then calculated and expressed in the same units as the MPA that is kg H_2SO_4/t.

The ANC/MPA ratio is frequently used as a means of assessing the risk of acid generation from mine wastes. A positive NAPP is equivalent to an ANC/MPA ratio less than 1, and a negative NAPP is equivalent to an ANC/MPA ratio greater than 1. A NAPP of zero is equivalent to an ANC/MPA ratio of 1. The purpose of the ANC/MPA ratio is to provide an indication of the relative margin of safety (or lack thereof) within a material.

3.2.2 Net Acid Generation (NAG) Test

The NAG test involves the addition of a solution of hydrogen peroxide (H_2O_2) to a prepared sample of mine rock/waste to oxidise contained reactive sulphides. This is followed by measurement of the pH of the reaction solution and titration of any net acidity produced by the acid generation and neutralisation reactions occurring in the sample. This can range from a detailed waste rock classification program to routine operational monitoring for simply identifying PAF and Non-Acid Forming (NAF) material types.

The single addition NAG test involves a single addition of 15% H_2O_2 to a 2.5 g of < 75 µm sample. The sample is allowed to react overnight. The entire sample is heated until gently bubbling for approximately 1-2 h to remove excess H_2O_2 and encourage release of inherent neutralising capacity. Once the sample has cooled to room temperature, pH and electrical conductivity (EC) are measured, then pH titrated acidity to pH 4.5 and 7.0 (in kg H_2SO_4/t of sample) of the solutions are measured.

Complete decomposition of the H_2O_2 can occur before all the reactive sulphides have oxidised. Thus the single addition NAG test may not account for the total acid potential of a given sample. Sequential NAG test are used to overcome peroxide decomposition effects through successive additions of H_2O_2 to the same sample. If solution pH < 4.5, the sample will be subjected to a sequential NAG test with 15% H_2O_2 on the one sample. At the end of each NAG test stage, the sample is filtered and the NAG pH and titrated NAG acidity of the solution are measured. The NAG test is then repeated on the solid residue. The cycle is repeated until the NAG pH is ≥ 4.5. All of the individual NAG acidities are then summed to give a total sequential NAG acidity in kg H_2SO_4/t.

3.2.3 $pH_{1:2}$ and Electrical Conductivity ($EC_{1:2}$)

A material categorised as NAF may still have existing acidity and salinity (major ion, ecotoxicity) risks that make it unsuitable for surface or uncontrolled placement due to potential effects on drainage and the surrounding environment.

The $pH_{1:2}$ and $EC_{1:2}$ of rock samples was determined by equilibrating samples in deionised water for 12 to 16 hours (or overnight), at a solid to water ratio of 1:2 (w/w). This gives an indication of the inherent acidity and extent of major ions released from the rock material when initially exposed in an area.

3.3 Potential Leachability of Pollutants from Rock Samples

Following excavation, rock material will be exposed to ambient air that will oxidise mineral phases such as S. Initially, excavated rock will be stored on land stockpiles; however, it is unclear how much of the rock material will react with oxygen in the air and how oxygen will affect the geochemical properties of the leachates. Subsequently the excavated rock will be stored sub-aqueously in reservoirs where it will be exposed to varying redox conditions (i.e. oxic and anoxic, if present) depending on placement in the reservoirs.

In this study, the potential environmental risk from the leaching of pollutants from rock samples was assessed using water (under oxic and anoxic conditions) and weak acid conditions to test mobility during long-term acid generating reactions (e.g. sulphide oxidation).

3.3.1 Water Leachability (Oxic and Anoxic Conditions)

Rock samples from bore holes were subject to water leaching according to the ASLP with reservoir water using a 1:20 mass/mass, sample to water ratio.

For the oxic ASLP, 40 mL of reservoir water was placed into a 50 mL centrifuge tube with 2 g of sample and tumbled for 18h at 30 rpm at room temperature. For the anoxic ASLP, the reservoir water will be purged with nitrogen and the experiments performed inside an anaerobic chamber at room temperature.

After mixing, the samples were allowed to settle for 30 min and solution pH and EC (and Eh for anoxic samples) measured. The solutions were then filtered to $< 0.45\mu m$ and analysed by ICP-OES and/or inductively coupled plasma-mass spectrometry (ICP-MS) for a range of elements including Aluminium (Al), Arsenic (As), Barium (Ba), Calcium (Ca), Cadmium (Cd), Chromium (Cr), Copper (Cu), Iron (Fe), Mercury (Hg), Potassium (K), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Sodium (Na), Nickel (Ni), Phosphorus (P), Sulphur (S), Lead (Pb), Antimony (Sb), Selenium (Se), Tin (Sn), Thorium (Th), Uranium (U), Vanadium (V), and Zinc (Zn) with sulphate, chloride (Cl) and fluoride (F) by ion chromatography, in addition to total nitrogen (TN) and total carbon (TC).

3.3.2 Dilute Acid Leachability

The leachability of pollutants (e.g. major ions, carbon, metals, and nutrients) from rock samples over extended periods of acidic conditions were evaluated using a weak acid leachability test. The rock samples were subject to analysis using dilute acetic acid as the leaching fluid (initial pH 4.93) according to ASLP 4439 specification using a 1:20 mass/mass, sample to solution ratio.

Approximately 40 mL of dilute acetic acid was placed into a 50 mL centrifuge tube with 2 g of sample and tumbled for 18 hr at 30 rpm at room temperature. The samples after mixing were allowed to settle for 30 min and solution pH and EC measured. Finally, the solutions were filtered to <0.45 µm and analysed by ICP-OES and/or ICP-MS for a range of elements including Al, As, Ba, Ca, Cd, Cr, Cu, Fe, Hg,. K, Mg, Mn, Mo, Na, Ni, P (total), S (total), Pb, Sb, Se, Sn, Th, U, V, and Zn, and TN and TC.

3.4 Option: Analysis of Existing Spillway Rocks

In the course of project development, an opportunity arose to sample rock excavated rock deposited ca. 50 years ago near the spillway in Talbingo Reservoir. These samples afford a rare opportunity to assess the nature of rock-water interaction for an extended period. In particular, surface-reaction rinds, if any, provide an insight into both the reactivity of the rock type, in addition to a measure of the net retention/partitioning of major and trace elements during extended weathering. The outcomes of these analyses (please refer to Appendix A.2 for a comprehensive report) are important as it is expected that the greatest water-rock interaction will occur during the first years to decades of immersion.

4 Results and Discussion

4.1 Categorisation and Selection of Rocks for P2, P4 and P5 Testing

This section details the strategy underpinning the categorisation and selection of rock samples received by CSIRO (nominally the samples used by GHD for UCS testing) from the Snowy 2.0 scheme. The strategy utilised a “first principles” approach based on geochemical composition derived from P1, hand specimen analysis in combination with geological unit descriptions, mapping and consideration of the complexity of the heavily deformed (folded/faulted) geology. In deriving these groupings, a variety of methods were used including n-scores to elucidate the natural, concentration-based groupings of elements, and a variety of bivariate and ternary diagrams. Samples that had fibrous/asbestiform minerals present were excluded from the grouping process and hence, Assignments P2, P4 and P5 on safety grounds.

Based on an analysis of the geology and geochemistry, the tunnel geology for the purposes of Assignments P2, P4 and P5 has been divided into seven geological zones from the west to east as follows:

> *(1) Ravine Group* and (2) *Byron/Boraig Group*, around the western portion of approximately 13 km of the tunnel transect and surge shaft;
>
> *(3) Shaw Hill Gabbro,* which is the only gabbro in the tunnel transect and constitutes approximately 1 km tunnel transect intersection;
>
> *(4) Gooandra Volcanics,* that comprises around 5 km of tunnel transect;
>
> *(5) Peppercorn/Tantangara/Temperance Formations* that constitute around 9 km of the tunnel transect of a mostly similar geology;
>
> *(6) Kellys Plain Volcanics,* which are in the intake area at the Tantangara Reservoir and constitute around 2 km of the tunnel; and
>
> *(7) Felsic/Granite/Gneiss/Ignimbrite* which is a compilation of granitic/extrusive equivalents present at various places along the tunnel transect.

Of the seven geological zones defined above, six constitute contiguous blocks of tunnel (Figure 2). This grouping into geological zones/reductionist approach is considered important for two main reasons:

- subsequent detailed ecotoxicological analysis undertaken in P4 and P5 is simplified; and
- when tunnelling takes place as it will allow contractors to operate on the macroscale of blast, cave, load and dump rather than considering the complexities of each geological unit/sub-unit encountered.

Each of the seven geological zones have also been subdivided into “Baseline” and “Enriched” compositions (defined as Groups, Table 2). Where possible, priority was given to rocks intersecting the tunnel transect, but where insufficient samples were available, stratigraphically/compositionally equivalent units were substituted. Where possible, eight samples of each of the Baseline and Enriched Groups have been identified to use in P2, P4 and P5. In some cases this has was not possible as there was simply too few samples available in either category. For use in P2, P4 and P5 it was recommended that composites were, where available, made up from the same amount of each sample. Additional pulp and as-received samples were reserved in the event of not enough material being available to make up the composite.

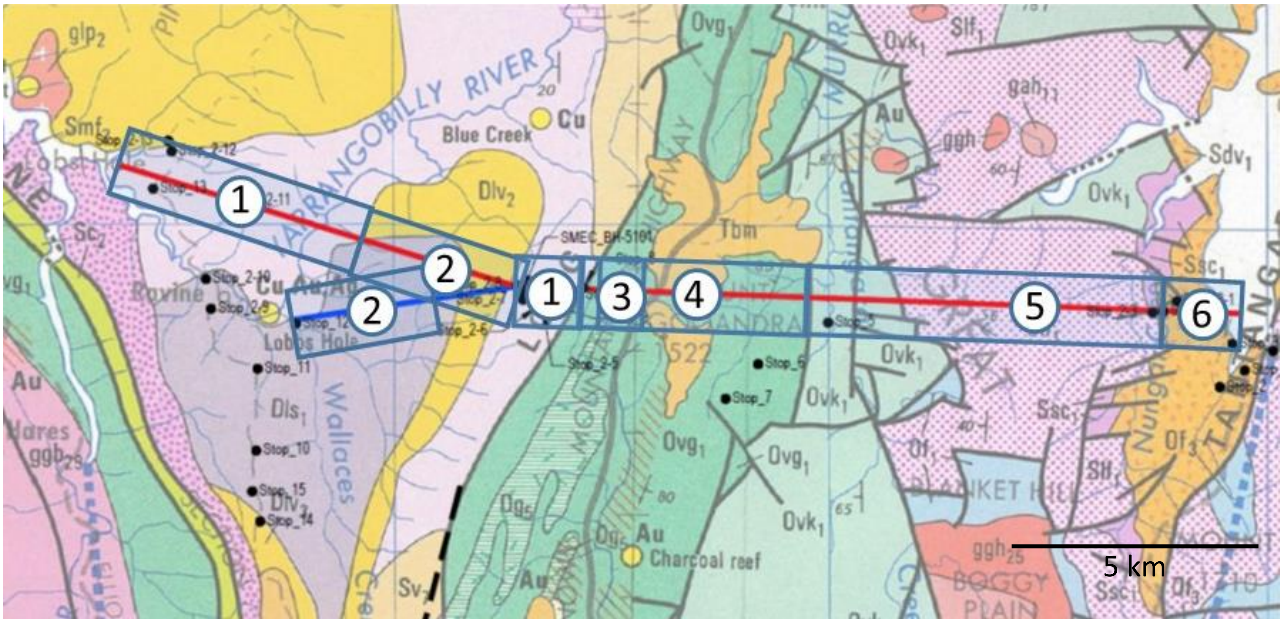


Figure 2. Geological map of the region between Talbingo Reservoir in the west and Tantangara Reservoir in the east.

Baseline samples constitute what is believed to be a representative baseline composition for a particular unit culled from a larger number of rock samples. In contrast, the Enriched samples constitute a set of samples that are enriched in a range of elements. In studying the compositions, samples classified as Enriched often contained higher concentrations of S (verified as sulphides in hand-specimen and XRD analysis), metalloids (As, Sb, Se), and on occasion, transition elements (Cd), metalloids (Bi, Tl), and base metals (Cu, Pb, Zn). A summary of mean concentrations of Baseline and Enriched Groups for each of the seven geological zones is given in Table 2.

An addition to the above, another method of classification was used to examine element ratios. The Post-Archaean Australian Shale (PAAS, Taylor and McLennan, 1985) method of classification which can be equated to an estimate of the composition of the upper crust as a reference was also adopted. The PAAS is of particular utility here due to the preponderance of shales, siltstone and metamorphic equivalents such as phyllites and schists present in the geology of the proposed tunnel transect. While there are igneous rocks present, such as basalts, gabbros and some granitoids, they are in the minority. Ranking all of the units to a common reference such as the PAAS constitutes a useful method to help determine differences in composition.

To this end, a series of diagrams that display both the Baseline and Enriched compositions of each of the seven geological zones has been constructed (Figure 3). For simplicity these diagrams are based on the average of each Baseline and Enriched composition. Based on the Enriched ratio of each element, the average geological zone compositions were then ranked from the smallest to largest ratio. Where ratios increasingly greater than unity are present (toward the right hand side of each diagram), there is an enrichment in these elements both relative to the PAAS, but also in the Enriched relative to the Baseline composition equivalent. It is of course understood that some units can have natural depletions with element ratios substantially less than unity as apparent on the left hand side of the PAAS element ratio diagrams and some units can have similar compositions to the PAAS (average upper Crust) with ratios near unity, and natural enrichments in various elements.

The Baseline and Enriched average compositions are readily differentiated in some geological zones such as the Peppercorn/Tantangara/Temperance Formation (Figure 3). In contrast, a more subtle differentiation is apparent, with little differentiation between Baseline and Enriched Groups in the Shaw River Gabbro such that this can be essentially considered a homogenous zone without the need to conduct separate leaching, and ecotoxicological testing in Assignments P2, P4 and P5.

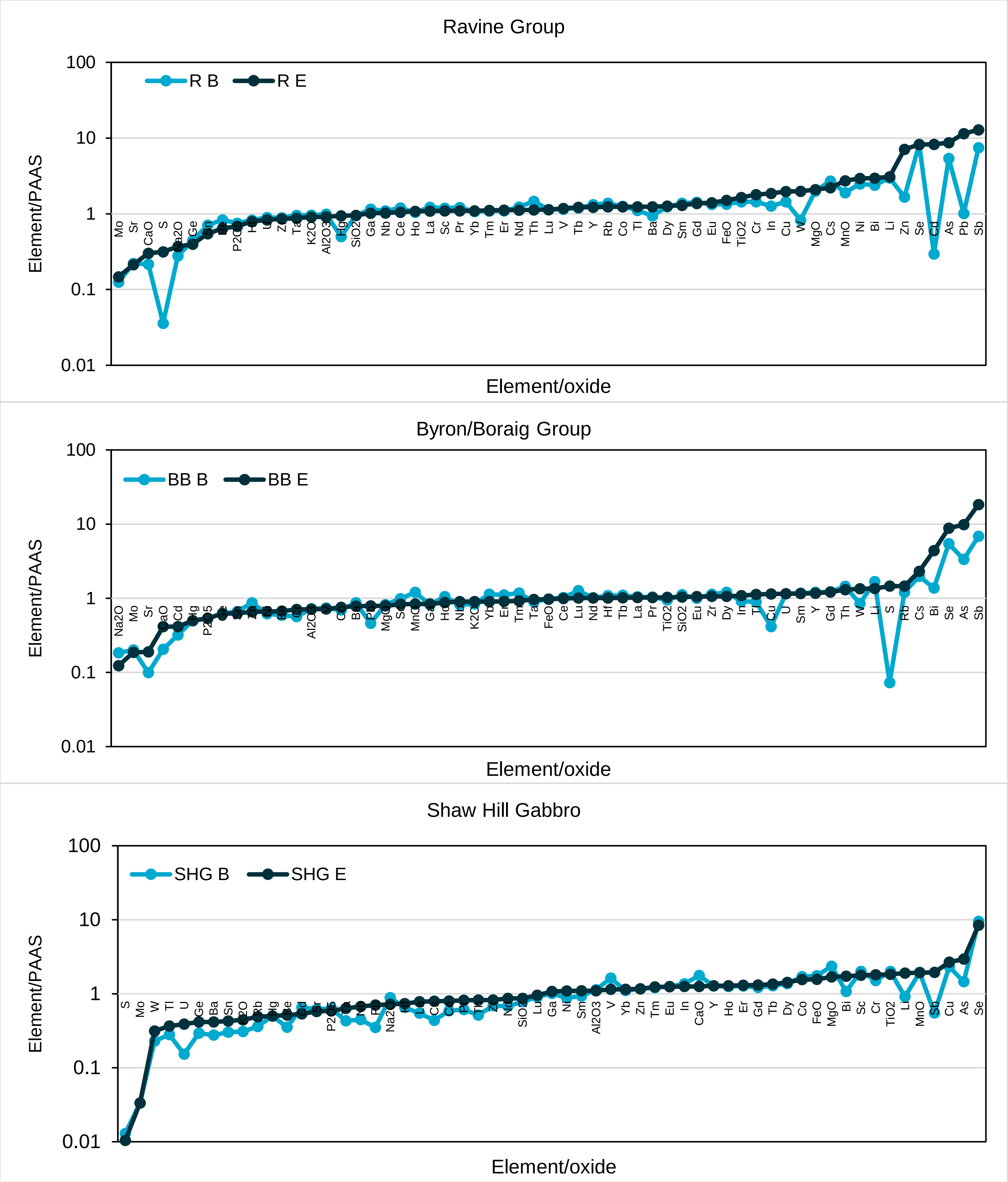


Figure 3a. Major and trace element ratios relative to the Post Archean Australian Shale (PAAS) and ranked according to increasing ratios in the Enriched sample group for the Ravine Group; Byron/Boraig Group; and Shaw Hill Gabbro; zones across the tunnel transect.

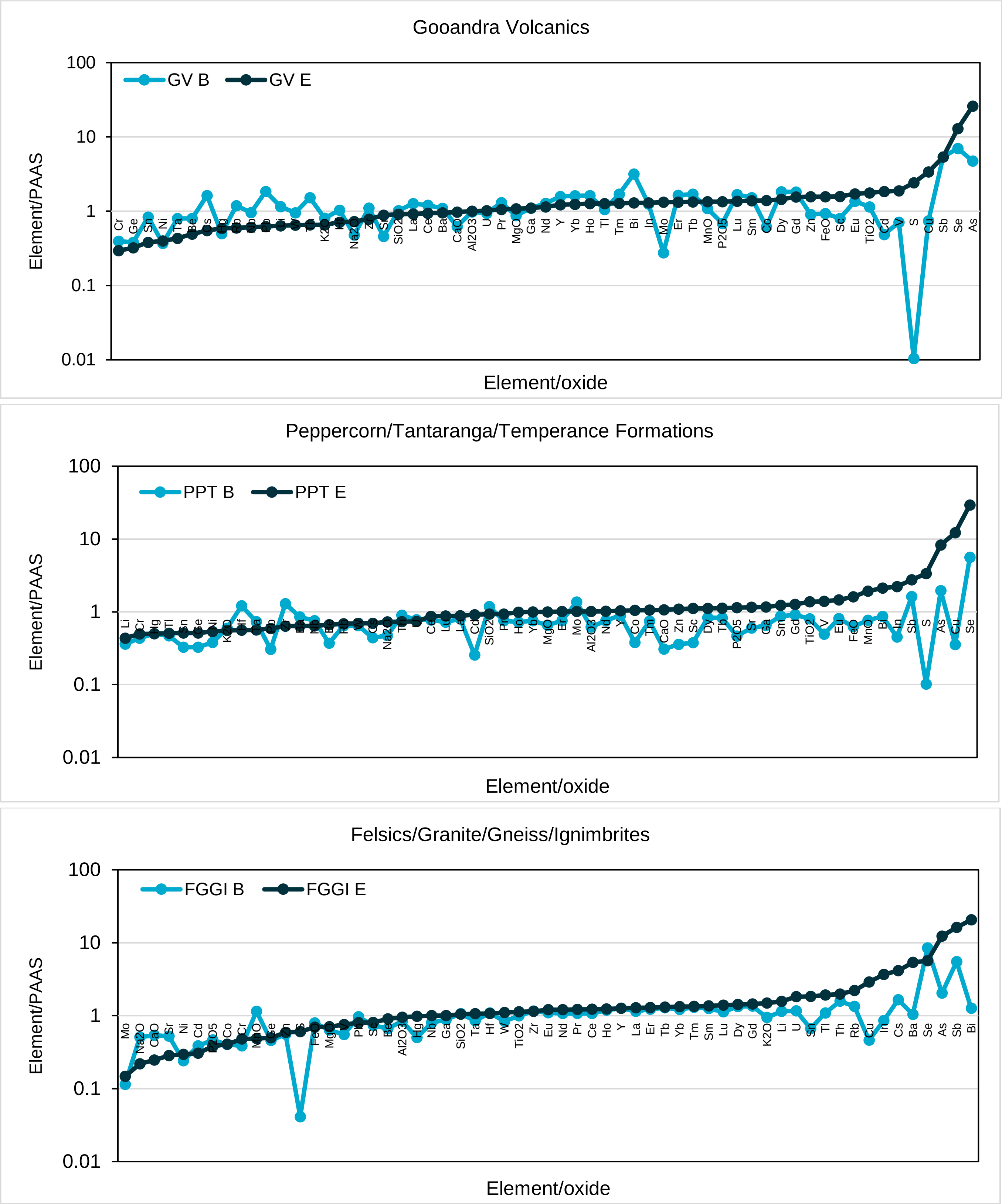


Figure 3b. Major and trace element ratios relative to the Post Archean Australian Shale (PAAS) and ranked according to increasing ratios in the Enriched sample group for the Gooandra Volcanics; Peppercorn/Tantangara/Temperance Formations; and Felsic/Granite/Gneiss/Ignimbrite zones across the tunnel transect.

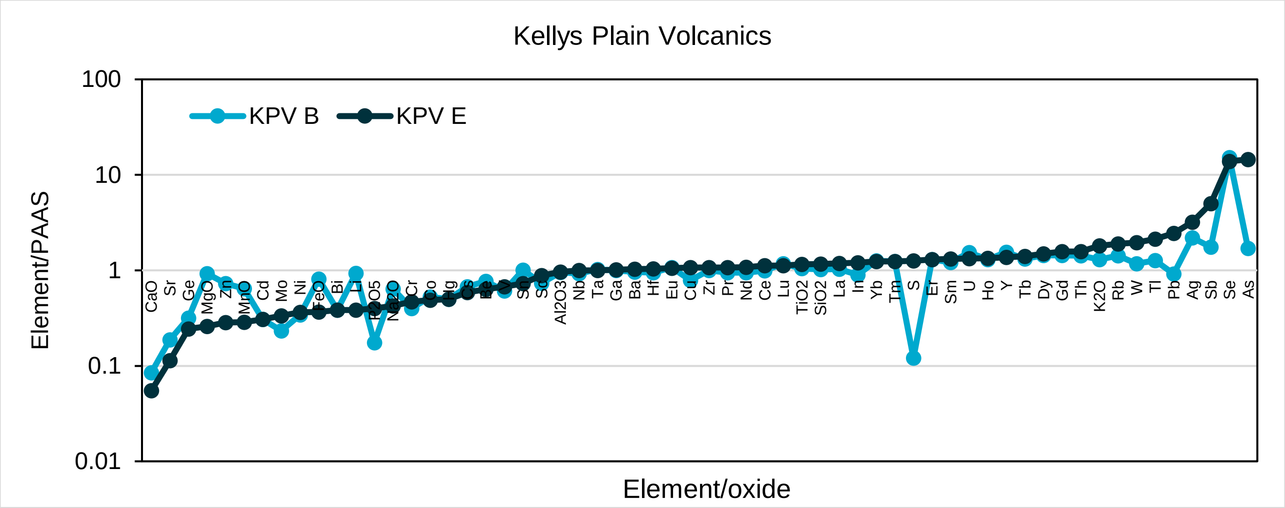


Figure 3c. Major and trace element ratios relative to the Post Archean Australian Shale (PAAS) and ranked according to increasing ratios in the Enriched sample group for the Kelly Plan Volcanics zone across the tunnel transect.

Table 2. Summary of mean concentrations of major element oxides (wt %), loss on ignition (LOI, wt %) and trace elements (mg/kg) for geological zones.

Geology	PPT B	PPT E	SHG B	SHG E	GV B	GV E	KPV B	KPV E	FGGI B	FGGI E	BB B	BB E	RV B	RV E
SiO_2	78.2	61.1	49.31	57.20	67.00	60.07	67.60	76.74	70.02	69.06	73.4	68.5	62.5	62.7
Al_2O_3	9.39	15.3	17.01	16.65	14.86	15.19	14.43	14.55	12.78	14.47	10.9	10.8	14.9	13.8
FeO	2.81	7.22	8.36	7.04	4.18	7.04	3.64	1.65	3.57	3.12	4.38	4.36	6.01	6.75
MnO	0.05	0.14	0.16	0.14	0.08	0.09	0.05	0.02	0.08	0.03	0.08	0.06	0.13	0.19
MgO	1.44	2.19	5.53	3.72	1.91	2.37	2.04	0.57	1.40	1.55	1.81	1.73	4.40	4.58
CaO	1.30	4.45	8.45	5.26	2.61	4.09	0.36	0.23	2.26	1.03	0.86	1.73	0.91	1.26
Na_2O	1.84	2.84	3.75	2.80	1.86	2.83	2.49	1.65	1.97	0.85	0.72	0.48	1.09	1.44
K_2O	2.01	1.88	0.67	1.51	2.73	2.22	4.41	6.13	3.21	5.04	2.84	3.06	3.26	3.07
TiO_2	0.40	0.69	1.03	0.92	0.57	0.88	0.53	0.58	0.50	0.56	0.47	0.52	0.72	0.82
P_2O_5	0.09	0.23	0.13	0.12	0.14	0.27	0.04	0.08	0.09	0.08	0.11	0.11	0.15	0.14
S	0.02	0.80	0.00	0.00	0.00	0.58	0.03	0.30	0.01	0.14	0.02	0.35	0.01	0.08
LOI	2.43	2.98	5.61	4.66	4.07	4.37	4.41	0.00	4.11	4.05	4.37	4.41	5.76	5.05
Ag	0.01	0.12	0.01	0.03	0.06	0.24	0.11	0.16	0.05	0.15	0.10	0.22	0.08	0.34
As	2.9	12.4	2.2	4.4	7.1	38.8	2.6	21.8	3.0	18.4	5.0	14.8	8.1	13.0
Ba	467	352	72	229	602	524	527	567	572	2960	479	430	519	683
Be	1.1	2.0	0.7	1.6	2.4	1.5	2	1.9	2.0	2.7	1.8	2.0	2.5	1.9
Bi	0.1	0.3	0.1	0.2	0.4	0.2	0.1	0.1	0.2	2.7	0.2	0.6	0.3	0.4
Cd	0.03	0.09	0.07	0.05	0.05	0.18	0.03	0.03	0.04	0.03	0.03	0.04	0.03	0.81
Ce	50	55	23	51	77	60	63	72	69	78	65	64	77	67
Co	6	18	32	26	10	24	9	8	7	7	12	13	21	21
Cr	37	42	148	154	34	25	34	40	33	41	48	60	123	152
Cs	2	3	1	4	7	3	3	3	8	19	9	11	12	10
Cu	9	306	69	67	19	85	20	26.7	12	72	10	29	36	49
Dy	2.9	3.9	4.4	5.0	6.4	5.1	5.0	5.2	4.7	5.0	4.2	3.7	4.3	4.4
Er	1.7	2.3	2.8	3.0	3.8	3.1	3.0	3.0	2.8	3.0	2.5	2.1	2.5	2.6
Eu	0.7	1.3	1.0	1.1	1.2	1.5	0.9	0.9	1.0	1.1	0.9	0.9	1.2	1.2
Ga	11.0	19.8	16.1	18.3	18.7	18.8	17	17.2	15.0	17.1	13.9	14.3	19.6	17.3
Gd	3.5	4.8	4.0	5.0	6.9	5.9	5.4	6	5.1	5.5	4.6	4.6	5.4	5.2
Ge	0.5	0.8	0.46	0.7	0.6	0.5	0.5	0.4	0.7	0.8	1.0	1.0	0.7	0.6
Hf	7.0	3.3	3.0	4.3	6.0	4.1	5.5	6	6.3	6.2	6.3	5.9	4.8	4.6
Hg	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.03	0.03	0.03	0.05
Ho	0.6	0.8	0.9	1.0	1.3	1.0	1.0	1.1	0.9	1.0	0.8	0.7	0.8	0.9
In	0.02	0.11	0.07	0.06	0.06	0.07	0.0	0.06	0.04	0.18	0.05	0.05	0.06	0.09
La	24	27	9	23	38	27	31	36	34	38	31	31	37	33
Li	7	9	13	38	23	13	19	7.7	23	31	34	27	60	62
Lu	0.2	0.3	0.3	0.3	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.4
Mo	2.04	1.52	0.05	0.05	0.41	1.99	0.4	0.5	0.17	0.22	0.30	0.28	0.19	0.22
Nb	9	8	4	8	11	7	11	12	10	12	10	11	13	12
Nd	20	27	13	22	33	30	25	28	28	31	26	26	32	29
Ni	17	24	44	48	16	18	15	16	11	13	27	29	110	129
Pb	5	10	2.9	12	31	11	16	42	16	14	8	13	17.2	195
Pr	5.3	6.6	2.9	5.8	9.3	7.5	6.7	7.6	7.6	8.6	7.4	7.3	8.6	7.8
Rb	72	77	17	55	133	67	159	212	151	248	134	164	155	139
Sb	0.3	0.6	0.1	0.4	1.1	1.1	0.4	1.0	1.1	3.2	1.4	3.7	1.5	2.6
Sc	5	15	30	24	11	22	10	12	10	11	13	11	16	15
Se	0.3	1.5	0.5	0.4	0.4	0.6	0.8	0.7	0.4	0.3	0.3	0.4	0.4	0.4
Sm	3.9	5.5	3.4	4.9	6.9	6.2	5.5	6.0	5.7	6.1	5.2	5.2	6.2	5.8
Sn	1.8	2.8	0.9	2.4	4.6	2.1	5.6	4.0	3.7	10.1	3.6	3.4	3.9	3.0
Sr	209	406	229	202	161	309	66	40	183	99	35	66	77	75
Ta	0.7	0.6	0.3	0.6	0.8	0.4	1.0	1.0	0.8	1.1	0.9	1.0	1.0	0.9
Tb	0.5	0.7	0.7	0.9	1.1	0.9	0.8	0.9	0.8	0.8	0.7	0.7	0.8	0.8
Te	0.03	0.11	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.03
Th	10	8	2	9	16	7	15	17	17	21	16	14	16	12
Tl	0.4	0.4	0.1	0.3	0.8	1.0	1.0	1.6	0.8	1.4	0.7	0.8	0.8	0.9
Tm	0.25	0.35	0.38	0.41	0.56	0.42	0.41	0.41	0.43	0.44	0.39	0.30	0.36	0.37
U	2.2	2.1	0.3	1.1	2.6	2.8	4.3	3.7	3.3	5.1	3.2	3.2	2.50	2.3
V	53	149	191	123	76	202	66	72	59	80	79	76	123	126
W	1.3	1.4	0.2	0.6	1.9	1.3	2.4	3.9	1.7	2.2	1.7	2.7	1.7	4.0
Y	20	23	26	28	35	27	34	30	28	28	27	26	29	27
Yb	1.7	2.2	2.3	2.5	3.5	2.7	2.8	2.7	2.7	2.9	2.5	2.0	2.4	2.4
Zn	25	77	76	83	64	111	52	20	39	42	62	47	118	504
Zr	246	121	107	156	209	148	190	203	220	218	216	201	169	163

Abbreviations for Baseline and Enriched Groups: Peppercorn/Tantangara/Temperance Formation (PTTB, PPT E); Shaw Hill Gabbro (SHG B, SHG E); Gooandra Volcanics (GA B, GA E); Kellys Plain Volcanics (KPV B, KPV E); Felsic/Granitoid/Gneiss/Ignimbrite (FGGI B, FGGI E); Byron/Boraig (BB B, BBE); Ravine (RV B, RV E).

4.2 Acid-Base Accounting (ABA) Results

A synopsis of the results of ABA experiments is given in Table 3. Due to their similarity in testing results, Baseline and Enriched groupings as outlined in Table 2 have been aggregated.

Total S, and hence MPA varied by a factor of 15 between Baseline (0.02 wt% S) and Enriched (0.30 wt% S) Groups respectively. A number of the Enriched samples contained visible sulphides in hand specimen.

Of the 115 samples analysed, none had an acidic pH following 1:2 soil:H_2O leaching with a mean pH of 9.3 and 9.1 for the Baseline and Enriched Groups respectively. Leachable salts, measured as EC were uniformly low at 0.20 and 0.23 dS/m respectively.

Only 26 samples (23%, pH range 2.4 to 6.9) could be classified to have NAG capacity. Mean ANC was similar in both Baseline (77 kg H_2SO_4/t) and Enriched (83 kg H_2SO_4/t) sample Groups. A comparison of ANC and MPA (ranked according to increasing MPA) shows that ANC is in excess of MPA for all of the 115 samples analysed in this study (Figure 4).

Table 3. Summary of mean, minimum and maximum Total S (%), pH, MPA, ANC and NAG, all kg H_2SO_4/tonne.

Sample type		Baseline				Enriched			
Parameter	**Unit**	**mean**	**std dev**	**min**	**max**	**mean**	**std dev**	**min**	**max**
Total S	**%**	0.02	0.02	0.00	0.09	0.30	0.35	0.00	1.4
MPA	**kg H_2SO_4/t**	0.6	0.64	0.01	2.68	9.23	10.63	0.05	43.0
Leach 1:2 soil:H_2O	**EC (dS/m)**	0.20	0.05	0.07	0.30	0.25	0.23	0.10	1.4
	pH	9.3	0.3	8.1	9.8	9.1	0.5	7.4	9.7
ANC	**kg H_2SO_4/t**	77	54	3	269	83	47	12	262
NAG (15% H_2O_2)	**E.C. dS/m**	0.2	0.10	0.06	0.51	0.37	0.41	0.08	2.1
	pH	8.6	1.4	3.8	11.3	7.5	2.7	2.4	11.1
	kg H_2SO_4/t	0.2	0.10	0.07	0.31	1.43	2.02	0.04	6.7

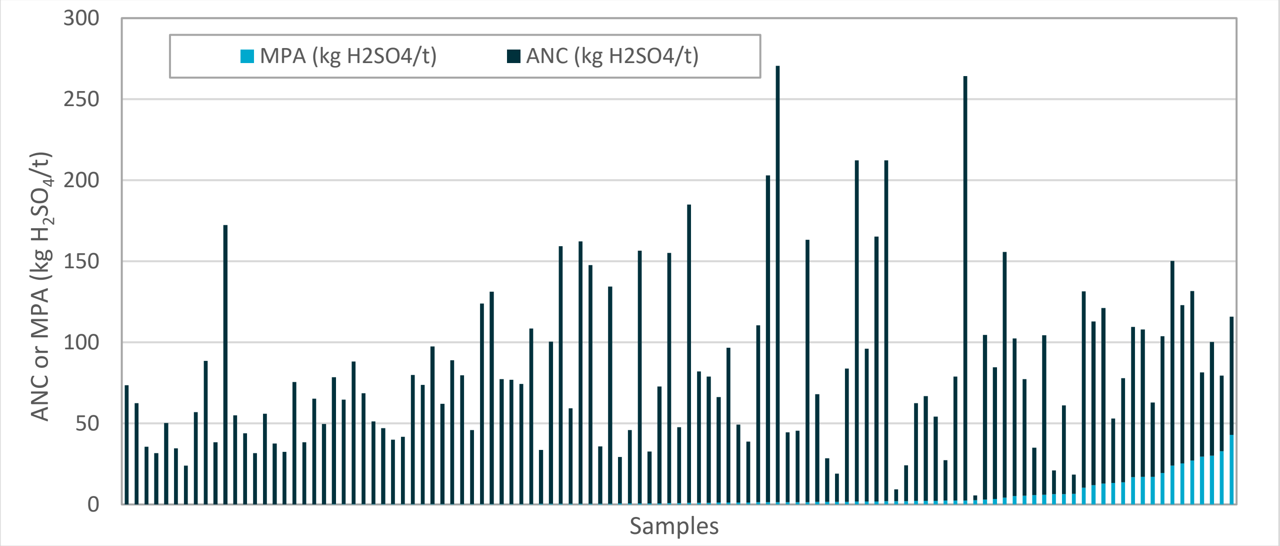


Figure 4. Comparison of MPA (kgH_2SO_4/t) and ANC (kg H_2SO_4/t) ranked according to increasing MPA for combined Baseline and Enriched Groups.

A further comparison of ANC and MPA shows that ANC is in excess of MPA for all of the 115 samples analysed in this study (Figure 5). This plot indicates that the is only one sample present in the Increased Risk area while only four samples are present each in the Low Risk and Potential Risk areas respectively, while the reminder of the samples (107 out of 115 or 93%) plot in the Very Low Risk area. Of the few high MPA samples, the highest (43 kg H_2SO_4/t) occurred in the Tantangara Formation with the other few high MPA samples mostly present in the Ravine and Byron/Boraig Groups. While ANC is in excess of MPA, absolute rates of acidity generation versus alkalinity neutralisation were not determined in this study and may require further investigation.

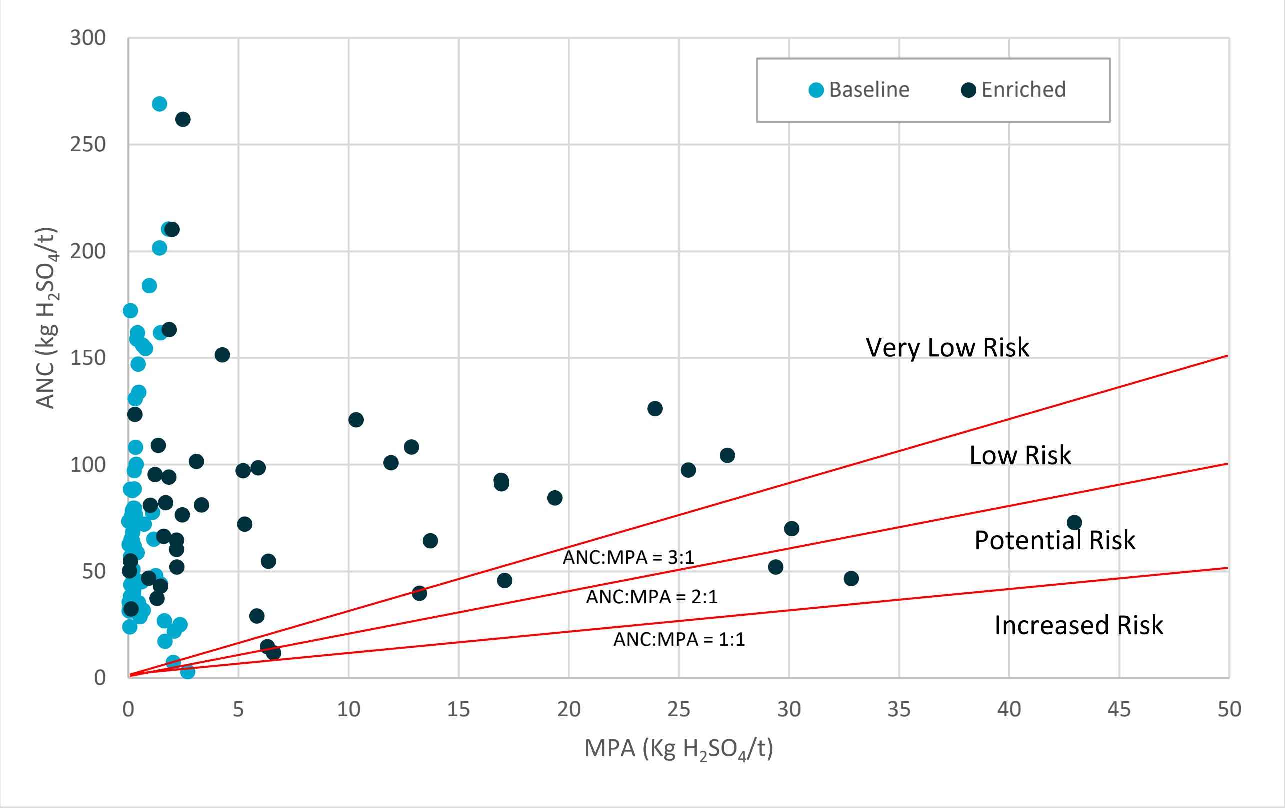
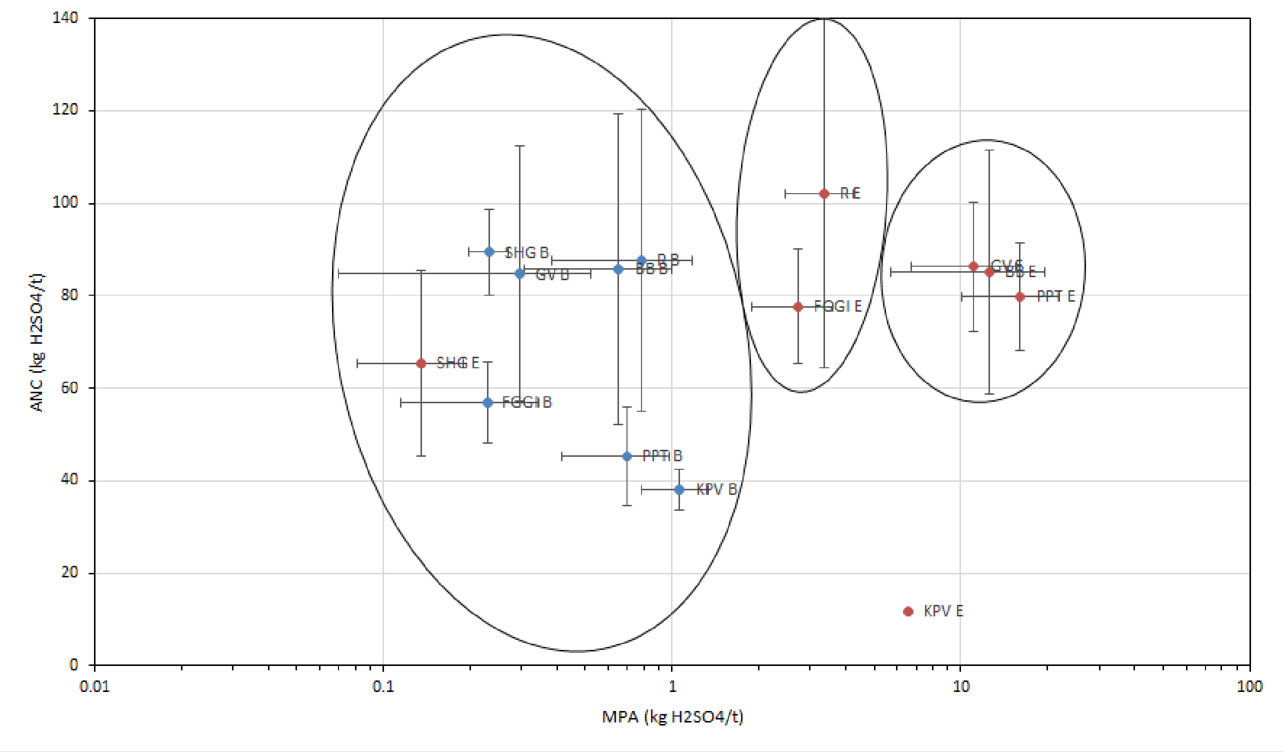


Figure 5. Categorisation of ANC (kg H_2SO_4/t) versus MPA (kgH_2SO_4/t) risk for Baseline and Enriched Groups.

Although the majority of samples analysed in this study plot in the Very Low Risk area in Figure 5, a simple risk ranking of the Baseline and Enriched Groups for each rock type has been developed based on a comparison of the mean ANC and MPA (Figure 6). Three groups of relative risk can be identified. All three groups have a considerable variation around the mean reflecting primary compositional variation and hence ANC and MPA.

The first group, with a low MPA, consists of all of the baseline units and the Enriched Shaw Hill Gabbro Group which contains similarly low S to the Baseline counterpart. These likely constitute a low risk for net acid generation. The second group with an intermediate MPA consists of the Enriched Ravine and Felsic/Granite/Gneiss/Ignimbrite Groups. The third group with the highest MPA, and with the smallest range of ANC mean and standard deviations consists of Enriched Gooandra Volcanics, Byron/Boraig, and Peppercorn/Tantangara/Temperance Groups and constitutes the highest, albeit likely low risk group of rocks. A single sample from the Enriched Kelly's Plain Volcanics remains unclassified, with too few samples made available at the time of writing, but it is notable in having a substantially higher MPA:ANC ratio than the three aforementioned groups.

Figure 6. Relative risk ranking of Baseline and Enriched Groups based on mean ANC (kg H_2SO_4/t) versus MPA (kgH_2SO_4/t).



4.3 Leachate Testing

Talbingo Reservoir water used in the oxic and anoxic leachate studies was characterised by a circumneutral pH and very low EC of 0.03 dS/m, and hence with low major ion concentration similar to that of modified rainwater. Nutrients and trace elements were also very low with only Al, Fe and Si above detection limits. A summary of leachate tests for samples aggregated into Baseline and Enriched Groups for Oxic, Anoxic and Dilute Acid are shown in Tables 4 to 6 respectively.

Importantly, the leaching ratio here (1:20) is similar to the projected volume ratio of rock to solute (5%) to be deposited in Talbingo Reservoir and Tantangara Reservoir, and so provided a good reference point under which to evaluate the results here. Under both oxic and anoxic conditions, major and trace element leaching often appeared to be limited, although elevated over what is essentially the modified rainwater composition of Talbingo Reservoir. Given the small particle size of the samples used in this study, it is likely that element release from the majority of the deposited excavated rock with a relatively large particle size, and hence, reduced effective/reactive surface area, will be largely attenuated with considerably slower water-rock reaction kinetics. Nonetheless, a proportion of finer material that may remain suspended following rock deposition, will likely have similar geochemical and leaching characteristics to the samples used in this study. A factor not considered in the P2 study was the effect of resuspension of reservoir bed sediments and their effects on water quality.

A comparison of aggregated Baseline to Enriched samples in oxic leachates revealed that despite there being similar mean pH and EC, there were substantial differences in the means and/or minima and maxima for a range of elements (Table 4). In particular, there are substantially higher mean concentrations in the Enriched leachates of Ca (2.6 times), S (5.5 times), Sb (2.1 times) and Se (1.3 times) with correspondingly higher maximum concentrations (1.4 to 6.7 times) than Baseline maximum leachate concentrations. In addition, maximum leachate concentrations of the alkaline earth metals: Ca (3.2 times), Mg (1.4 times), Sr (1.7 times), in addition to EC (2.1 times), can at times also be present in the Enriched relative to the Baseline leachates.

A similar comparison of aggregated Baseline to Enriched samples in anoxic leachates revealed that despite there being similar mean pH and EC, albeit approximately two pH units lower than on the oxic leachates, there were substantial differences in the means and/or minima and maxima for a range of elements (Table 5). In particular, there were substantial higher mean concentrations in the Enriched leachates of Ba (2.5 times) and S (6.6 times). In addition, maximum leachate concentrations of Al (7.5 times), Ba (3.4 times, Co (2.2 times), Mn (1.8 times), S (2.0 times), Sb (9.3 times), Se (2.5 times) and Th (2.0 times) can at times also be present in the Enriched relative to the Baseline leachates.

A further comparison of dilute acid leachates in aggregated Baseline to Enriched samples revealed a similar mean pH to the oxic leachates, despite the increased, albeit dilute acidity being present, with an initial pH of 4.9, suggesting an efficient buffering capacity. In contrast to other leachates, EC increased reflecting the presence of the added acid (Table 6). There were substantially higher mean concentrations in the Enriched leachates of a more numerous and diverse array of elements including Al (1.7 times), As (1.5 times), Ba (2.3 times), Cd (1.3 times), Mn (1.5 times), S (8.4 times), Sb (2.1 times), Se (1.4 times), TN (1.5 times) and Cl (1.6 times). Furthermore, maximum leachate concentrations of Al (2.9 times), As (1.8 times), the alkaline earth metals: Ba (5.4 times), Ca (2.6 times), Mg (1.4 times) and Sr (1.5 times), in addition to Mn (2.4 times), S (8.8 times), Sb (3.7 times), Se (2.2 times), and Si (2.1 times) can at times also be present in the Enriched relative to the Baseline leachates.

Assuming that oxic conditions predominate in Tantangara Reservoir and Talbingo Reservoir, a further analysis of the leachate data has been undertaken using a pairwise analysis using ratios of anoxic to oxic and dilute acid to oxic data. Ratios of anoxic and dilute acid to oxic leachates, ranked according to an increasing ratio in the Baseline Group are shown in Table 7.

In the case of the anoxic to oxic leachate ratios, in the Baseline and Enriched Groups, substantially higher Mn (30.0 to 34.1 times), reflecting the anoxic conditions and consequent reductive dissolution, and to a lesser extent the alkaline earth metals: Ca (7.3 to 10.2 times), Mg (3.8 to 4.6 times), Sr (3.3 to 3.6 times) and Ba (2.8 to 2.9 times) in addition to TC (3.4 to 3.8 times) were present. Alkali metals: K (1.6 times) and Na (1.2 times) were also relatively enriched in the anoxic relative to oxic leachates. Some trace elements were elevated in the anoxic relative to anoxic leachates, in particular Co (1.4 times), Ni (1.4 times) and Mo (1.2 times), all of which are often associated with Mn oxides/hydroxides. A range of elements (B, Cd, Hg, P, all below detection limits) and NO_3 and Cl can at times have similar leachate concentrations, and hence ratios in the anoxic to oxic leachates irrespective of whether they were in the Baseline or Enriched Groups. In contrast, a range of elements were substantially depleted in the anoxic relative to oxic leachates including Al (0.03 times), V (0.1 times), Pb (0.1 to 0.2 times), Fe (0.1 to 0.2 times) and As (0.2 times).

In the case of the dilute acid to oxic leachate ratios, in the Baseline and Enriched Groups, substantially higher Cr (1.3 to 1.7 times), Ca (1.3 to 1.5 times), TC (1.2 to 1.4 times), Sr (1.2 to 1.4 times), Mo (1.2 times for Baseline only), NO_3 (1.2 times) and TN (2.0 times Enriched only) were present. A range of elements (e.g. Se, Ba, Mg) can at times have similar leachate concentrations, and hence ratios in the dilute acid to oxic leachates irrespective of whether they are in the Baseline or Enriched Groups. In contrast, a range of elements were substantially depleted in the dilute acid relative to oxic leachates including Pb (0.2 times), U (0.3 times), Fe (0.3 times), Al (0.4 to 0.6 times), and S (0.6 to 0.9 times).

Table 4. Summary of mean, standard deviation, minimum and maximum concentrations of oxic leachates of aggregated Baseline and Enriched Groups for each of the seven geological zones.

Oxic		Baseline				Enriched			
Element	**units**	**mean**	**std dev**	**min**	**max**	**mean**	**std dev**	**min**	**max**
Al	mg/L	0.75	0.99	0.03	5.01	0.90	0.91	0.03	3.65
As	µg/L	5.64	12.94	0.25	83.60	6.45	11.50	0.25	64.80
B	mg/L	0.03	0.00	0.03	0.03	0.03	0.00	0.03	0.03
Ba	µg/L	7.7	10.3	0.3	51.9	20.0	55.1	0.3	347
Ca	mg/L	2.9	1.5	0.1	7.1	4.3	3.7	0.1	22.5
Cd	µg/L	0.05	0.00	0.05	0.05	0.05	0.00	0.05	0.05
Co	µg/L	0.09	0.14	0.05	1.10	0.09	0.09	0.05	0.60
Cr	µg/L	0.93	1.32	0.50	8.00	0.66	0.48	0.50	3.00
Cu	µg/L	0.40	0.37	0.25	1.90	0.42	0.40	0.25	2.40
Fe	µg/L	87	87	1	332	93	101	1	400
Hg	µg/L	0.25	0.00	0.25	0.25	0.25	0.00	0.25	0.25
K	mg/L	9.3	4.3	0.3	18.6	9.8	6.4	0.3	23.4
Mg	mg/L	1.2	0.9	0.3	5.0	1.4	1.1	0.5	6.7
Mn	µg/L	5.6	9.6	0.5	74.0	5.7	8.0	0.5	46.0
Mo	µg/L	0.77	3.11	0.05	25.20	0.67	0.85	0.05	3.40
Na	mg/L	4.0	2.1	1.8	10.3	4.2	2.0	1.8	11.4
Ni	µg/L	0.37	0.31	0.25	1.80	0.34	0.22	0.25	1.30
P	mg/L	0.10	0.00	0.10	0.10	0.10	0.00	0.10	0.10
Pb	µg/L	0.39	1.31	0.05	10.60	0.28	0.40	0.05	2.10
S	mg/L	0.38	0.43	0.10	3.44	2.06	3.87	0.10	24.56
Sb	µg/L	1.61	1.79	0.25	8.40	3.42	5.35	0.25	24.10
Se	µg/L	0.32	0.20	0.25	1.40	0.41	0.46	0.25	2.70
Si	mg/L	3.06	1.49	0.86	8.31	3.03	1.74	0.86	8.40
Sn	µg/L	0.23	0.19	0.05	0.80	0.24	0.14	0.05	0.50
Sr	µg/L	28	31	2	154	32	44	1	263
Th	µg/L	0.11	0.16	0.05	1.10	0.09	0.10	0.05	0.50
U	µg/L	0.19	0.28	0.03	1.24	0.16	0.18	0.03	0.81
V	µg/L	4.13	5.05	0.40	32.60	4.16	3.62	0.40	17.80
Zn	µg/L	0.68	1.15	0.25	5.70	0.37	0.42	0.25	2.70
EC	dS/m	0.08	0.01	0.04	0.11	0.09	0.03	0.05	0.24
pH	-	9.5	0.3	8.4	10.1	9.4	0.4	8.1	9.9
TC	mg/L	8.1	3.5	2.2	13.7	9.0	3.2	2.5	14.7
TN	mg/L	0.36	0.71	0.00	5.95	0.29	0.18	0.00	0.71
F-	mg/L	0.12	0.09	0.03	0.55	0.12	0.09	0.03	0.39
Cl-	mg/L	2.0	1.0	1.3	7.3	1.9	0.6	1.3	3.7
Br-	mg/L	0.03	0.00	0.03	0.03	0.03	0.00	0.03	0.03
NO_3-	mg/L	0.06	0.02	0.03	0.14	0.06	0.03	0.03	0.14

Note: Elements in red are below detection limits in the leachates

Table 5. Summary of mean, standard deviation, minimum and maximum concentrations of anoxic leachates of aggregated Baseline and Enriched Groups.

Anoxic		Baseline				Enriched			
Element	**units**	**mean**	**std dev**	**min**	**max**	**mean**	**std dev**	**min**	**max**
Al	mg/L	0.03	0.00	0.03	0.03	0.03	0.02	0.03	0.19
As	µg/L	1.40	3.44	0.25	21.6	1.28	2.27	0.25	11.4
B	mg/L	0.03	0.00	0.03	0.03	0.03	0.00	0.03	0.03
Ba	µg/L	23	35	1	210	56	127	1	710
Ca	mg/L	29.5	16.1	1.9	67.4	31.1	14.1	2.0	57.0
Cd	µg/L	0.05	0.00	0.05	0.05	0.05	0.00	0.05	0.05
Co	µg/L	0.10	0.11	0.05	0.60	0.12	0.23	0.05	1.30
Cr	µg/L	0.50	0.00	0.50	0.50	0.50	0.00	0.50	0.50
Cu	µg/L	0.27	0.12	0.25	1.20	0.26	0.04	0.25	0.50
Fe	µg/L	14	46	1	348	12	55	1	357
Hg	µg/L	0.25	0.00	0.25	0.25	0.25	0.00	0.25	0.25
K	mg/L	14.9	6.7	1.0	31.2	15.4	9.7	0.7	36.2
Mg	mg/L	5.6	3.3	1.7	16.7	5.4	2.4	2.3	12.5
Mn	µg/L	193	205	13	929	172	276	14	1699
Mo	µg/L	1.0	3.3	0.1	25.4	0.8	1.0	0.1	5.4
Na	mg/L	4.7	2.5	1.8	13.6	4.9	2.3	1.9	11.9
Ni	µg/L	0.39	0.40	0.25	2.80	0.49	0.67	0.25	3.20
P	mg/L	0.10	0.00	0.10	0.10	0.10	0.00	0.10	0.10
Pb	µg/L	0.05	0.01	0.05	0.10	0.05	0.02	0.05	0.20
S	mg/L	0.3	0.3	0.1	2.6	1.7	3.8	0.1	24.7
Sb	µg/L	1.46	2.06	0.25	10.10	2.81	4.85	0.25	24.90
Se	µg/L	0.26	0.07	0.25	0.80	0.29	0.14	0.25	0.90
Si	mg/L	2.6	1.0	1.3	6.0	2.4	1.0	1.2	5.2
Sn	µg/L	0.25	0.29	0.05	2.20	0.17	0.10	0.05	0.50
Sr	µg/L	99	93	10	465	106	103	10	541
Th	µg/L	0.05	0.00	0.05	0.05	0.05	0.01	0.05	0.10
U	µg/L	0.06	0.14	0.03	0.86	0.08	0.11	0.03	0.40
V	µg/L	0.36	0.55	0.05	2.70	0.36	0.33	0.05	1.90
Zn	µg/L	0.41	0.46	0.25	3.00	0.45	0.60	0.25	3.50
EC	dS/m	0.22	0.05	0.09	0.32	0.23	0.05	0.10	0.32
pH	-	7.1	0.2	6.5	7.5	7.1	0.3	6.2	7.7
TC	mg/L	30.8	7.8	11.3	50.8	30.9	7.7	11.1	44.5
TN	mg/L	0.22	0.14	0.00	0.58	0.22	0.19	0.00	0.85
F-	mg/L	0.07	0.10	0.03	0.69	0.07	0.11	0.03	0.75
Cl-	mg/L	2.0	0.5	1.4	3.5	2.0	0.5	1.4	4.0
Br-	mg/L	0.03	0.00	0.03	0.03	0.03	0.00	0.03	0.03
NO_3-	mg/L	0.06	0.04	0.03	0.22	0.05	0.03	0.03	0.16

Note: Elements in red are below detection limits in the leachates

Table 6. Summary of mean, standard deviation, minimum and maximum concentrations of dilute acid leachates of aggregated Baseline and Enriched Groups.

Dilute acid		Baseline				Enriched			
Element	**units**	**mean**	**std dev**	**min**	**max**	**mean**	**std dev**	**min**	**max**
Al	mg/L	0.32	0.29	0.03	1.50	0.55	0.76	0.03	4.37
As	µg/L	4.21	7.71	0.25	47.60	6.52	13.54	0.25	87.00
B	mg/L	0.03	0.00	0.03	0.03	0.03	0.00	0.03	0.03
Ba	µg/L	7.52	10.81	0.25	57.70	21.37	55.18	0.25	311.00
Ca	mg/L	4.4	2.3	0.1	9.5	5.7	4.1	0.1	24.3
Cd	µg/L	0.05	0.00	0.05	0.05	0.05	0.00	0.05	0.05
Co	µg/L	0.06	0.02	0.05	0.20	0.07	0.06	0.05	0.40
Cr	µg/L	1.55	2.01	0.50	12.00	0.87	0.76	0.50	3.00
Cu	µg/L	0.36	0.23	0.25	1.10	0.30	0.13	0.25	0.70
Fe	µg/L	27	46	1	218	25	32	1	132
Hg	µg/L	0.25	0.00	0.25	0.25	0.25	0.00	0.25	0.25
K	mg/L	10	5	0	20	11	7	0	25
Mg	mg/L	1.3	0.9	0.1	4.6	1.4	1.2	0.4	6.4
Mn	µg/L	5.8	9.0	0.5	62.0	8.7	21.9	0.5	148.0
Mo	µg/L	0.95	4.25	0.05	34.40	0.59	0.91	0.05	4.00
Na	mg/L	3	2	0	10	3	2	0	12
Ni	µg/L	0.40	0.31	0.25	1.40	0.38	0.25	0.25	1.20
P	mg/L	0.10	0.00	0.10	0.10	0.10	0.00	0.10	0.10
Pb	µg/L	0.06	0.06	0.05	0.40	0.07	0.06	0.05	0.30
S	mg/L	0.23	0.33	0.10	2.67	1.94	3.83	0.10	23.36
Sb	µg/L	1.83	2.07	0.25	8.90	3.80	6.16	0.25	33.10
Se	µg/L	0.31	0.21	0.25	1.40	0.43	0.51	0.25	3.10
Si	mg/L	2.1	0.8	0.7	4.1	2.2	1.5	0.7	8.6
Sn	µg/L	0.17	0.13	0.05	0.60	0.15	0.09	0.05	0.40
Sr	µg/L	38	44	1	177	40	48	0	266
Th	µg/L	0.06	0.03	0.05	0.20	0.05	0.01	0.05	0.10
U	µg/L	0.06	0.06	0.03	0.35	0.05	0.05	0.03	0.28
V	µg/L	3.24	4.38	0.20	30.90	3.31	2.36	0.30	10.90
Zn	µg/L	0.42	0.84	0.25	6.70	0.30	0.25	0.25	1.90
EC	dS/m	0.08	0.02	0.04	0.12	0.10	0.04	0.04	0.27
pH	-	9.2	0.4	7.6	9.9	9.2	0.5	8.0	9.8
TC	mg/L	11.1	3.1	3.8	18.0	11.1	3.3	3.8	16.7
TN	mg/L	0.40	0.73	0.00	4.18	0.58	1.24	0.00	4.89
F-	mg/L	0.07	0.06	0.03	0.35	0.08	0.07	0.03	0.28
Cl-	mg/L	1.7	2.8	0.3	17.6	2.7	4.5	0.4	20.6
Br-	mg/L	0.03	0.00	0.03	0.03	0.03	0.00	0.03	0.03
NO_3-	mg/L	0.07	0.03	0.03	0.17	0.07	0.03	0.03	0.15

Note: Elements in red are below detection limits in the leachates

Table 7. Ratio of element concentrations of anoxic to oxic and dilute acid to oxic leachates.

Anoxic/Oxic		Baseline	Enriched	Dilute acid/Oxic		Baseline	Enriched
Element	**units**	**mean**	**mean**	**Element**	**units**	**mean**	**mean**
Al	mg/L	0.03	0.03	**Pb**	µg/L	0.2	0.2
V	µg/L	0.1	0.1	**U**	µg/L	0.3	0.3
Pb	µg/L	0.1	0.2	**Fe**	µg/L	0.3	0.3
Fe	µg/L	0.2	0.1	**Al**	mg/L	0.4	0.6
As	µg/L	0.2	0.2	**Th**	µg/L	0.5	0.6
U	µg/L	0.3	0.5	**F-**	mg/L	0.6	0.6
Th	µg/L	0.4	0.6	**S**	mg/L	0.6	0.9
F-	mg/L	0.5	0.6	**Zn**	µg/L	0.6	0.8
Cr	µg/L	0.5	0.8	**Co**	µg/L	0.6	0.8
Zn	µg/L	0.6	1.2	**Si**	mg/L	0.7	0.7
TN	mg/L	0.6	0.8	**Na**	mg/L	0.7	0.7
Cu	µg/L	0.7	0.6	**Sn**	µg/L	0.7	0.6
S	mg/L	0.7	0.8	**As**	µg/L	0.7	1.0
pH	-	0.8	0.8	**V**	µg/L	0.8	0.8
Se	µg/L	0.8	0.7	**Cl-**	mg/L	0.9	1.5
Si	mg/L	0.8	0.8	**Cu**	µg/L	0.9	0.7
Sb	µg/L	0.9	0.8	**Se**	µg/L	1.0	1.1
B	mg/L	1.0	1.0	**pH**	-	1.0	1.0
Cd	µg/L	1.0	1.0	**Ba**	µg/L	1.0	1.1
Hg	µg/L	1.0	1.0	**B**	mg/L	1.0	1.0
P	mg/L	1.0	1.0	**Cd**	µg/L	1.0	1.0
Br-	mg/L	1.0	1.0	**Hg**	µg/L	1.0	1.0
NO_3-	mg/L	1.0	0.9	**P**	mg/L	1.0	1.0
Cl-	mg/L	1.0	1.1	**Br-**	mg/L	1.0	1.0
Ni	µg/L	1.1	1.4	**Mn**	µg/L	1.0	1.5
Sn	µg/L	1.1	0.7	**Mg**	mg/L	1.0	1.0
Co	µg/L	1.1	1.4	**EC**	dS/m	1.0	1.1
Na	mg/L	1.2	1.2	**K**	mg/L	1.1	1.1
Mo	µg/L	1.3	1.2	**Ni**	µg/L	1.1	1.1
K	mg/L	1.6	1.6	**TN**	mg/L	1.1	2.0
EC	dS/m	2.7	2.5	**Sb**	µg/L	1.1	1.1
Ba	µg/L	2.9	2.8	**NO_3-**	mg/L	1.2	1.2
Sr	µg/L	3.6	3.3	**Mo**	µg/L	1.2	0.9
TC	mg/L	3.8	3.4	**Sr**	µg/L	1.4	1.2
Mg	mg/L	4.6	3.8	**TC**	mg/L	1.4	1.2
Ca	mg/L	10.2	7.3	**Ca**	mg/L	1.5	1.3
Mn	µg/L	34.1	30.0	**Cr**	µg/L	1.7	1.3

Note: Elements in red are below detection limits in the leachates

4.4 Spillway rock surface coating analysis

Twelve rock samples that have been submerged in the Talbingo spillway for approximately 50 years were investigated to assess leaching characteristics and the potential to form secondary reactive surface rinds as hosts for trace elements. The similar size and angular nature of the rock specimens suggest that most, if not all were derived from rock blasting, and as such likely constitute fresh rock surfaces prior to immersion in Talbingo Reservoir. As such, this reconnaissance study constituted an ideal opportunity to determine the geochemical behaviour of the rocks during the initial years to decades post-deposition when water-rock reactions are likely to be at their most dynamic.

A full report on the 12 rock samples is contained in Schoneveld et al, (2018) which is included in Appendix A.2. For this P2 Final report, one Talbingo spillway rock, sample 8, is reported with a description of the core and rind regions to understand geochemical changes associated with immersion for five decades.

Sample 8 displayed a narrow weathering rind which was visible in reflected light as a paler region (Figure 6) with a corresponding increase in Fe and Mn as the red and blue traces respectively in the upper in the XRF map (Figure 7). The traverse across this sample showed consistent results for more than 1000 µm that changed significantly in the 250 µm closest to the surface (Figure 7). A range of other elements were also enriched in the reaction rind including Ca, Sc, V, As and the Light Rare Earth Elements (REE – La, Ce, Pr, Nd, Gd). While a reaction rind and element enrichment did not occur in all of the rocks sampled from the Talbingo spillway, there was evidence that at least some rock types, via surface reactions following immersion, had the capacity to act as a sink for a range of trace elements. Given that the reaction rind appeared to be primarily composed of Fe-Mn oxides/hydroxides, the incorporated trace elements would be likely to be stable under the predominantly oxic, circumneutral pH conditions currently present.

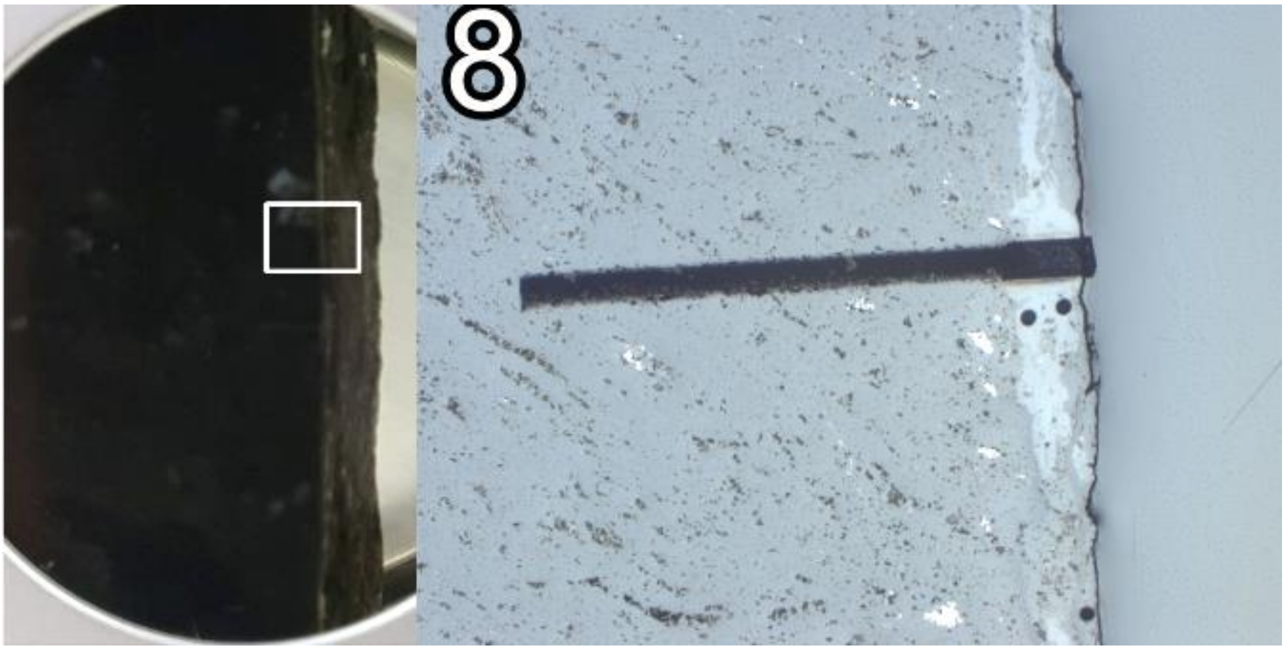


Figure 7. Talbingo spillway sample 8 (left) photograph of a polished extracted rock round and region of analysis (box) and (right) a reflected light image of a LA-ICP-MS traverse and LA-ICP-MS spots (ca. 50 µm in diameter) in the reaction rind.

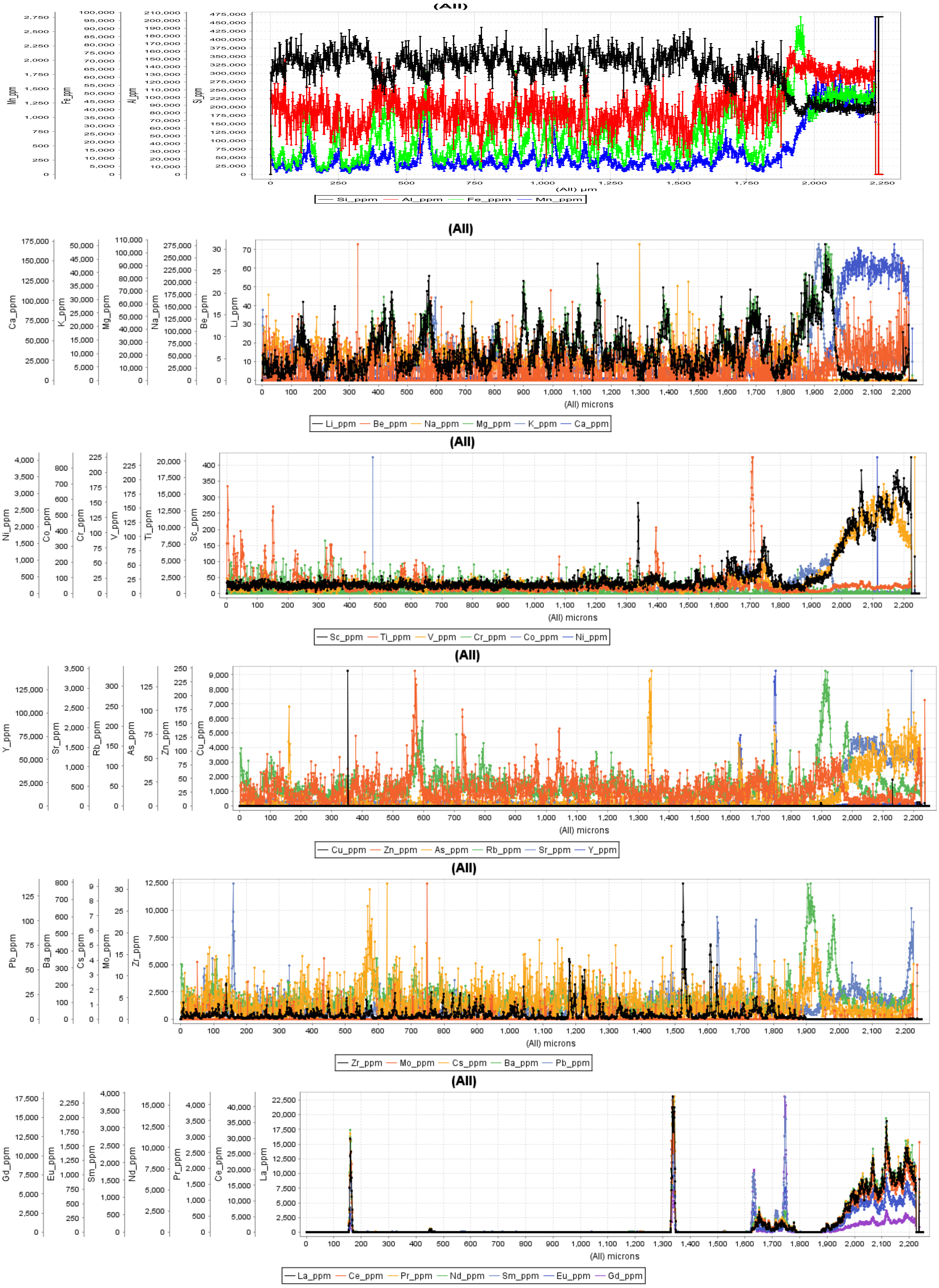


Figure 8. LA-ICP-MS semi-quantitative traverses across Talbingo spillway rock sample 8.

5 Summary

A first principles approach based on the geochemical composition, hand specimen analysis, and examination of the regional geology between Tantangara Reservoir and Talbingo Reservoir, was used to define seven geological zones. A further classification based on a comparison to the Post-Archean Australian Shale, an average upper crustal composition, was used to assist in the selection of Baseline and Enriched Groups, with the most common attribute of the Enriched Group being elevated S and trace element concentrations.

Following this classification, 115 samples were selected for Acid-Base Accounting and oxic, anoxic and acid leachate analysis. Major outcomes of these studies are given below:

Acid-Base Accounting

- Total S, and hence MPA, varied by a factor of 15 between Baseline (0.02 wt % S) and Enriched (0.30 wt % S) Groups respectively.
- None of the 115 samples had an acidic leachate pH with a mean pH of 9.3 and 9.1 for the Baseline and Enriched sample Groups respectively. Leachate EC was also low at 0.20 and 0.23 dS/m respectively.
- Only 26 samples (23%) could be classified to have NAG capacity. Mean ANC was similar in both Baseline (77 kg H_2SO_4/t) and Enriched (83 kg H_2SO_4/t) sample Groups. The ANC is always in excess of MPA.
- Of the samples 115 samples analysed, 93% can be nominally classified as very low risk.
- A relative risk ranking based on mean ANC and MPA indicates the greatest potential for generation of acidity from the Gooandra Volcanics, Byron/Boraig Groups and Peppercorn/Tantangara/Temperance Groups.

Leachate testing

- Talbingo Reservoir water used in the oxic and anoxic leachate studies has a circumneutral pH and very low EC or 0.03 dS/m.
- Under both oxic and anoxic conditions, major and trace element leaching was limited, although elevated over the modified rainwater composition of Talbingo Reservoir.
- A comparison of aggregated Baseline to Enriched samples in oxic leachates reveals a similar mean pH and EC, but with substantially higher mean concentrations in Enriched leachates of Ca (2.6 times), S (5.5 times), Sb (2.1 times) and Se (1.3 times) with correspondingly higher maximum concentrations (1.4 to 6.7) times than Baseline maximum leachate concentrations. Maximum leachate concentrations of alkaline earth metals: Ca (3.2 times), Mg (1.4 times), Sr (1.7 times), in addition to EC (2.1 times) are present in the Enriched leachates.
- A comparison of aggregated Baseline to Enriched samples in anoxic leachates revealed a similar mean pH and EC, but two pH units lower than oxic leachates. There were substantial higher mean concentrations in the Enriched leachates of Ba (2.5 times) and S (6.6 times). Maximum leachate concentrations of Al (7.5 times), Ba (3.4 times, Co (2.2 times), Mn (1.8

times), S (2.0 times), Sb (9.3 times), Se (2.5 times) and Th (2.0 times) can at times be present in the Enriched leachates.

- A comparison of aggregated Baseline to Enriched samples in dilute acid leachates revealed a similar mean pH to oxic leachates, suggesting a good buffering capacity. Substantially higher mean concentrations in the Enriched leachates of a more diverse array of elements include Al (1.7 times), As (1.5 times), Ba (2.3 times), Cd (1.3 times), Mn (1.5 times), S (8.4 times), Sb (2.1 times), Se (1.4 times), TN (1.5 times) and Cl (1.6 times). Maximum leachate concentrations of Al (2.9 times), As (1.8 times), the alkaline earth metals: Ba (5.4 times), Ca (2.6 times), Mg (1.4 times) and Sr (1.5 times), in addition to Mn (2.4 times), S (8.8 times), Sb (3.7 times), Se (2.2 times), and Si (2.1 times) can at times be present in the Enriched leachates.
- In the case of the anoxic to oxic leachate ratios, in the Baseline and Enriched Groups, substantially higher Mn (30.0 to 34.1 times) occurs, and to a lesser extent the alkaline earth metals: Ca (7.3 to 10.2 times), Mg (3.8 to 4.6 times), Sr (3.3 to 3.6 times) and Ba (2.8 to 2.9 times) in addition to TC (3.4 to 3.8 times) were present. Alkali metals: K (1.6 times) and Na (1.2 times) were also enriched in the anoxic leachates. Some trace elements elevated in the anoxic leachates included Co (1.4 times), Ni (1.4 times) and Mo (1.2 times). A range of elements were substantially depleted in the anoxic leachates including Al (0.03 times), V (0.1 times), Pb (0.1 to 0.2 times), Fe (0.1 to 0.2 times) and As (0.2 times).
- In the case of the dilute acid to oxic leachate ratios, in the Baseline and Enriched Groups, substantially higher Cr (1.3 to 1.7 times), Ca (1.3 to 1.5 times), TC (1.2 to 1.4 times), Sr (1.2 to 1.4 times), Mo (1.2 times for Baseline only), NO_3 (1.2 times) and TN (2.0 times Enriched only) were present. In contrast, a range of elements are substantially depleted in the dilute acid relative to oxic leachates including Pb (0.2 times), U (0.3 times), Fe (0.3 times), Al (0.4 to 0.6 times), and S (0.6 to 0.9 times).

Spillway rock analysis

- A study was undertaken of 12 rocks that had been immersed in the Talbingo spillway for approximately 50 years.
- Distinct weathering rinds were present. In one example a 250 µm deep weathering rind is present. A LA-ICP-MS traverse across the rind indicated elevated Fe and Mn with concurrent enrichment in Ca, Sc, V, As and the Light Rare Earth Elements.
- These results indicated that some rock types, via surface reactions following immersion, had the capacity to act as a sink for trace elements. With the reaction rinds dominated by Fe-Mn oxides/hydroxides, and possibly carbonates, the incorporated trace elements would be likely to be stable under the predominantly oxic, circumneutral pH conditions currently present in Talbingo Reservoir.

Recommendations for further work

- Whilst the MPA is generally low relative to the ANC, and hence a potential for the generation of acidity is low in most samples characterised in this study, relative rates of acidity versus alkalinity generation are uncertain and require further investigation.
- For many of the geological zones there still remains insufficient information on the natural compositional variation, and hence it is recommended that where possible, additional drilling, sampling, and analysis is undertaken, particularly in areas where larger volumes of

excavated rock will be generated to better quantify potential risks of acidity generation and contaminant release over and above this initial study. If this cannot be completed prior to construction of the tunnel, sampling and analysis of excavated rock prior to placement should be undertaken.

- While ambient concentrations of nutrients are low in Talbingo Reservoir, considerable N and Si were released during leaching of a range of rock types. On this basis, a study into the potential of the nutrients to reduce growth limitation with respect to phytoplankton should be undertaken.
- Considerable turbidity generated from samples used in the leachate studies highlights the potential for widespread turbidity to occur during in-reservoir deposition of excavated rock. Hence, a study of the generation of turbidity and methods to facilitate the flocculation of suspended solids is recommended.

6 References

Schoneveld, L., Douglas G, and Fraser, R. (2018); Snowy2.0 P2: A LA-ICP-MS analysis of surface weathering behaviour of Talbingo Reservoir spillway rocks. CSIRO, Australia.

Taylor, S.R. and McLennan, S.M. (1985). The Continental Crust, its Composition and Evolution. Blackwell Scientific Publications, 312pp. IBSN 0632011483

7 Appendix

A.1 Please refer to attached file: “Snowy P2 combined final report-002.xlsx” for all analytical results delivered in the P2 program

A.2 Please refer to attached file: “Snowy2.0-P2a-Spillway analysis report FINAL.docx”

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Snowy 2.0 P2a:

LA-ICP-MS analysis of surface weathering behaviour of Talbingo Reservoir spillway rocks

Final Report

Louise Schoneveld, Grant Douglas, Ryan Fraser

November 2018

For Snowy 2.0 Scheme, Snowy Hydro
Commercial-in-Confidence

Citation

Schoneveld, L., Douglas G, and Fraser, R. (2018); Snowy2.0 P2a: LA-ICP-MS analysis of surface weathering behaviour of Talbingo Reservoir spillway rocks. CSIRO, Australia.

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Important disclaimer

Foreword and Assignment Summary

CSIRO was requested by Snowy Hydro Limited (SHL) in November 2017 to provide scientific expertise and capability in relation to identifying and assessing the environmental risks associated with the placement of excavated rocks from the development and operations of the proposed Snowy 2.0 scheme. EMM Consulting (EMM) had been selected to prepare the Environmental Impact Statement (EIS) on behalf of SHL, and CSIRO's role is to develop and undertake a series of Assignments to provide information for environmental risk assessment associated with handling of excavated rock materials from the proposed works. In December 2017, CSIRO worked with EMM to develop conceptual models to provide information to the environmental risk assessment (ERA). As a result CSIRO agreed to undertake an initial series of five assignments.

In March 2018, Haskoning Australia (HKA) was engaged to provide additional capability, specifically to take the role of leading the project entitled: "Engineering Option for placement of Excavated Rocks". The draft work assignments CSIRO had previously provided to SHL and EMM (in late January 2018) were subsequently updated to ensure they would fulfil the needs of EIS requirements and HKA's "Engineering Option for placement of Excavated Rocks" project. These updated Assignment(s) have been executed and are providing relevant input into the ERA. This report details the results of one of the Assignments, P2: Environmental Risk Categorisation of Rock Materials.

Disclaimer

This Assignment Subcontract and all documents and information provided by CSIRO to HKA under this Assignment Subcontract are prepared (i) as inputs for further scientific services to be performed for HKA by CSIRO under separate Assignment Subcontracts that has been agreed; and (ii) to assist HKA in its development of an excavated rock disposal and management plan as part of the environmental impact assessment process for the proposed Snowy 2.0 Pumped Hydro Electric Scheme("Purpose"), and for no other purpose. This Assignment Subcontract does not involve the provision of advice or recommendations in relation to specific risks or mitigations associated with excavated rock disposal and management or design and construction of the Snowy 2.0 project however it is understood that the inputs provided by CSIRO are for the Purpose and are based on CSIRO's professional skill, care and~~,~~ diligence in performing this Assignment Subcontract. In the course of performing this Assignment Subcontract, CSIRO may rely on stated assumptions and/or information provided by HKA or third parties which is not within the control of CSIRO, and this Assignment does not involve CSIRO verifying such assumptions or information except to the extent expressly stated herein. If CSIRO provides any forecasts or projections, CSIRO does not represent that they will be realised as forecast or projected and actual outcomes may vary materially from forecast or projected outcomes. Documents and information provided to HKA under this Assignment Subcontract are to be read as a whole, and if reproduced must be reproduced in full and no part should be read or relied upon out of context. CSIRO does not accept responsibility for, or liability arising from, any error in, or omission in connection with, stated assumptions or third party-supplied information, or reliance on documents or information provided under this Assignment by HKA other than for the Purpose, or by any other person.

Contents

Figures

Tables

Acknowledgments

CSIRO would like to acknowledge the support from Haskoning Australia Pty Ltd for their assistance in acquiring information for this report.

Executive summary

This reconnaissance study investigates the weathering characteristics of rocks from the Talbingo Reservoir spillway that have been immersed for ~50 years. Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) was used to analyse transects from the inner rock to the outer surfaces to determine changes in major and trace element composition as the result of water-rock interaction. This study augments other leaching studies conducted on various rock types to better understand the risk associated with the deposition of excavated rock materials generated from the Snowy 2.0 project into Talbingo Reservoir and Tantangara Reservoir.

Results of this LA-ICP-MS-based study indicate that a range of weathering behaviours exist within the seven rocks analysed in this study with at least some of these rock samples derived from the Byron and Boraig Groups. Weathering rinds were present in all but one of seven samples, however, they were not necessarily obvious in hand specimen, natural or reflected light microscopic scale, and were only identified via the LA-ICP-MS traverse. Spillway rock orientation and depth of burial, and hence the prevailing Eh-pH environment were also likely to be key determinants in the formation and extent of a weathering rind.

A range of element behaviours were evident during formation of a weathering rind. In general, the weathering rinds were signified by an enrichment of iron (Fe) and manganese (Mn) relative to the internal rock. Spot analysis also confirmed Fe and Mn enrichment and substantial heterogeneity on the 35 to 50 µm scale within both the rind and the unaltered rock reflecting both natural mineralogical heterogeneity, as well as an inherent variability in the depth and composition of the weathering rinds. Numerous micro-fractures may also act as conduits for rock alteration.

In general, the weathering rinds constitute a net sink for a variety of elements, in particular the Rare Earth Elements (REE), and on occasion, metals and metalloids. Many of the weathering rinds contain many orders of magnitude higher concentrations of trace elements than the average internal rock. A total of 64% of the elements in all samples increased in the weathering rind (rind/unaltered ratio >1). Of these, 15 elements show an increase greater than one order of magnitude in the rinds.

In general, the Light REE (LREE) and yttrium (Y) showed a substantial and mostly consistent degree of enrichment in the weathering rinds. Similar enrichment was also apparent for the alkali earth elements beryllium (Be), magnesium (Mg), calcium (Ca), strontium (Sr) and barium (Ba) suggesting the secondary carbonate minerals may also be present in addition to likely Fe-Mn oxides or (oxy) hydroxides within the weathering rinds. The alkali metals, in particular, sodium (Na) and rubidium (Rb), but to a more variable extent potassium (K), showed a net loss within the weathering rind. Both silicon (Si) and aluminium (Al) generally behaved conservatively, while zirconium (Zr) was depleted in the weathering rind. More sporadic enrichments of transition metals such as copper (Cu) and zinc (Zn) may be present within the weathering rinds.

While a reaction rind and element enrichment did not occur in all of the rocks sampled from the Talbingo spillway, there was evidence that at least some rock types, via surface reactions following immersion had the capacity to act as a net sink for a range of trace elements. Given that the reaction rind appears to be primarily composed of Fe-Mn oxides/hydroxides and also possibly secondary carbonates and organic matter, the incorporated trace elements would be likely to be stable under the predominantly oxic, circumneutral pH conditions currently present in Talbingo Reservoir.

1 Introduction

1.1 Background and Proposal Summary

Snowy Hydro Limited (SHL) are embarking on the development of the landmark Snowy 2.0 expansion. As part of this expansion, options are being sought for the management and ultimately disposal of “excavated rock” as part of an Environmental Impact Statement (EIS) and practical engineering options for its management. There are several challenges that are associated with this expansion and a suitable, extensive, but ultimately urgent environmental assessment is necessary. To accomplish Snowy 2.0, SHL will require tunnelling between the two reservoirs, Talbingo and Tantangara, and in the process approximately 10 million m^3 of excavated rock will need to be disposed of within these two reservoirs as land-based disposal of excavated rock is not possible within the National Park, nor is it practical to remove it from the National Park. This report details results of a study of the potential long term effects of water-rock interaction on submerged excavated rocks.

Haskoning Australia Pty Ltd (HKA) have been appointed to manage and deliver an Engineering Option for excavated rock placement for Snowy 2.0. CSIRO has been requested to provide scientific insight into the environmental impacts associated with the excavated rock placement options.

1.2 Project Opportunity: Assignment P2: Environmental Rock Risk Categorisation

As the subsurface geology at a localised scale is largely unknown, a geological study (GHD & SMEC) complemented by a geochemical (Assignment P1 – *Comprehensive Geochemistry Examination* (P1)) and mineralogical characterisation (Assignment P2– *Environmental Risk Categorisation of Rock Materials* (P2)) was required to determine the composition of the materials to be extracted in the construction phase. The excavated rock will eventually need to be disposed of within the reservoirs, however, initially the excavated rock will likely be temporarily stockpiled on land and then relocated along with other materials in the reservoirs. It is required that the excavated rocks are deemed stable now and into the future so the ecological state of the environment is not compromised. In brief, Assignment P2 - *Environmental Risk Categorisation of Rock Materials* sought to assess reactivity, leachability, and potential environmental consequences of excavated rock placement on land and in reservoirs. Further details on Assignment P2: Environmental Rock Risk Categorisation are contained in Douglas et al. (2018).

1.3 Project Opportunity: Assignment P2a LA-ICP-MS Analysis of Surface Weathering Behaviour of Talbingo Reservoir Spillway Rocks

In the course of completing Snowy 2.0 Assignment P2 - Environmental Risk Categorisation of Rock Materials, an opportunity arose to sample rocks deposited ~50 years ago during construction of the spillway in Talbingo Reservoir. These samples afforded a rare opportunity to assess the nature of rock-water interaction for an extended period. In particular, any surface reaction rinds provide an insight into both the reactivity of the rock type in addition to a measure of the net gain/loss of major and trace elements during extended weathering. The outcomes of these analyses are important as it is likely that during the first years to decades of immersion that the most significant water-rock interaction on fresh rock surface created during blasting will occur. The angular nature of all of the rocks and their immediate proximity to the Talbingo spillway indicate that they were likely derived from blasting and construction activities during the construction phase approximately 50 years ago. Thus the rocks sampled here likely had fresh surfaces similar to that to be generated in the Snowy 2.0 work prior to immersion on Talbingo Reservoir.

2 Methods

2.1 Sample collection and preparation

Twelve samples of rock from the region of the Talbingo Reservoir spillway were collected. The samples were then transported after drying to CSIRO Mineral Resources, Kensington, WA. Upon receipt the rock samples were assessed at hand specimen scale and then categorised into seven groups with an emphasis on the identification of any surface weathering features. Thereafter the rocks were coated in epoxy to protect the weathering surface, orientated to ensure that both unaltered rock and the weathering rind were present in the final sample, then slabbed to a 1-2 cm thickness using a rock saw.

2.2 Analytical methods

Spillway rock sample slabs were mapped for qualitative major element variations using X-ray fluorescence (XRF) mapping. The unaltered rock and the weathering rinds were analysed using a Laser Ablation-Inductively-Coupled Plasma-Mass Spectrometer (LA-ICP-MS) to determine the difference in trace element concentrations between the weathering rind and the nominally unaltered internal portion.

The XRF mapping was conducted using a Bruker desktop microbeam XRF mapper – M4 Tornado™, at CSIRO Mineral Resources, Western Australia. The device is equipped with a rhodium X–ray tube which was set to 50 kV and 500 nA and an XFlash® silicon drift X–ray detector. Maps were created using a 40 µm spot size on a 40 µm raster with dwell times of 5 ms per pixel. Element maps represent the unquantified background corrected peak height data for Kα peaks for each element, scaled either linearly or logarithmically between minimum and maximum measured counts over the sample. The elements were then stacked in red-green-blue (RGB) coloured images to determine gain and loss of elements between the core and edges of the samples.

Trace elements were collected using a Photonmachines ATLex 300si-x Excite 193nm Excimer ArF laser with samples in a Helix-II sample cell. Two sampling routines were undertaken: 1) a rectangular beam (155* 10µm), with the long edge perpendicular to the weathering rind, was traversed at 2 µm/s from within the sample to the edge (Germinario et al., 2017; Graue et al., 2012) and, 2) a 50 µm or 35 µm circular spot was placed on the sample edge. For both the routines, the laser was set 3 J/cm^2 fluence at a rate of 9 Hz. Helium carrier gas was set at 0.6 L/min in both the cup and cell (1.2 L/min total) and was mixed with 0.7 L/min of argon (Ar) before being analysed in an Agilent 7700 ICP-MS. The plasma conditions were optimized daily, to obtain highest counts with oxide production (^{248}ThO/^{232}Th) remaining below 0.4%.

The element isotopes measured in this study were lithium-7 (^{7}Li), beryllium-9 (^{9}Be), sodium-23 (^{23}Na), magnesium-24 (^{24}Mg), ^{25}Mg, aluminium-27 (^{27}Al), silicon-29 (^{29}Si), potassium-39 (^{39}K), calcium-44 (^{44}Ca), scandium-45 (^{45}Sc), titanium-49 (^{49}Ti), vanadium-51 (^{51}V), chromium-52 (^{52}Cr), manganese-55 (^{55}Mn), iron-57 (^{57}Fe), cobalt-59 (^{59}Co), nickel-60 (^{60}Ni), copper-65 (^{65}Cu), zinc-66 (^{66}Zn), ^{68}Zn, rubidium-85 (^{85}Rb), strontium-87 (^{87}Sr), ^{88}Sr, yttrium-89 (^{89}Y), zinc-90 (^{90}Zr), molybdenum-95 (^{95}Mo), caesium-153 (^{133}Cs), barium-137 (^{137}Ba), lanthanum-139 (^{139}La), cerium-140 (^{140}Ce), praseodymium-141 (^{141}Pr), neodymium-146 (^{146}Nd), samarium-147 (^{147}Sm), europium-153 (^{153}Eu), gadolinium-157 (^{157}Gd), lead-208 (^{208}Pb). Each element was measured with a dwell time of 10 ms with major elements (Na, Mg, Al, Si and Ca) measured with 5 ms dwell. This gives a total sampling period of 0.406 seconds. For the traverses, this is equivalent to a data point every 0.812 µm.

The certified reference material was NIST-610 standard glass with an internal standard element of Si^{29}. The USGS Basaltic Glass (BCR2G) was used to assess precision and accuracy. Standards were measured at the beginning and end of the run, and every ~20 minutes of unknown analysis. Thirty seconds of background was collected at the start of each analysis. Data was reduced using Iolite software (Paton et al., 2011) using semi-quantitative methods and the quality of data is examined below.

2.3 Quality Assurance and Control

The semi-quantitative method uses the known concentrations in the standard (NIST-610) and compares the counts generated from the standard to those obtained from the unknown. These values were then converted to oxides and summed to 100%. The BCR2G was used as a secondary standard to compare the accuracy and precision of this semi-quantitative method as it has natural concentrations of trace elements. Twenty four of the 34 measured masses have an accuracy of within 10% of the recommended value. The precision was also good with 28 of the 34 measured masses varying less than 5% from the average value. Iron had poor accuracy in this comparison as theNIST-610 is nominally iron free, however, the BCR2G is primarily iron.

Table 1. USGS Basaltic Glass composition and experimental precision and accuracy.

Average	Average BCR2g_1	Normalised BCR2g_1	PUBLISHED BCR2g_1	Precision BCR2g_1	Accuracy BCR2g_1
Li_ppm_SQ_m7	7.45	9.897702	9	4%	9%
Be_ppm_SQ_m9	1.553333	2.063682	2.3	9%	-11%
Na_ppm_SQ_m23	18536.67	24626.9	23962	3%	3%
Mg_ppm_SQ_m25	16280	21628.8	21467	4%	1%
Al_ppm_SQ_m27	55080	73176.56	70913	2%	3%
Si_ppm_SQ_m29	213133.3	283158.4	254270	3%	10%
K_ppm_SQ_m39	11923.33	15840.75	14900	2%	6%
Ca_ppm_SQ_m44	37553.33	49891.5	50429	1%	-1%
Sc_ppm_SQ_m45	32.29333	42.90333	33	13%	23%
Ti_ppm_SQ_m49	10470	13909.92	14100	3%	-1%
V_ppm_SQ_m51	352.0333	467.6941	425	2%	9%
Cr_ppm_SQ_m52	12.05667	16.01789	17	13%	-6%
Mn_ppm_SQ_m55	1218.333	1618.617	1550	2%	4%
Fe_ppm_SQ_m57	36580	48598.38	96385	25%	-98%
Co_ppm_SQ_m59	30.33	40.29494	38	1%	6%
Ni_ppm_SQ_m60	9.946667	13.21465	13	2%	2%
Cu_ppm_SQ_m65	16.39667	21.7838	21	5%	4%
Zn_ppm_SQ_m66	138.6	184.1371	125	2%	32%
As_ppm_SQ_m75	0.91	1.208981		6%	
Rb_ppm_SQ_m85	37.70667	50.09521	47	2%	6%
Sr_ppm_SQ_m88	259.2333	344.4046	342	2%	1%
Y_ppm_SQ_m89	21.37667	28.39998	35	1%	-23%
Zr_ppm_SQ_m90	116.3	154.5104	184	2%	-19%
Mo_ppm_SQ_m95	206.7667	274.7	270	2%	2%
Cs_ppm_SQ_m133	0.901333	1.197467	1.16	3%	3%
Ba_ppm_SQ_m137	538.2333	715.0702	683	3%	4%
La_ppm_SQ_m139	17.55	23.31606	24.7	2%	-6%

Ce_ppm_SQ_m140	41.2	54.73628	53.3	2%	3%
Pr_ppm_SQ_m141	4.89	6.496612	6.7	2%	-3%
Nd_ppm_SQ_m146	19.63	26.07945	28.9	1%	-11%
Sm_ppm_SQ_m147	4.64	6.164475	6.59	3%	-7%
Eu_ppm_SQ_m153	1.486667	1.975112	1.97	2%	0%
Gd_ppm_SQ_m157	4.39	5.832337	6.71	6%	-15%
Pb_ppm_SQ_m208	8.97	11.9171	11	2%	8%

3 Results and Discussion

3.1 Categorisation and Selection of Rocks for XRF and LA-ICP-MS analysis

Hand specimen analysis of the Talbingo spillway rocks resulted in their classification into seven groups (Table 2, Figure 1). The seven samples selected for further XRF and LA-ICP-MS analysis in this study were numbers 2, 5, 6, 8, 10, 11 and 12, thus encompassing rock types from each of the seven hand specimen groups. The average semi-quantitative XRF composition of each rock is given in Table 3.

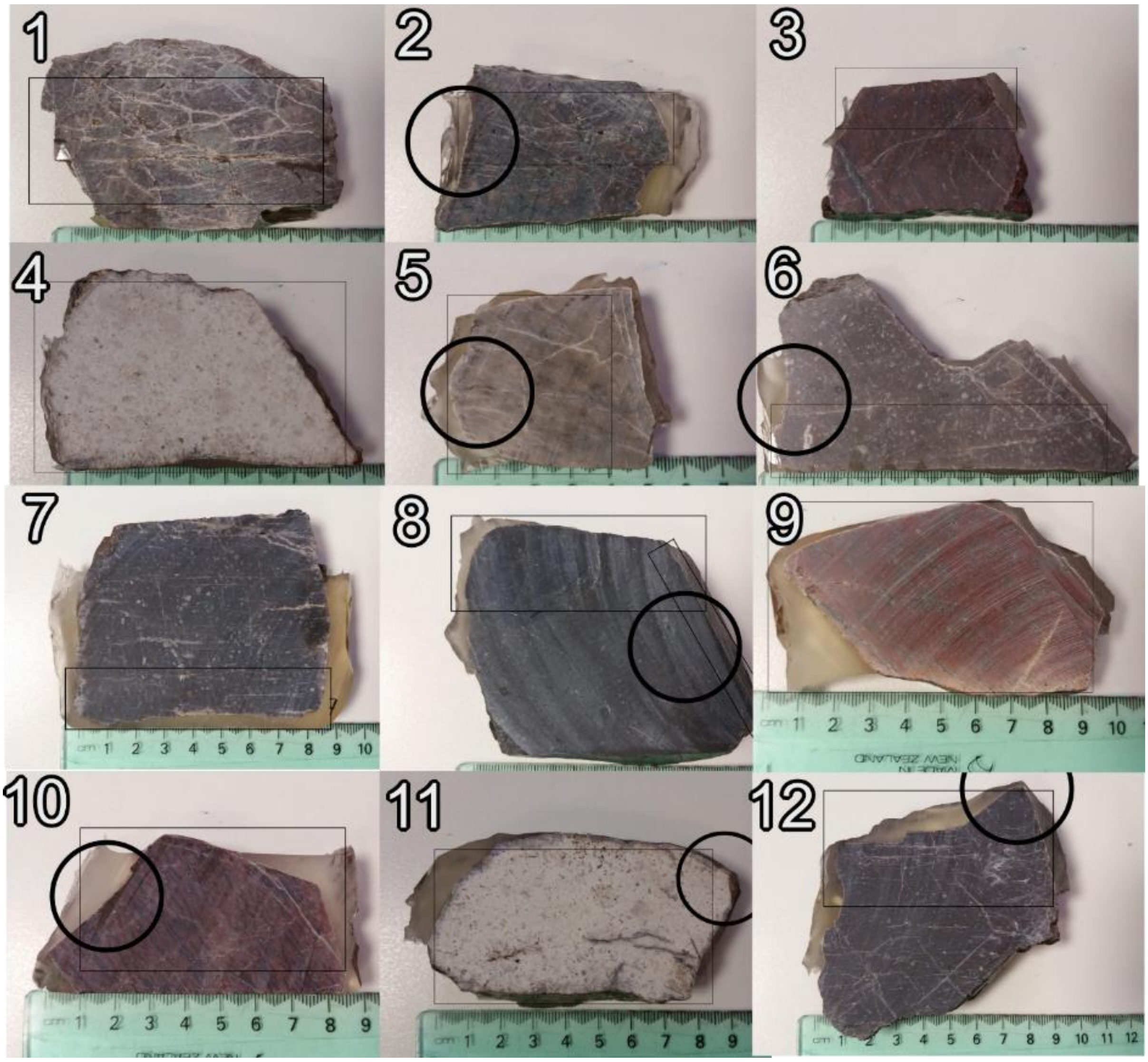

Figure 1. Slabbed sections of Talbingo spillway samples 1 to 12.

Table 2. Hand specimen classification of Talbingo spillway rocks. Samples numbers in bold italics were selected for XRF and LA-ICP-MS analysis.

Description	Samples
Silica-rich, brecciated and veined. Purple-green in colour.	1, ***2***
Maroon red with black linear features. Some veining.	3, 9, ***10***
White, powdery, felsic in appearance, some crystals visible	4,***11***
Silica-rich rock, yellow/white in appearance	***5***
Pyroclastic rock, purple matrix with visible clasts/crystals	***6***
Black rock with linear features	7, ***12***
Visible clasts, black, fine-grained, crystalline	***8***

Table 3. Semi-quantitative XRF analysis of Talbingo spillway rocks.

Sample	**2**	**5**	**6**	**8**	**10**	**11**	**12**
SiO_2	62.01	72.79	69.67	67.82	70.92	69.41	70.56
Al_2O_3	32.13	26.93	30.07	30.22	28.41	30.46	29.08
FeO	0.11	0.05	0.02	0.37	0.17	0.03	0.15
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	5.60	0.00	0.00	1.03	0.00	0.00	0.00
CaO	0.10	0.08	0.14	0.04	0.08	0.04	0.09
K_2O	0.02	0.11	0.03	0.47	0.37	0.02	0.06
TiO_2	0.02	0.03	0.05	0.06	0.05	0.03	0.05
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

The primary goal of this study concentrated on the identification and geochemical quantification of weathering rinds on a range of rock from the Talbingo spillway placed during the construction of the original Snowy Scheme. It is apparent from the composition and appearance that at least one or more of 1, 2, 3, 5, 8, 9, and 10, are likely to have been derived from the Byron and Boraig units which occur in the immediate area. Samples such as 6, 7 and 11 are likely represent acidic volcanics which occur intermittently throughout the proposed tunnel traverse.

3.2 XRF and LA-ICP-MS analysis

3.2.1 Sample 2

A false colour XRF image of Sample 2 is shown in Figure 2. This sample is dominated by Si (blue) with lesser Fe (red) as distinct irregular accumulations or along possible fractures, Ti (green) associated with Fe and K (white) as distinct accumulations. This sample contains the lowest SiO_2 and highest Al_2O_3 and MgO concentrations of the rocks analysed in this study (Table 3).

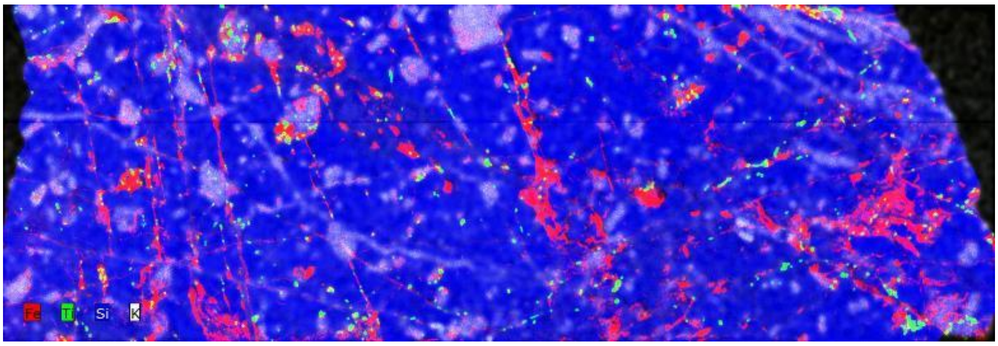

Figure 2. False colour XRF image of Sample 2.

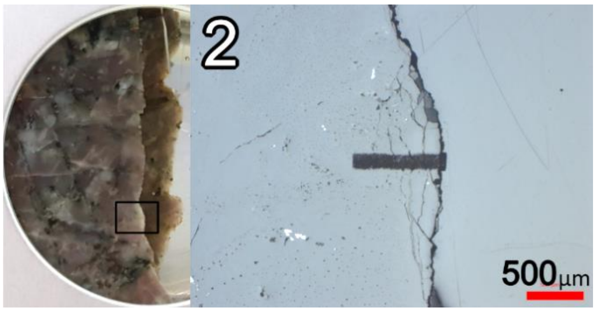

Figure 3. Sample 2 – (left) photograph of polished round with laser traverse marked with a box. (right) reflected light image of completed 550 µm LA-ICP-MS traverse.

There is no visible weathering surface in cross section for this sample (Figure 3). A traverse of 550 µm was conducted. The area between 300-450 µm was averaged to represent “unaltered” rock and compared to spot analysis (50 µm diameter) on the rim.

The data from the traverse suggests that the 50 µm closest to the edge show increases in Fe and Mn and decrease in Si (Figure 3), however, a similar signal is present deeper within the rock (200 µm). Hence, this could represent a traverse across an iron rich mineral that naturally occurs within the rock.

Comparing the average internal composition and the 50 µm circular spot on the edge of the sample (Figure 6) one of the rind spot shows a substantial enrichment in some trace elements, in particular the Light Rare Earth Elements (LREE - La, Ce, Pr, Nd), and on occasion, Y, Ti and V (Figures 4-6). Despite the enrichment of Mn and Fe and some trace elements, given the substantial internal heterogeneity of the rock, it is difficult to definitively confirm the presence of a weathering rind.

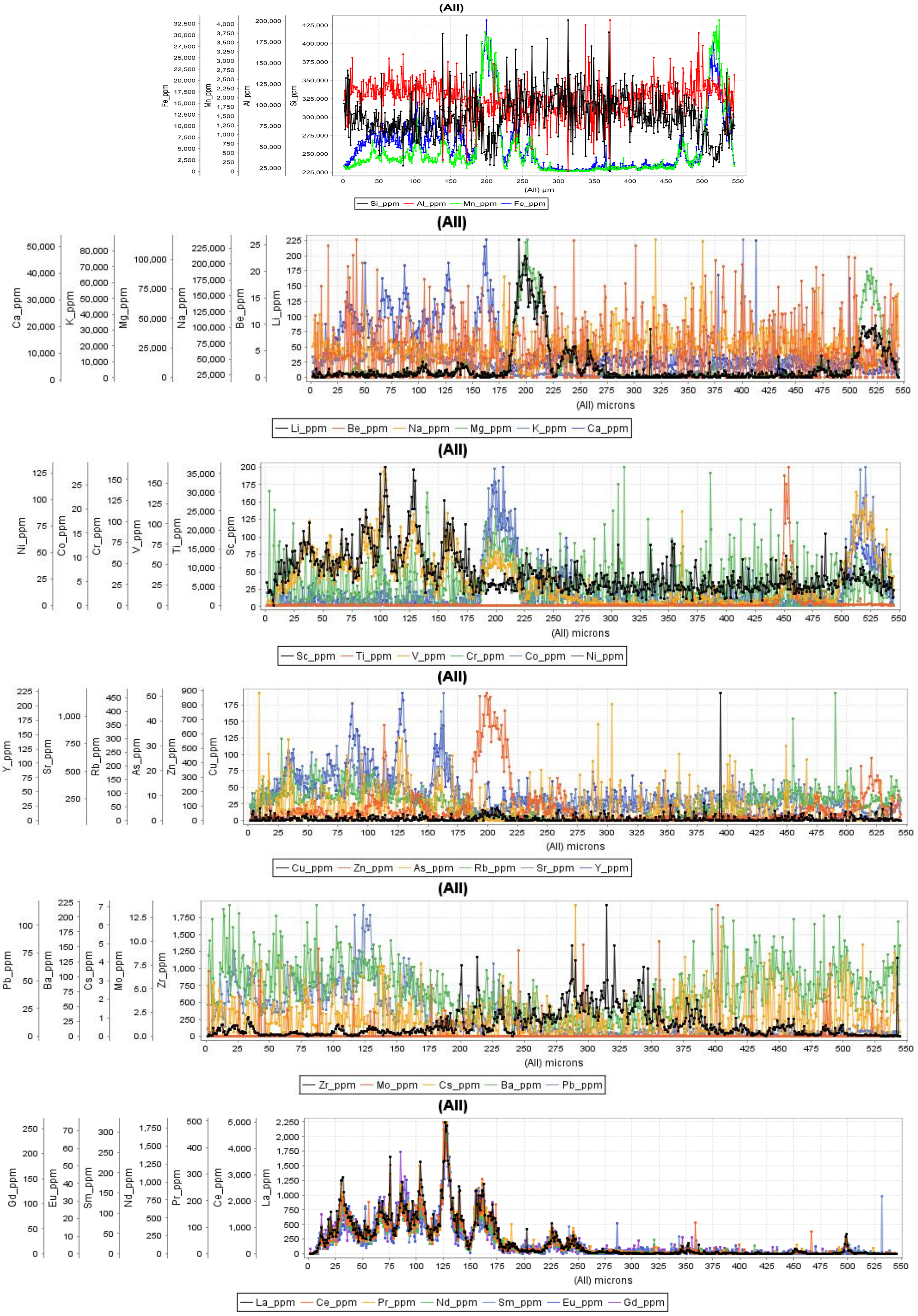

Figure 4. Sample 2 – LA-ICP-MS traverse from inner rock (left) to the surface (right).

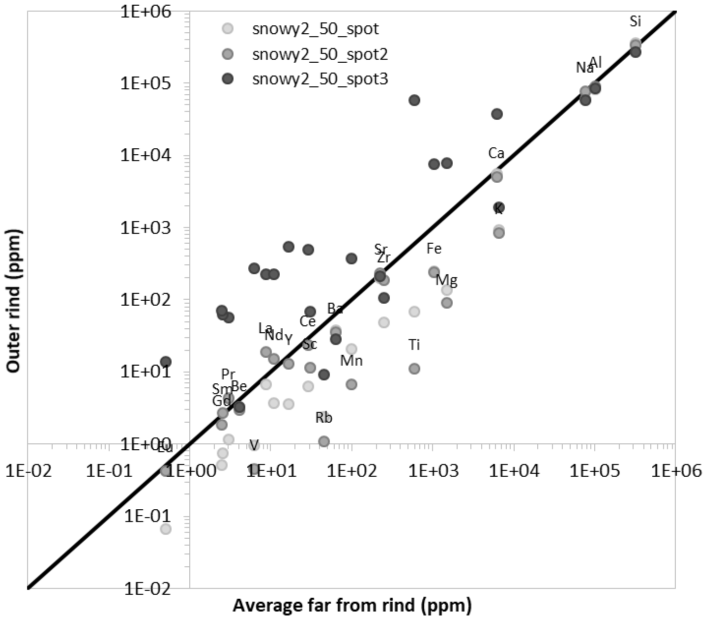

Figure 5. Sample 2 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from 50 µm diameter spots on the weathering surface. Element label is embedded within a vertical sequence of spot measurement concentrations.

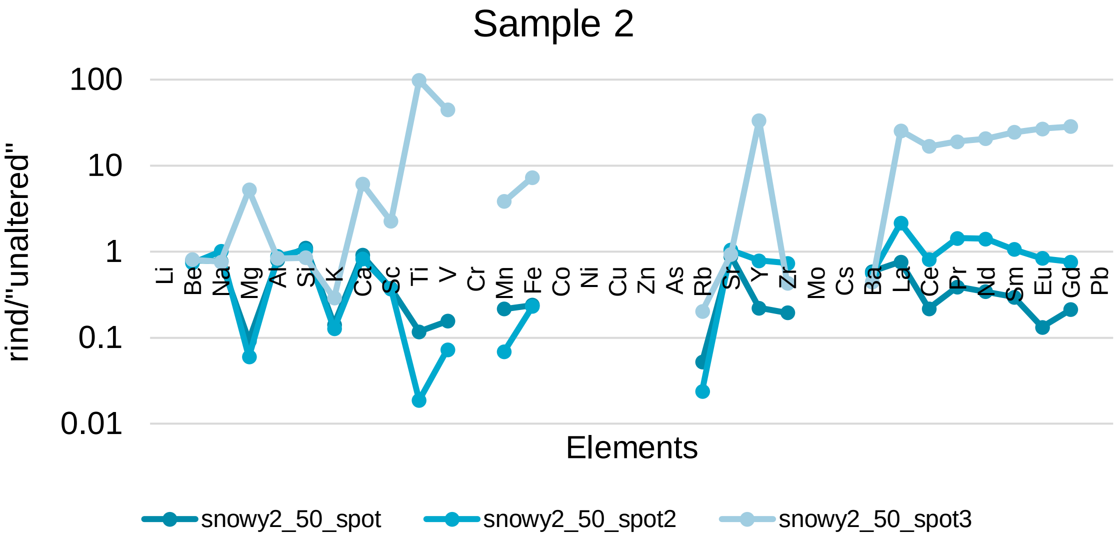

Figure 6. Sample 2 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from spots on the weathering surface. Spot size is 50 µm. Rind/unaltered ratios >1 represent elements enriched in the rind with values <1 represent element loss.

3.2.2 Sample 5

A false colour XRF image of Sample 5 is shown in Figure 7. This sample is dominated by silica (blue) with lesser iron (red), titanium (green) and potassium (white). The rock has a distinct linear fabric in addition to irregular Fe- and Ti-bearing accumulations. This sample contains the highest SiO_2 and lowest Al_2O_3 and MgO concentrations of the rocks analysed in this study (Table 3).

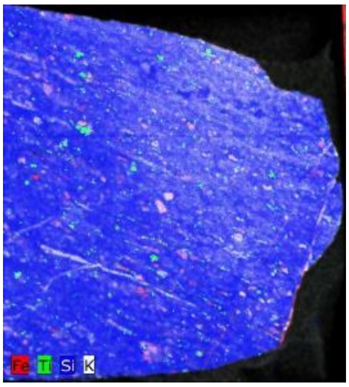

Figure 7. False colour XRF image of Sample 5.

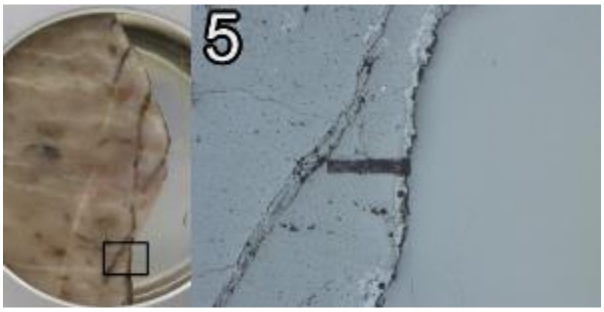

Figure 8. Sample 5 – (left) photograph of polished round with laser traverse marked with a box and (right) reflected light image of the completed 775 µm LA-ICP-MS traverse.

This sample has a visible weathering surface in the cross section when viewed with a reflected light microscope (Figure 8). The weathering surface is approximately 50-75 µm thick and is discontinuous along the edge of the rock.

The 50 µm rind spots were positioned on the visible weathering rind (Figure 9). The weathering surface has an enrichment of V, Fe and Sr with a depletion in Na, K and Rb when compared with the average composition of the unaltered whole rock (Figure 10, 11). The rare earth elements (REE) may show variable enrichment within the rock but were also enriched within the outermost 25 µm of the weathering rind.

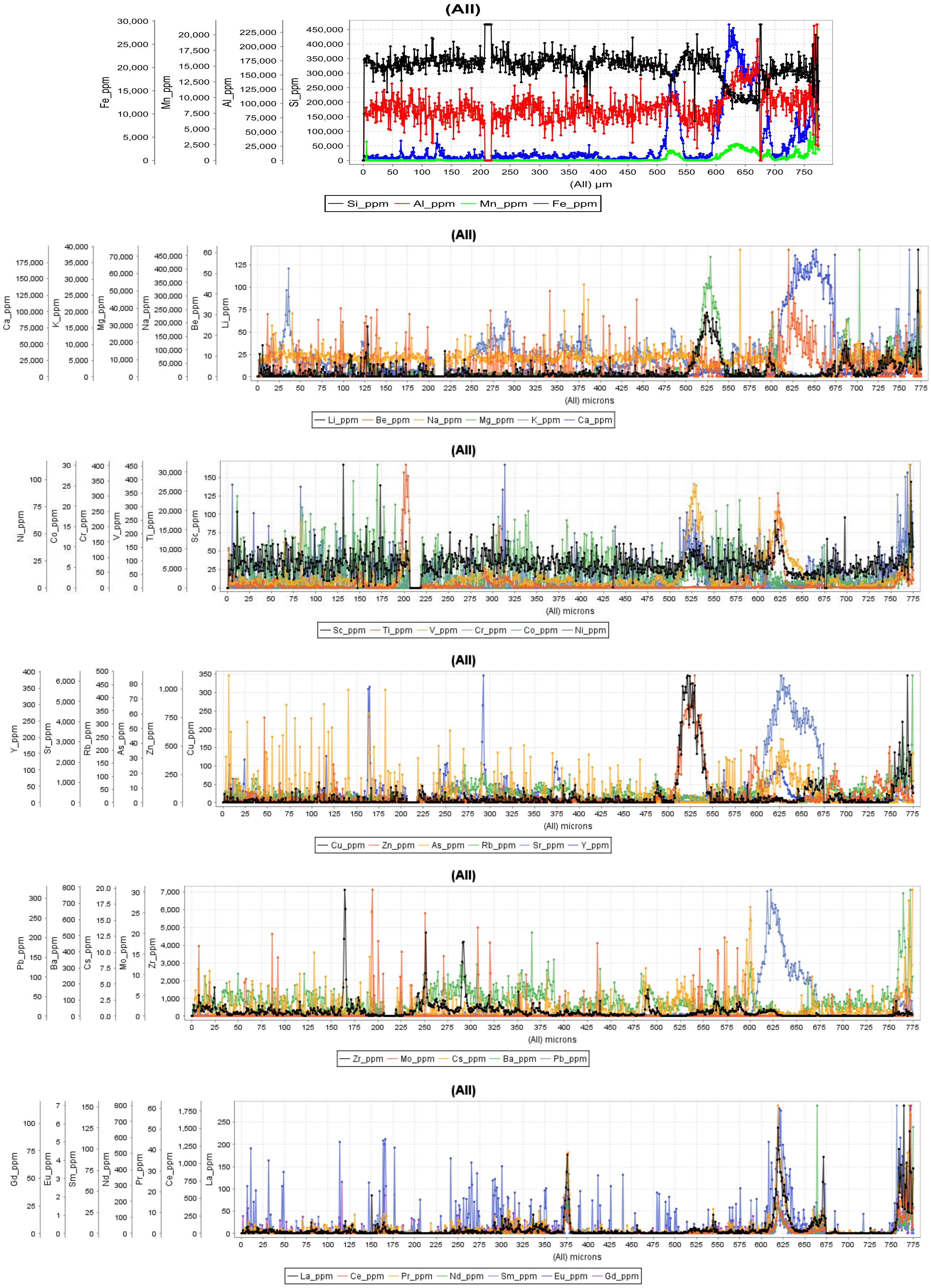

Figure 9. Sample 5 – LA-ICP-MS traverse from inner rock (left) to the surface (right).

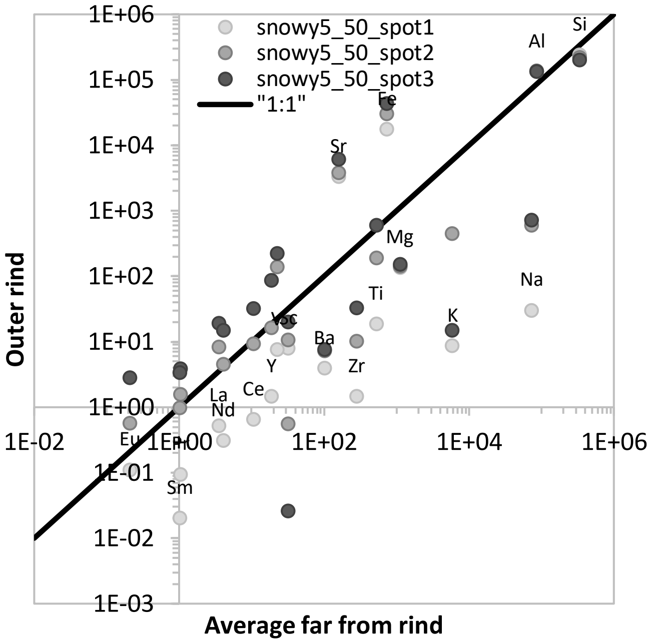

Figure 10. Sample 5 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from 50 µm diameter spots on the weathering surface. Element label is embedded within a vertical sequence of spot measurement concentrations.

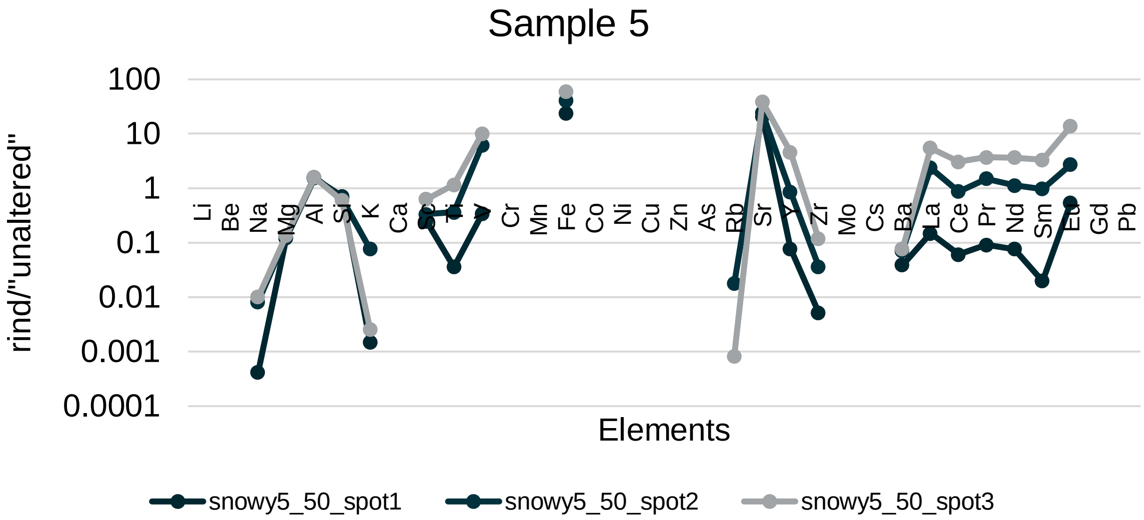

Figure 11. Sample 5 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from spots on the weathering surface. Spot size is 50 µm. Values >1 represent elements gained in the rind and values <1 represent elemental loss.

3.2.3 Sample 6

A false colour XRF image of Sample 6 is shown in Figure 12. This sample is dominated by Si (blue) with lesser Fe (red) and Ti (green), which occurs as distinct accumulations (Figure 12). A number of micro-fractures were also apparent. This sample contains the highest CaO and lowest FeO and MgO concentrations of the rocks analysed in this study (Table 3).

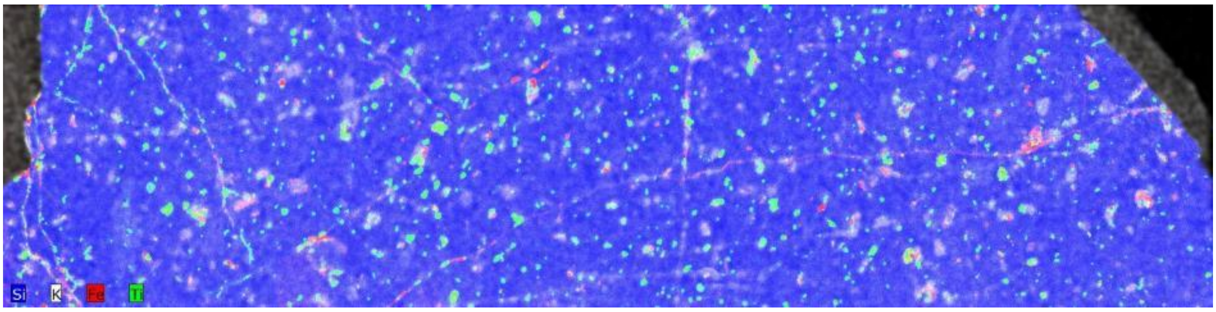

Figure 12. False colour XRF image of Sample 2.

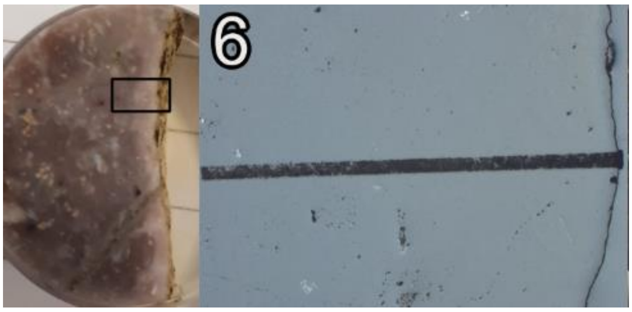

Figure 13. Sample 6 – (left) photograph of polished round with laser traverse marked with a box. (right) reflected light image of the completed 3400 µm LA-ICP-MS traverse.

This sample has a visibly paler rim, however, this is not apparent in reflected light microscopy (Figure 13). The LA-ICP-MS mapping suggests no significant changes in composition of the rock which is supported by the absence of major difference in a comparison between weathering surface spots and average of the internal rock composition (Figures 14 and 15). Nonetheless, in the last 250 µm of the traverse the trace elements become more variable, with Mn, Li, Fe and Co showing increases in concentration suggestive of a weathering rind. Of the three rind spots, only the smaller 35 µm spot shows an increase in trace element concentrations (Figure 16).

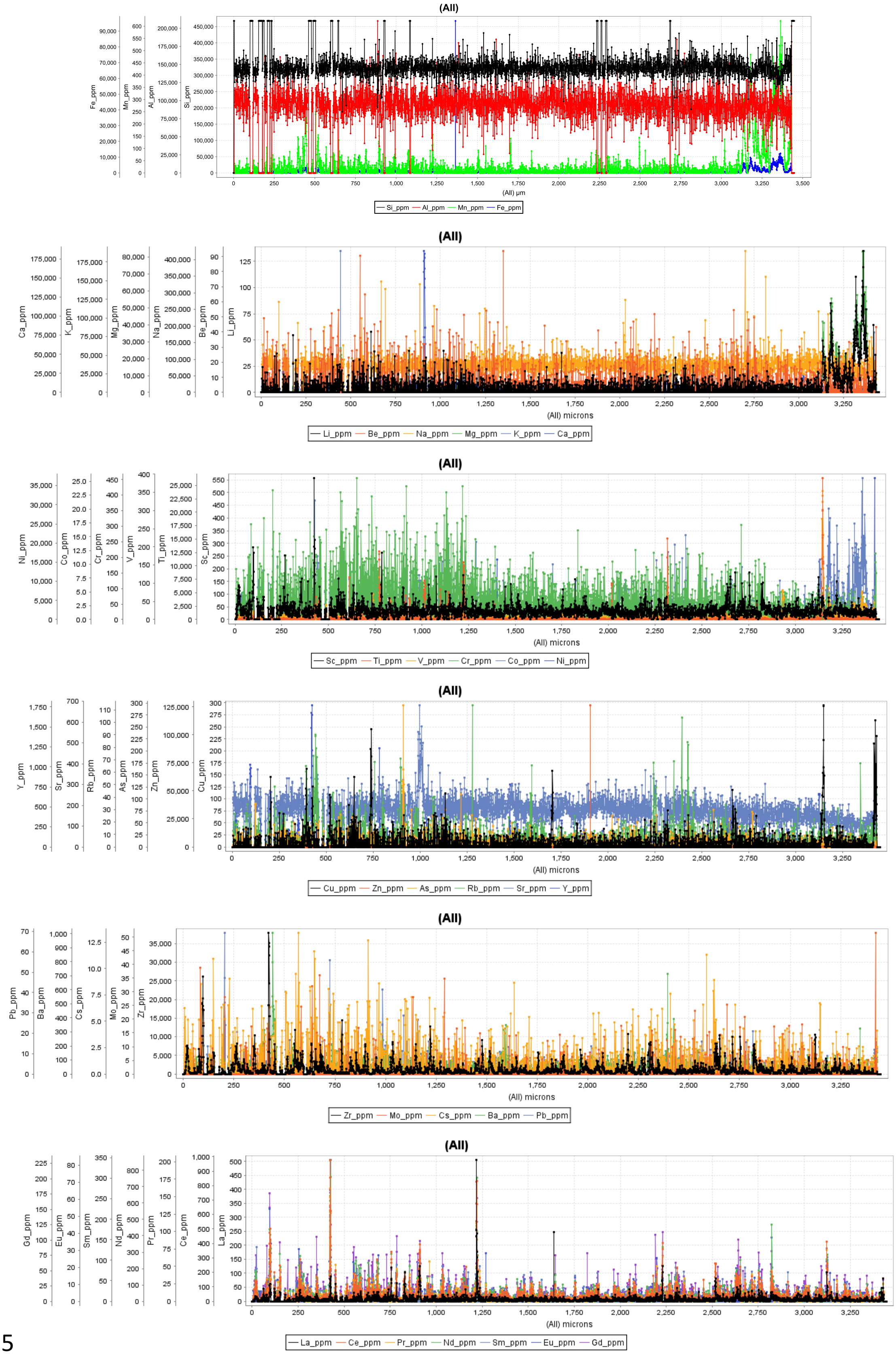

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Figure 14. Sample 6 – LA-ICP-MS traverse from inner rock (left) to the surface (right).

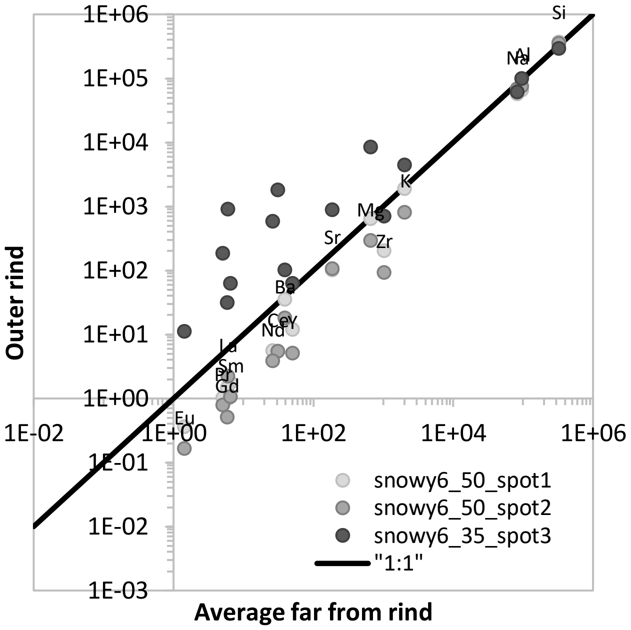

Figure 15. Sample 6 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from 35 and 50 µm diameter spots on the weathering surface. Element label is embedded within a vertical sequence of spot measurement concentrations.

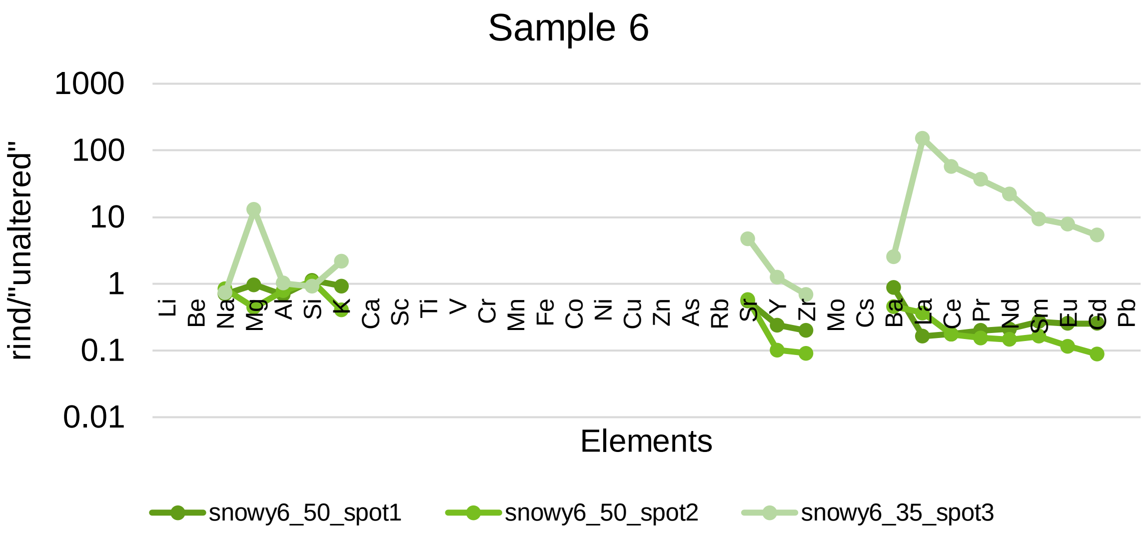

Figure 16. Sample 6 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from 50 µm diameter spots on the weathering surface. Values >1 represent elements gained in the rind and values <1 represent element loss.

3.2.4 Sample 8

A false colour XRF image of Sample 8 is shown in Figure 17. This sample is dominated by Si (blue) with substantial Fe (red) and K (white) with titanium (green). This sample contains the highest FeO and K_2O concentrations of the rocks analysed in this study (Table 3).

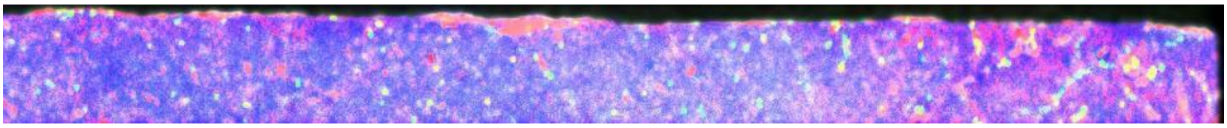

Figure 17. False colour XRF image of Sample 8.

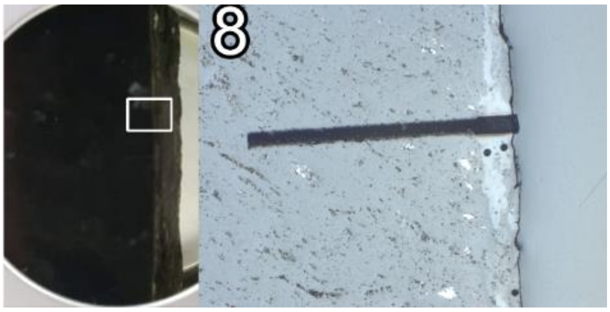

Figure 18. Sample 8 – (left) photograph of polished round with laser traverse marked with a box. (right) reflected light image of the completed 2250 µm LA-ICP-MS traverse and the LA-ICP-MS rind spots.

Sample 8 displays a narrow weathering rind which is visible in reflected light as a paler region (Figure 18) with a corresponding increase in Fe and Mn as the red and blue trace respectively trace in the upper in the XRF map (Figure 18). The LA-ICP-MS traverse across this sample shows consistent results for more than 1000 µm that changes significantly in the 250 µm closest to the surface suggestive of the presence of a weathering rind (Figure 19). A range of other elements were also enriched in the reaction rind including Ca, Sc, V, As and the LREE (La, Ce, Pr, Nd, Gd). There is a notable enrichment of the REE and Y, in addition to instances of Ca, Sr, Fe and Mn enrichment in the weathering rind relative to the whole rock composition (Figures 20 and 21).

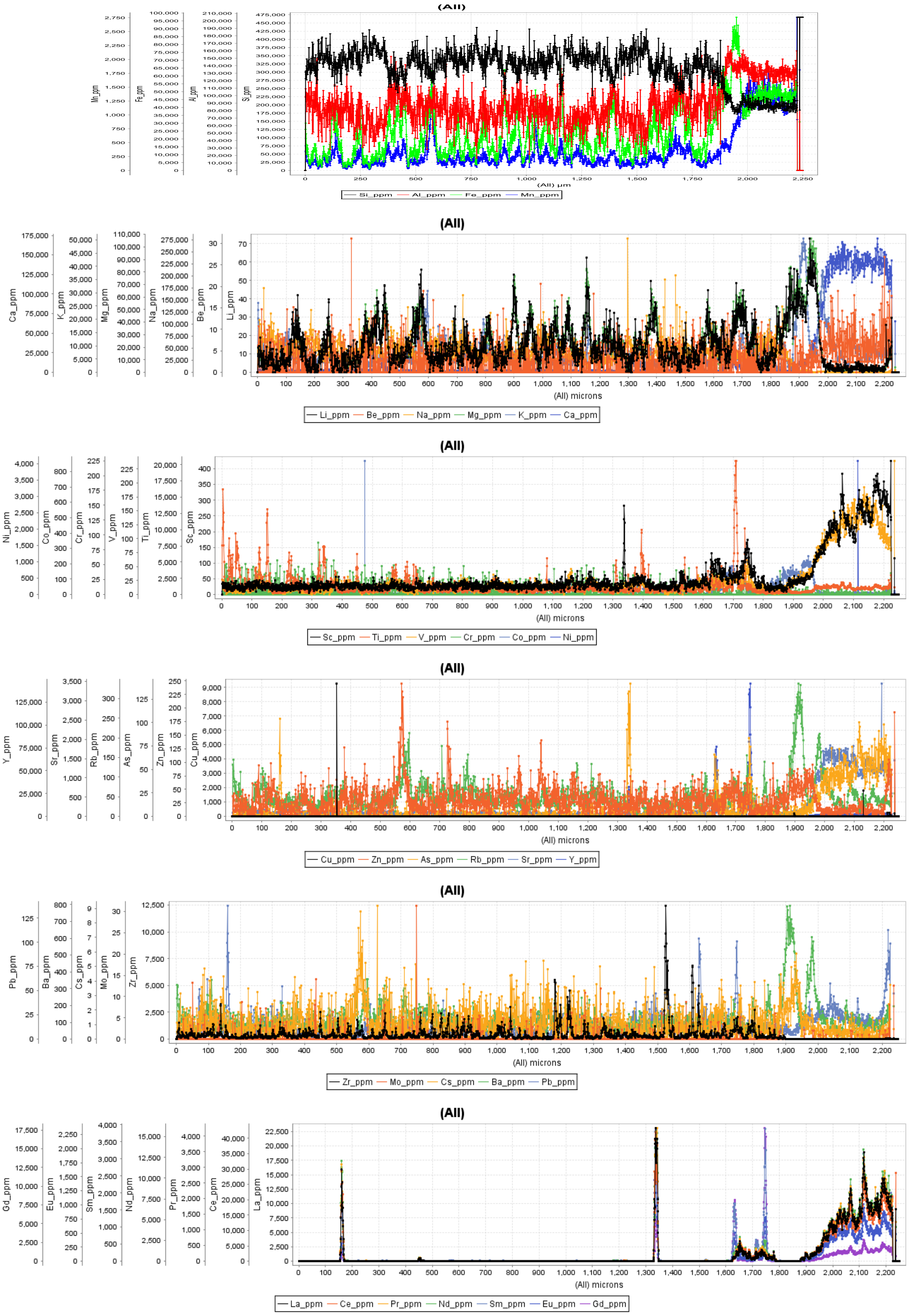

Figure 19. Sample 8 – LA-ICP-MS traverse from inner rock (left) to the surface (right).

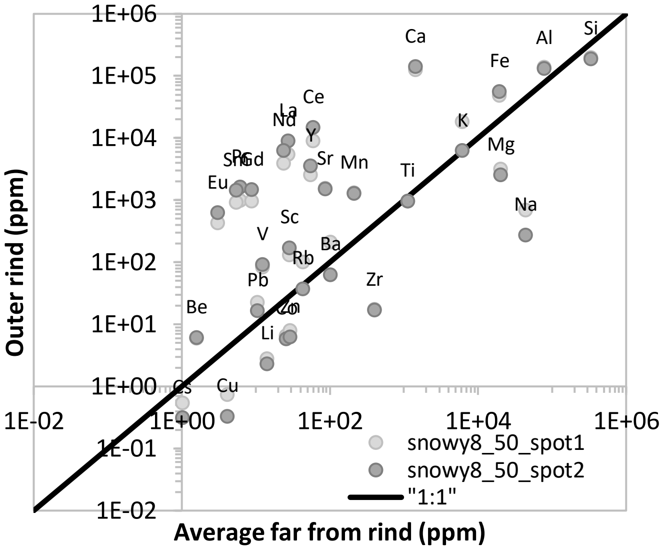

Figure 20. Sample 8 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from 50 µm diameter spots on the weathering surface. Element label is embedded within a vertical sequence of spot measurement concentrations.

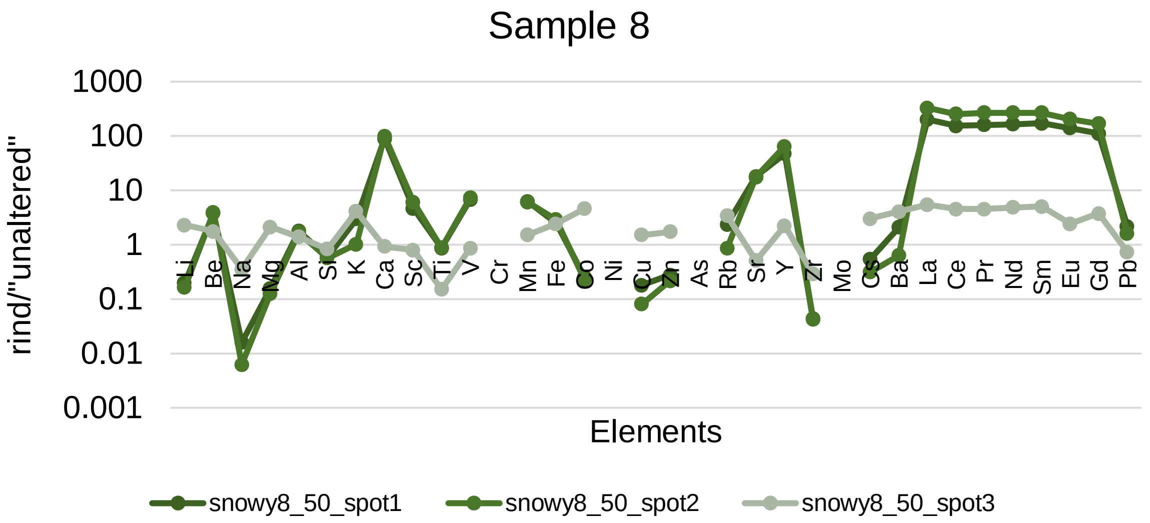

Figure 21. Sample 8 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from spots on the weathering surface. Spot size is 50 µm. Values >1 represent elements gained in the rind and values <1 represent element loss.

3.2.5 Sample 10

A false colour XRF image of Sample 8 is shown in Figure 22. This sample is dominated by Si (blue), K (white) and Fe (red) with lesser Ti (green). A fabric in the rock is cross-cut by micro-fractures containing either mostly Si or Si and Fe. This sample contains amongst the highest SiO_2 and K_2O concentrations of the rocks analysed in this study (Table 3).

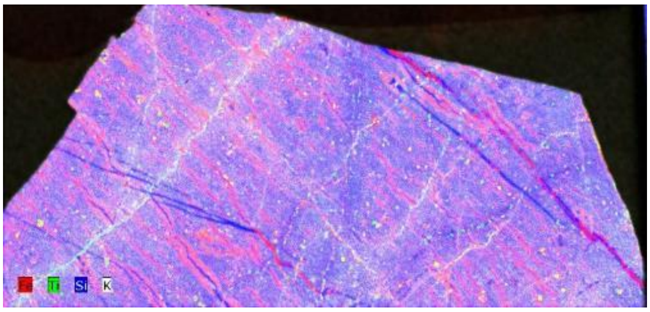

Figure 22. False colour XRF image of Sample 10.

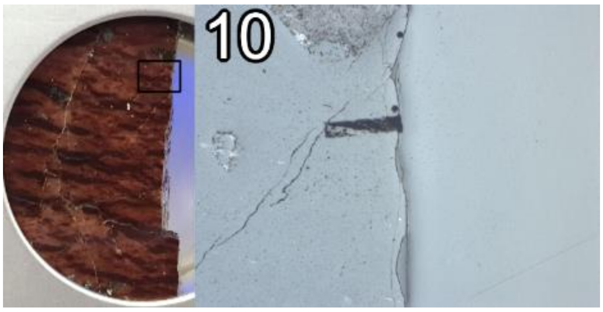

Figure 23. Sample 10 – (left) photograph of polished round with laser traverse marked with a box. (right) reflected light image of the completed 650 µm LA-ICP-MS traverse.

This sample has no visible weathering surface in cross section, either on the XRF map (Figure 22) or the reflected light images (Figure 23). In contrast, however, there is a substantial change in the LA-ICP-MS signal over the last 20 µm of the traverse (Figure 24) with a substantial enrichment in Fe, Mn and Mg in particular suggesting the presence of a weathering rind. Trace element enrichments were also apparent in Cu, Zn, Ni, V, and Ba. In contrast to other spillway samples, no enrichments in the REE were apparent (Figures 24-26).

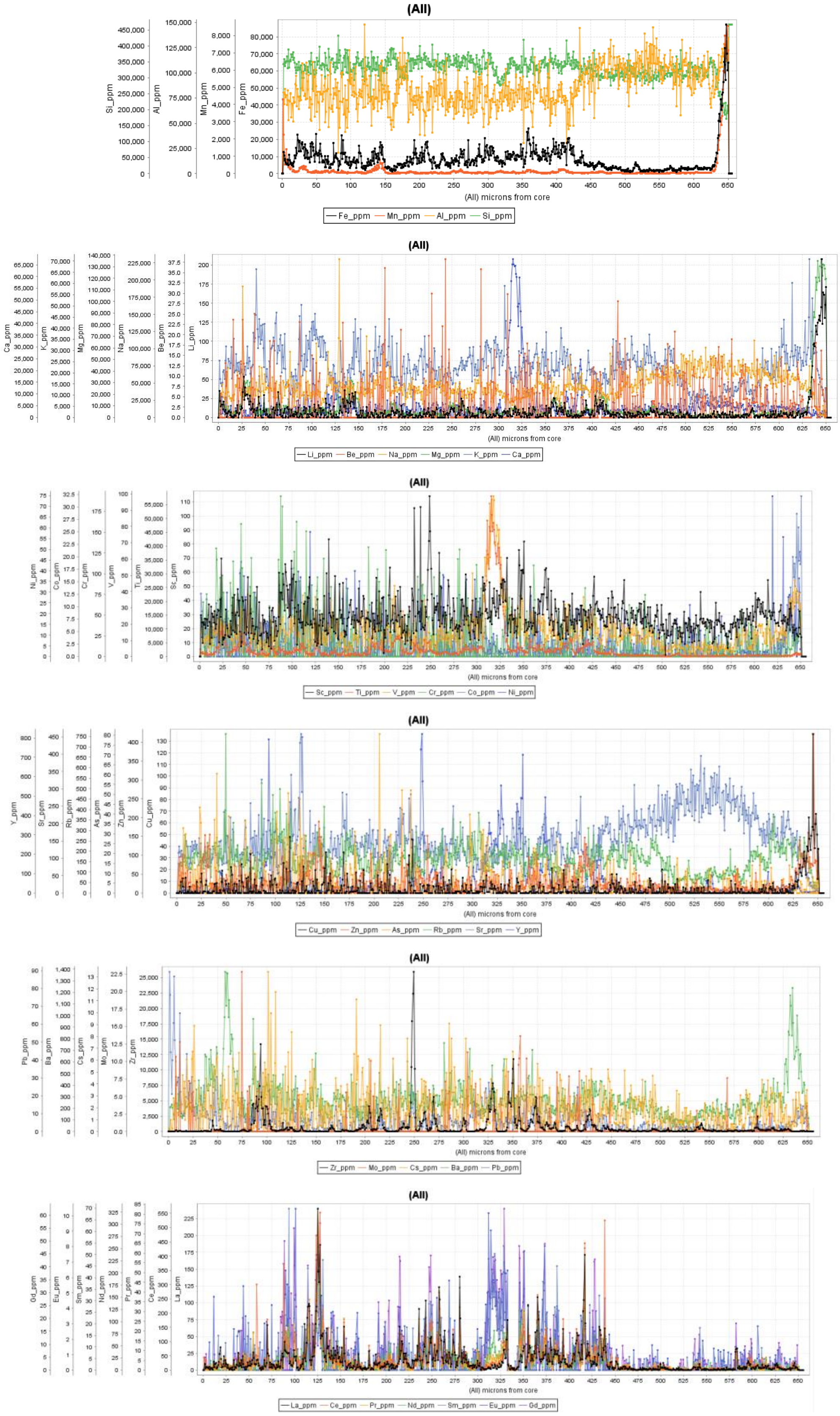

Figure 24. Sample 10 – LA-ICP-MS traverse from inner rock (left) to the surface (right).

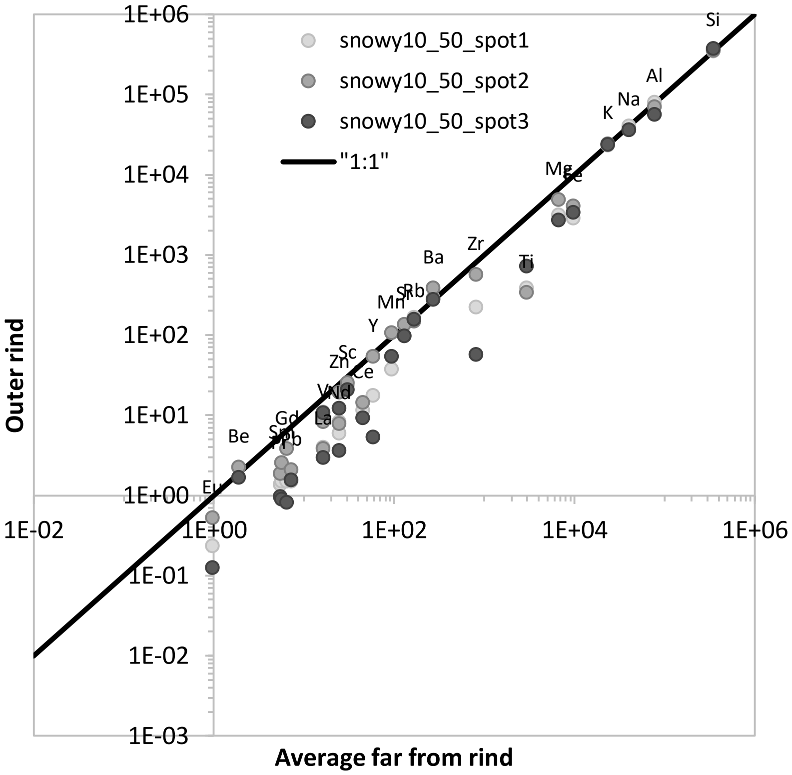

Figure 25. Sample 10 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from 50 µm diameter spots on the weathering surface. Element label is embedded within a vertical sequence of spot measurement concentrations.

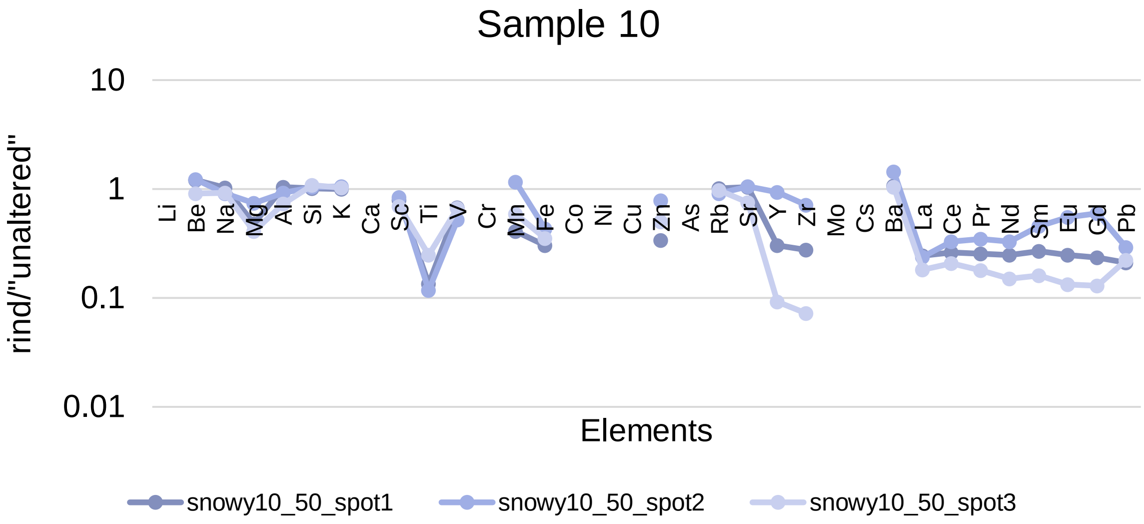

Figure 26. Sample 10 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from spots on the weathering surface. Spot size is 50 µm. Values >1 represent elements gained in the rind and values <1 represent element loss.

3.2.6 Sample 11

A false colour XRF image of Sample 8 is shown in Figure 27. This sample is dominated by silica (blue) with lesser iron (red) and titanium (green) while K occurs in discrete, often globular accumulations within the mostly siliceous matrix. This sample contains amongst the lowest FeO and K_2O concentrations of the rocks analysed in this study (Table 3).

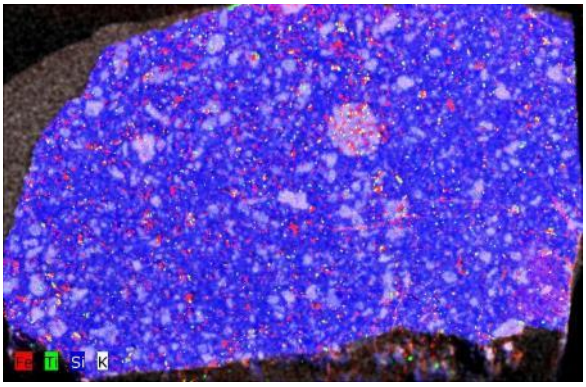

Figure 27. False colour XRF image of Sample 11.

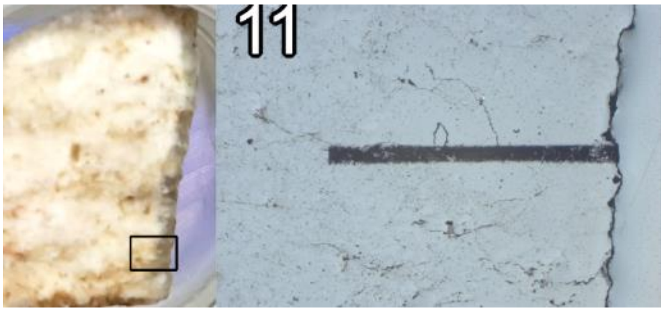

Figure 28. Sample 11 – (left) photograph of polished round with laser traverse marked with a box. (right) reflected light image of the completed 2300 µm LA-ICP-MS traverse.

Although there is no visible weathering surface in cross section, in the XRF map and the reflected light images, the LA-ICP-MS traverse shows an increase in Mn and Fe within the 25 µm closest to the surface consistent with the presence of a weathering rind. A similar Ca enrichment is also apparent while the trace elements including As and Ba may also be enriched (Figures 29 to 31). While REE may be enriched in the weathering rind, higher REE concentrations may also occur sporadically along the LA-ICP-MS traverse (Figure 29).

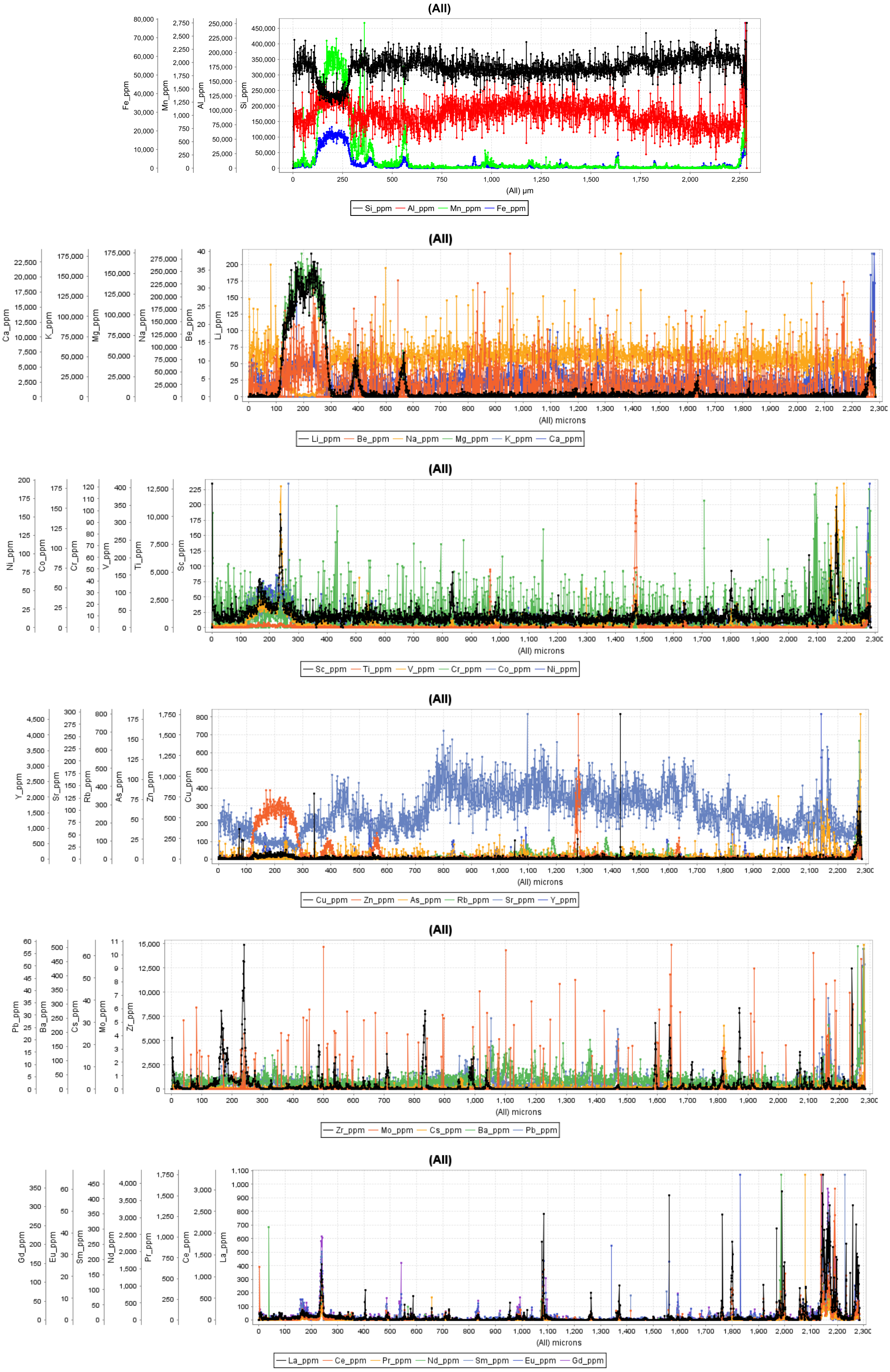

Figure 29. Sample 11 – LA-ICP-MS traverse from inner rock (left) to the surface (right).

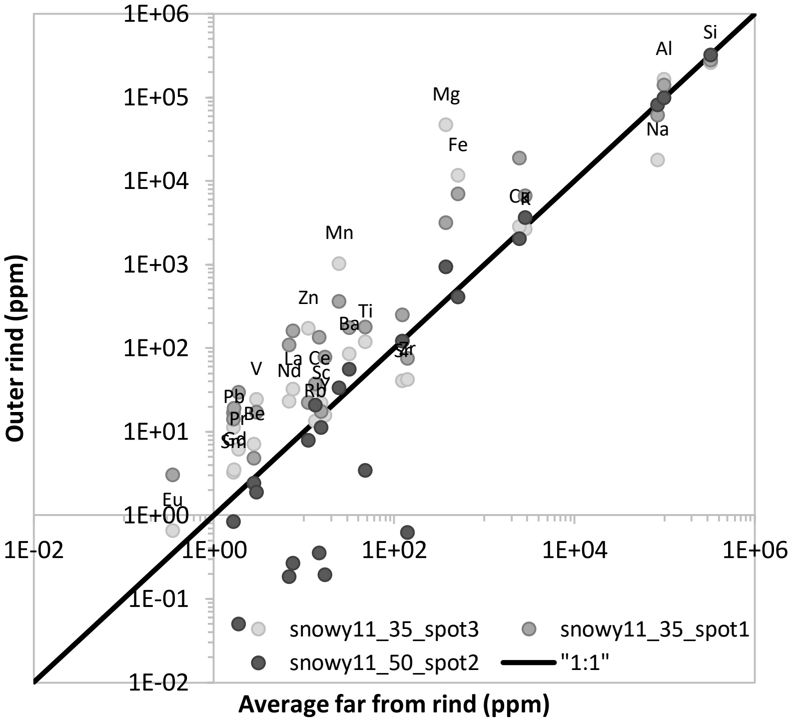

Figure 30. Sample 11 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from 50 µm diameter spots on the weathering surface. Element label is embedded within a vertical sequence of spot measurement concentrations.

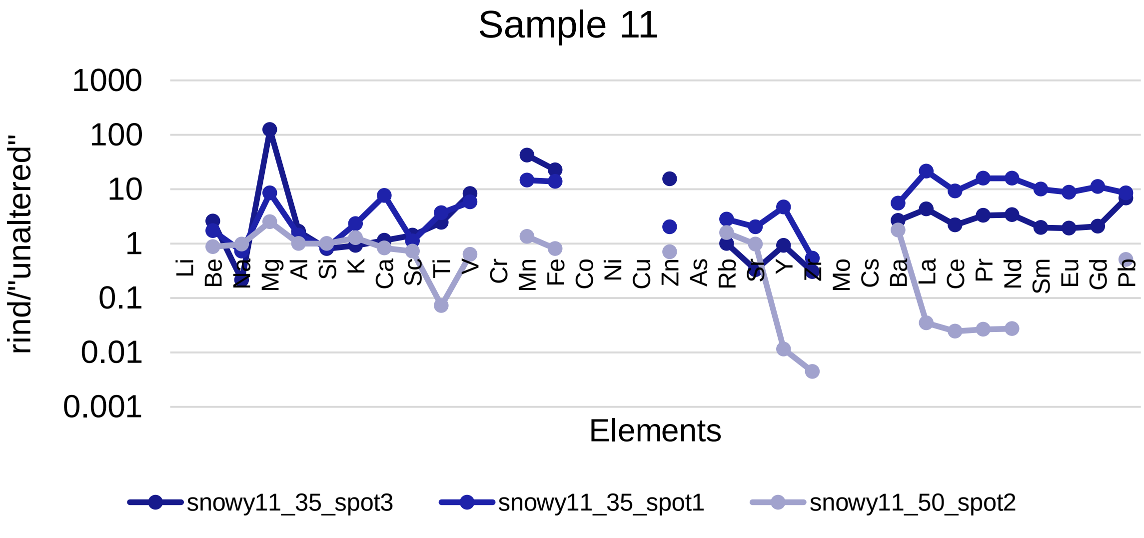

Figure 31. Sample 11 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from 50 µm diameter spots on the weathering surface. Values >1 represent elements gained in the rind and values <1 represent element loss.

3.2.7 Sample 12

A false colour XRF image of Sample 12 is shown in Figure 32. This sample is dominated by silica (blue), Fe (red), and to a lesser extent K (white) as alternating layers of relative enrichment, while Ti (green) may occur as irregular accumulations. This sample contains amongst the highest SiO_2 and FeO and lowest K_2O concentrations of the rocks analysed in this study (Table 3).

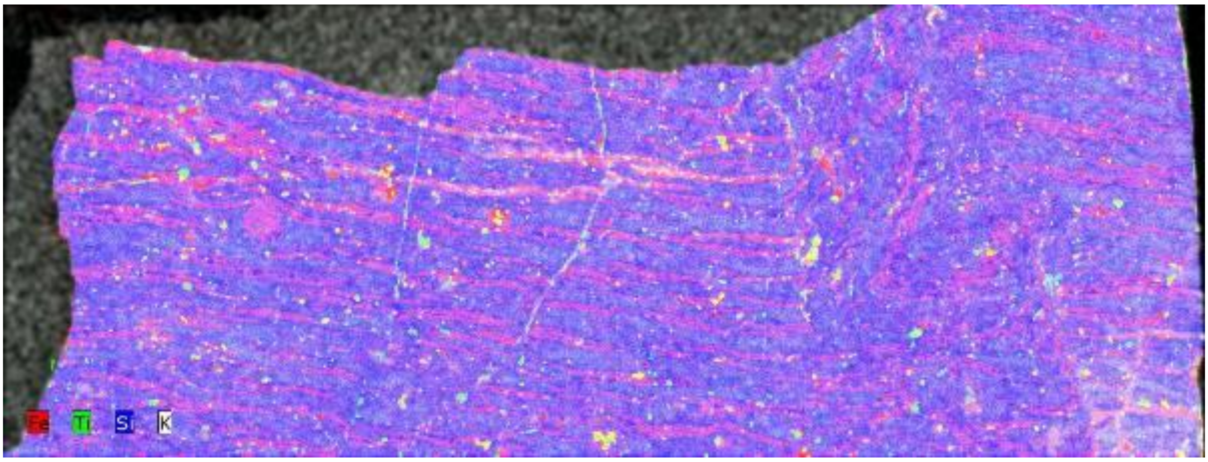

Figure 32. False colour XRF image of Sample 12.

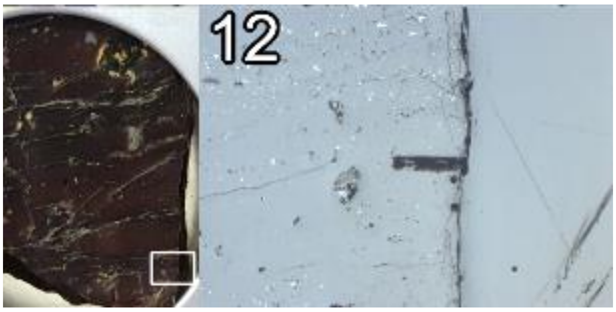

Figure 33. Sample 12 – (left) photograph of polished round with laser traverse marked with a box. (right) reflected light image of the completed 625 µm LA-ICP-MS traverse.

There is no visible weathering surface in the cross section of this sample in either XRF mapping (Figure 32) or reflected light (Figure 33). The LA-ICP-MS traverse (Figure 34) shows an increase in a range of major (Fe, Mn and Ca) trace (Cu, Zn, Ba and the REE) elements in the last 25-50 µm. Spot analysis suggests a more heterogeneous distribution of elements, however, for the majority of the cases Mg, and in all cases the REE, were enriched within a weathering rind (Figures 35 and 36).

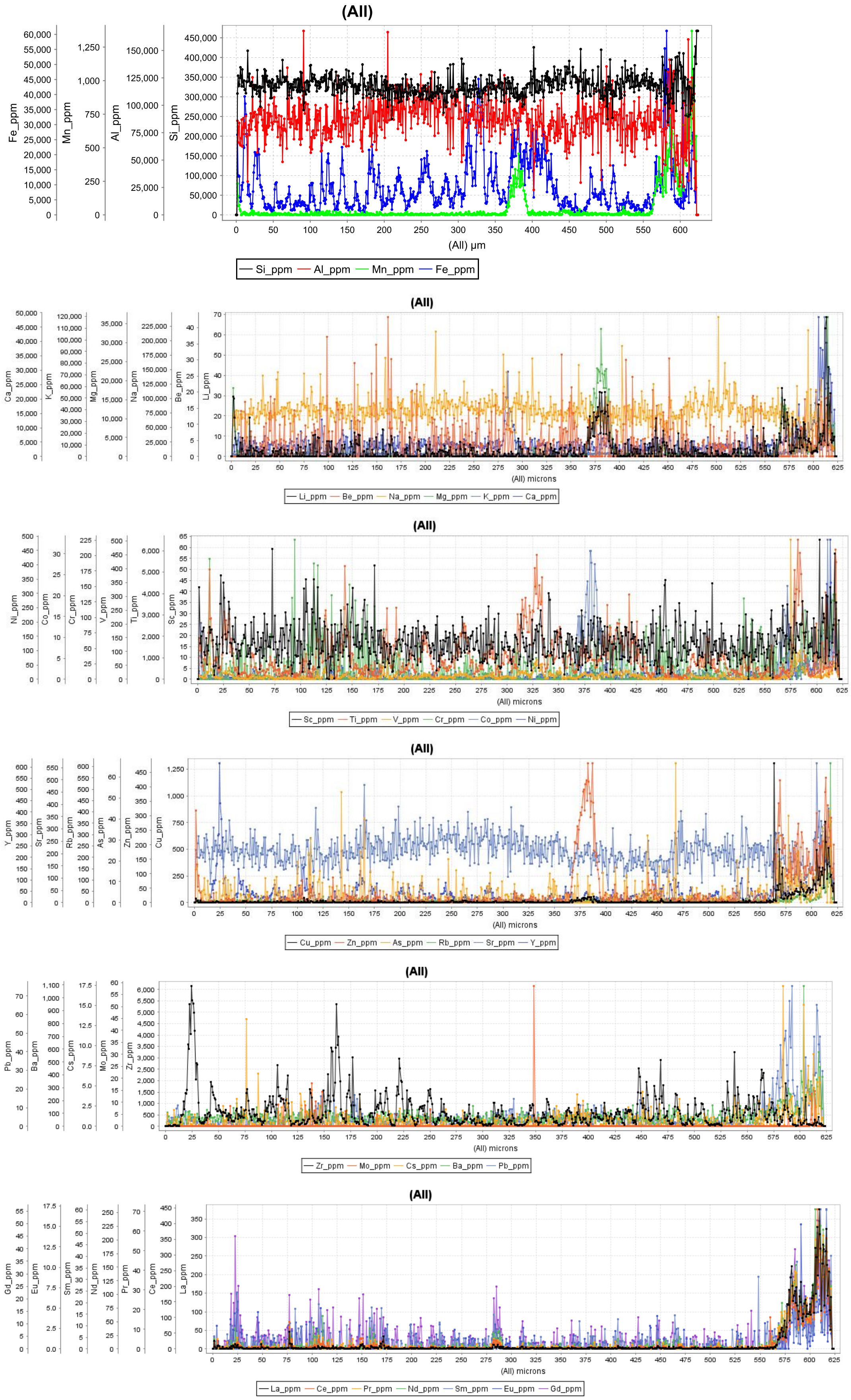

Figure 34. Sample 12 – LA-ICP-MS traverse from inner rock (left) to the surface (right).

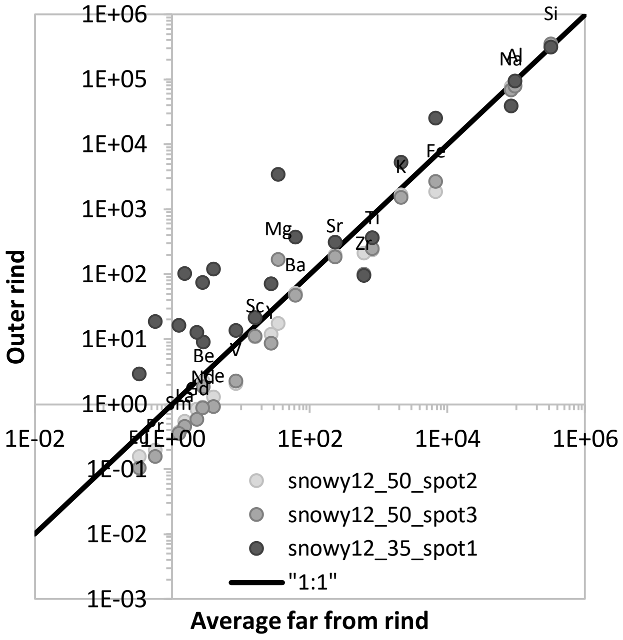

Figure 35. Sample 12 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from 50 µm diameter spots on the weathering surface. Element label is embedded within a vertical sequence of spot measurement concentrations.

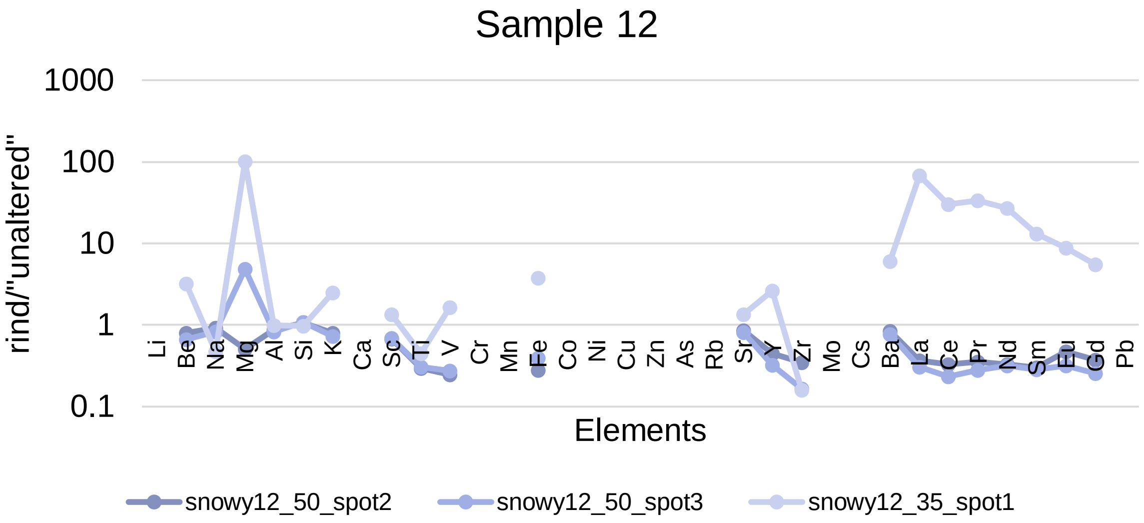

Figure 36. Sample 11 – Comparison of the semi-quantitative LA-ICP-MS data averaged from the "unaltered" profile with data collected from 50 µm diameter spots on the weathering surface. Values >1 represent elements gained in the rind and values <1 represent elemental loss.

4 Summary

A summary of the composition of weathering rinds in comparison to unaltered rocks for the seven samples examined in this study is shown in Figure 37. Weathering rinds were present in all but sample 2, however, were not always visible in hand specimen, or under natural or reflected light microscopy. The weathering rinds, however, could be detected using the LA-ICP-MS geochemical traverse across sample core to edge. The orientation of the rock fragment in the spillway and its depth of burial within the rock pile, features which control the prevailing Eh-pH environment, may be key determinants in the formation of the weathering rinds.

A range of element behaviours were evident in relation to the formation of a weathering rind. In general, the weathering rinds were signified by an enrichment of Fe and Mn relative to the internal, unaltered rock. Spot analysis also confirmed Fe and Mn enrichment and also substantial heterogeneity on the 35 to 50 um scale within both the rind and the unaltered rock reflecting both natural mineralogical heterogeneity at this scale, as well as an inherent variability in the depth and composition of the weathering rinds. Numerous micro-fractures act as conduits for rock alteration, resulting in local heterogeneity.

In general, the weathering rinds constitute a net sink for a variety of elements, in particular the REE, and on occasion, metals and metalloids. Many of the weathering rinds contain many orders of magnitude higher concentrations of trace elements than the average internal rock. A total of 64% of the elements in all samples increased in the weathering rind (rind/unaltered ratio >1). Of these, 15 elements show an increase greater than one order of magnitude in the weathering rinds.

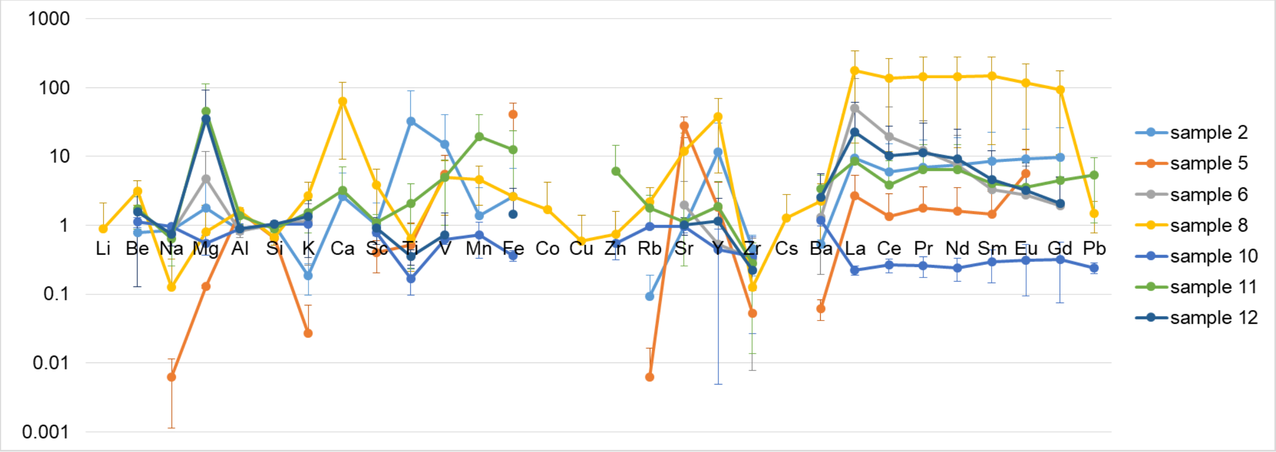

Figure 37. A comparison between the average concentration in the rind and the "unaltered" rock. Ratios >1 represent elements enriched in the rind and <1 represents a loss in the rind.

In general, the LREE and Y showed a substantial and mostly consistent degree of enrichment in the weathering rinds in all but sample 10. Similar enrichment was also apparent for the alkali earth elements Be, Mg, Ca, Sr and Ba suggesting the secondary carbonate minerals may also be present in addition to likely Fe-Mn oxides or (oxy) hydroxides within the weathering rinds. The alkali metals, in particular, Na and Rb, but to a more variable extent K, showed a net loss within the weathering rind. Both Si and Al generally behaved conservatively, while Zr was depleted in the weathering rind. More sporadic enrichments of transition metals such as Cu and Zn may be present within the weathering rinds.

While a reaction rind and element enrichment does not occur in all of the rocks sampled from the Talbingo Reservoir spillway, there is evidence that at least some rock types, via surface reactions following immersion have the capacity to act as a net sink for a range of trace elements. Given that the reaction rind appears to be primarily composed of Fe-Mn oxides/hydroxides and also possibly secondary carbonates and organic matter (e.g. Adhikari et al, 2019), the incorporated trace elements would be likely to be stable under the predominantly oxic, circumneutral pH conditions currently present in Talbingo Reservoir water.

5 References

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