APPENDIX O.1

PALEOZOIC GEODIVERSITY ASSESSMENT

Palaeozoic Geodiversity assessment

Snowy 2.0 Main Works

Prepared for Snowy Hydro Limited
September 2019

EMM
creating opportunities

Palaeozoic Geodiversity assessment

Snowy 2.0 Main Works Environmental Impact Statement

Report Number

J17188 RP#1

Client

Snowy Hydro Limited

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Prepared by

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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 Palaeozoic Geodiversity 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.

Snowy 2.0 Main Works is shown in Figure 1.1. If approved, the Snowy 2.0 Main Works would commence before completion of Exploratory Works.

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 (DEE) 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 DEE. 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 (LGAs).

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 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 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 Tantangara and Talbingo 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;
- **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, although the disturbance footprint for the project during construction is less than 0.25% of the total KNP area. 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 Chapter 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 1.1. 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;
- KNP, within which the majority of the project area is located. 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.

1.3 Proponent

Snowy Hydro 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 this report

This Palaeozoic Geodiversity Assessment supports the EIS for the Snowy 2.0 Main Works. It reviews the Palaeozoic geology of the region (extending from approximately 465 to 393 million years ago) and documents 40 sites of geodiversity significance within this age range, grouping these according to whether they are directly, or potentially, or unlikely to be, impacted by construction within the disturbance footprint. Ten of these sites were previously listed in the Plan of Management for Kosciuszko National Park (NPWS 2006) and the Kosciuszko National Park Geodiversity Action Plan 2012-2017 (OEH 2012). The remaining thirty sites are newly identified from the scientific literature. Recommendations for management measures specific to each site or potential locality are presented that are designed to avoid and minimise associated impacts. The majority of sites identified in this survey are not impacted by the Main Works, but are included because they were not previously identified in geodiversity surveys conducted for Kosciuszko National Park. Their inclusion in this study gives confidence that no unforeseen impacts to the Palaeozoic geodiversity of the region will arise during the course of the Snowy 2.0 Main Works.

The specific objectives of this assessment are to:

- describe the existing Palaeozoic geodiversity values as identified in the KNP Plan of Management (NPWS 2006) and the associated KGAP study (OEH 2012);
- identify and assess the potential for presence of previously unrecognised Palaeozoic geodiversity sites;
- identify impacts arising from the Snowy 2.0 Main Works on these sites; and
- recommend site-specific mitigation measures to reduce the impacts from the project on Palaeozoigeo diversity sites wherever possible

Note that an accompanying report (Troedson 2019) deals specifically with geodiversity sites of Cenozoic (66 million years to the present) age.

i Assessment guidelines and requirements

This Palaeozoic Geodiversity 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 this assessment and where they are addressed in this report.

Table 1.1 Relevant matters raised in SEARs

Requirement	Section addressed
Assessment of impacts of the project on: • The geodiversity values of the site, including potential impacts on Karst systems, fossil beds and boulder streams;	3.1–3.6, 4.1–4.3, and Appendix (section 2)

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:

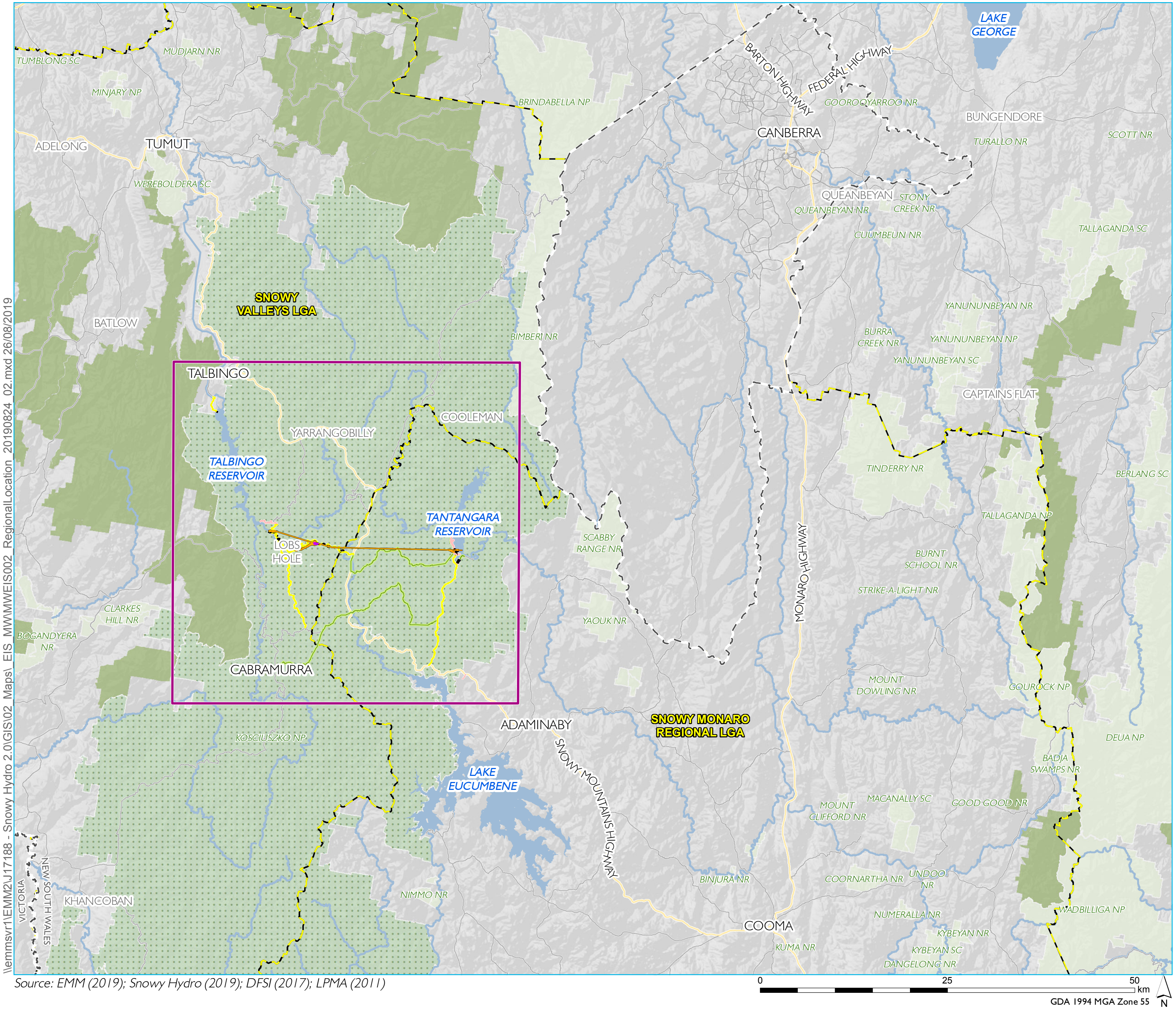
- Snowy 2.0 Exploratory Works (SSI-9208) – a Snowy Hydro project with Minister's approval;
- Snowy 2.0 Transmission Connect Project (SSI-9717) – a project proposed by TransGrid; and
- Snowy 2.0 – Segment Factory (SSI-10034) – a project proposed by Snowy Hydro.

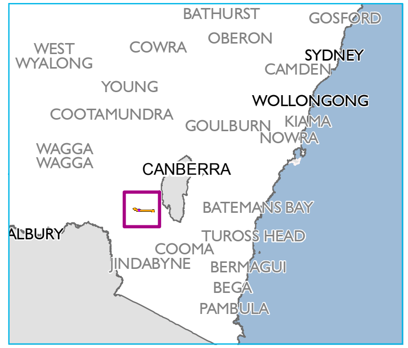
While these projects form part of the CSSI declaration for Snowy 2.0 and Transmission Project, they do not form part of Snowy Hydro's application for Snowy 2.0 Main Works. These related projects are subject to separate application and approval processes. Staged submission and separate approval is appropriate for a project of this magnitude, due to its complexity and funding and procurement processes. However, cumulative impacts have been considered in this report where relevant.

1.6 Other relevant reports

This Palaeozoic Geodiversity assessment has been prepared with reference to other technical reports that were prepared as part of the Snowy 2.0 Main Works EIS. The other relevant reports referenced in this Palaeozoic Geodiversity assessment are listed below.

- Groundwater assessment (EMM 2019)
- Noise and vibration impact assessment (EMM 2019)
- Cenozoic Geodiversity assessment (Troedson 2019)
- Water assessment (EMM 2019)





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

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KEY

- Project area

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

Existing environment

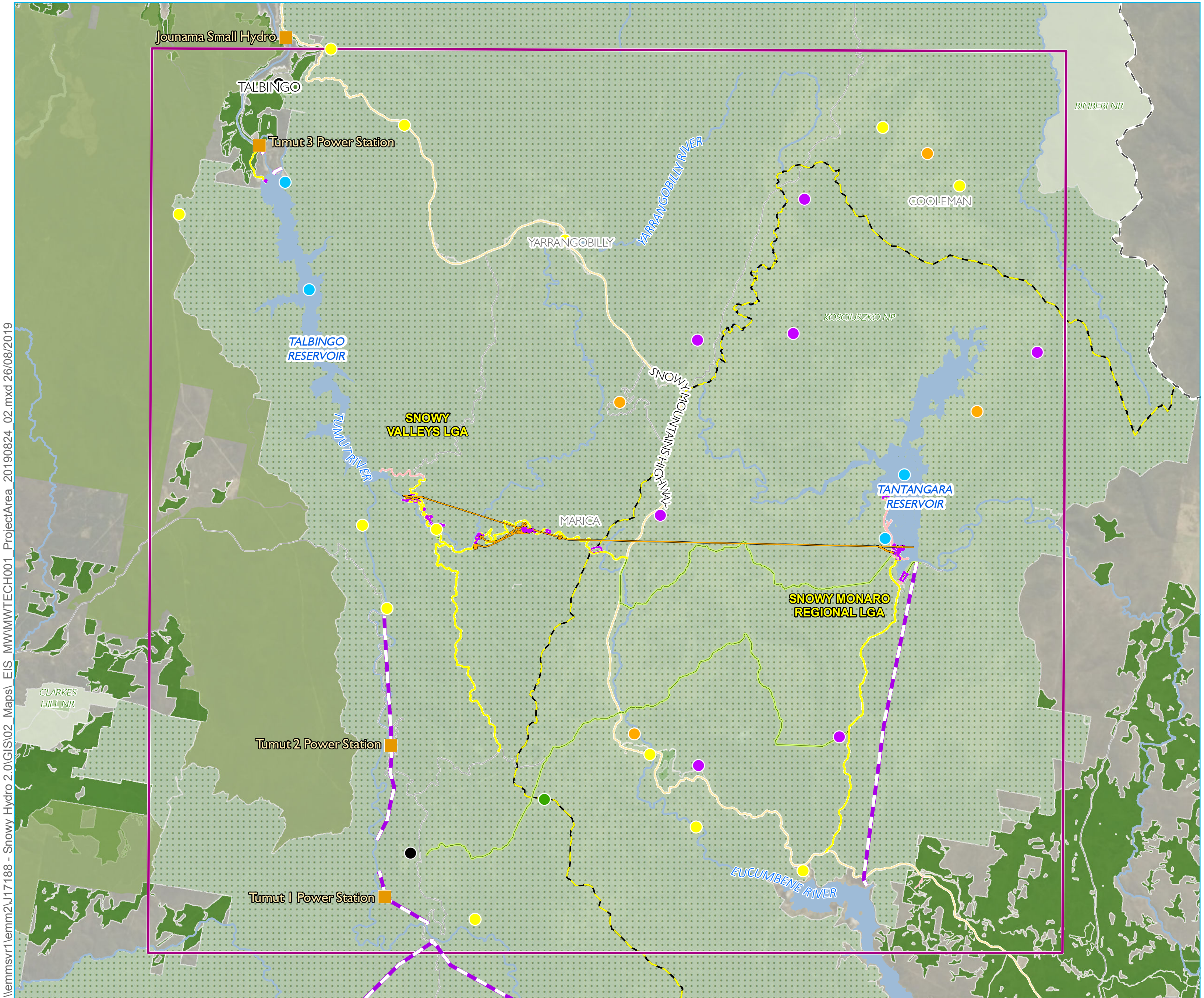
- Main road
- Local road
- Watercourse
- Waterbodies
- Kosciuszko National Park
- NPWS reserve
- State forest
- Local government area boundary
- State boundary

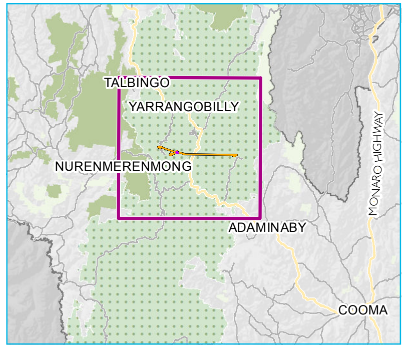
Regional setting

Snowy 2.0
Paleozoic geodiversity report
Main Works
Figure 1.1

snowy 2.0

EMM creating opportunities





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

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KEY

Existing Snowy Scheme
- Power station

Pipeline tunnel
- Snowy Tumut pipeline tunnel
- Project area

Recreational use areas
- Camping
- Camping - horses permitted
- Fishing and boating
- Place of interest
- Ski resort
- Township

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

Existing environment
- Main road
- Local road
- Watercourse
- Waterbodies
- Kosciuszko National Park
- NPWS reserve
- State forest
- Grazing
- Local government area boundary
- State boundary

Snowy 2.0 project area

Snowy 2.0
Paleozoic geodiversity report
Main Works
Figure 1.2

snowy 2.0

EMM creating opportunities

2 Description of the project

This chapter 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

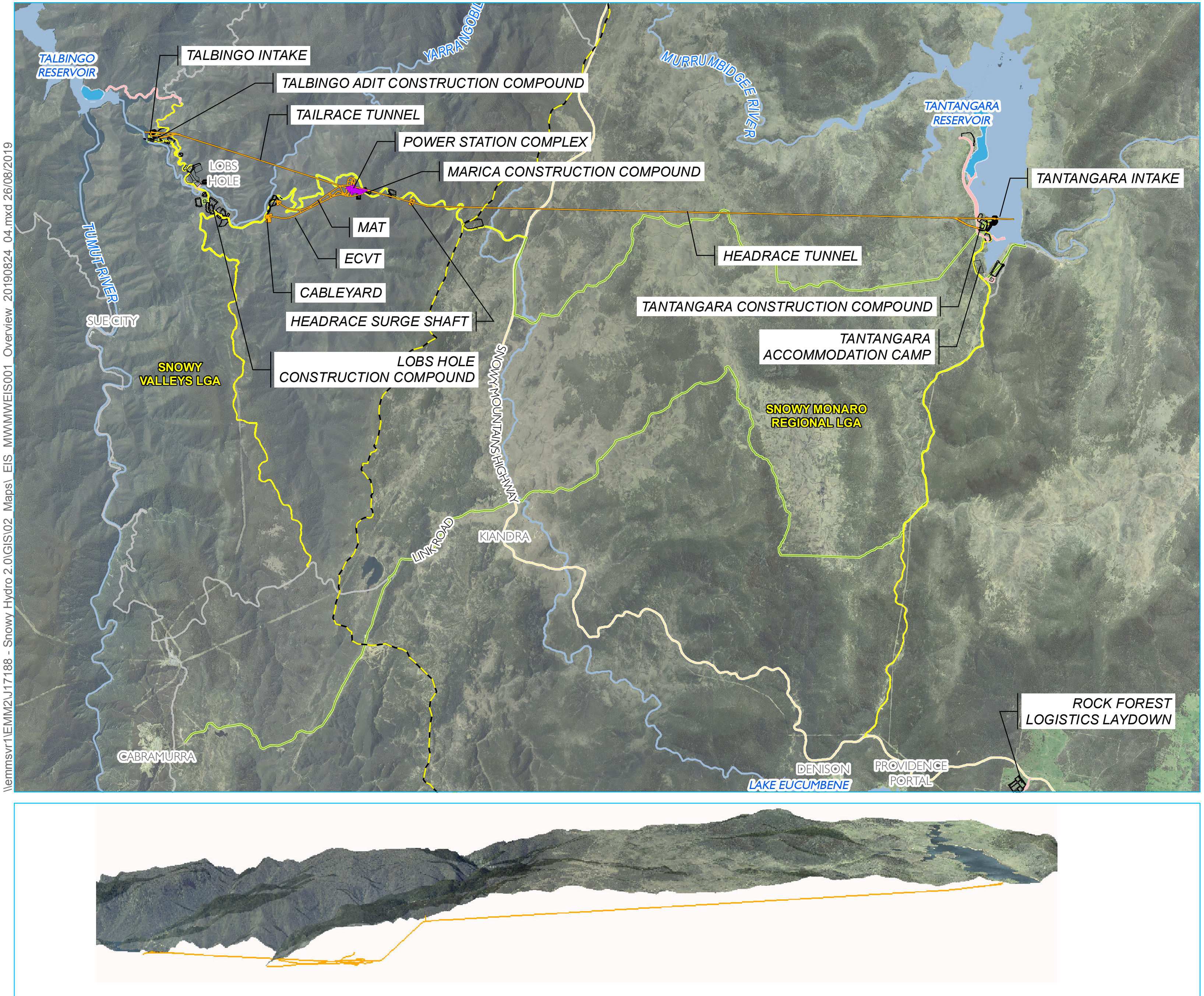
Snowy 2.0 will link the existing Tantangara and Talbingo reservoirs within the Snowy Scheme through a series of underground tunnels and a new hydro-electric power station will be built underground. An overview of Snowy 2.0 is shown on Figure 2.1, and the key project elements of Snowy 2.0 are summarised 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 Snowy 2.0 Main Works are anticipated.
Permanent infrastructure	Snowy 2.0 infrastructure to be built and operated for the life of the assets include the: • intake and gate structures and surface buildings at Tantangara and Talbingo reservoirs; • power waterway tunnels primarily comprising the headrace tunnel, headrace surge structure, inclined pressure tunnel, pressure pipelines, tailrace surge tank and tailrace tunnel; • 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 main access tunnel (MAT) and emergency egress, communication, and ventilation tunnel (ECVT); • establishment of a portal building and helipad at the MAT portal; • communication, water and power supply including the continued use of the Lobs Hole substation; • cable yard 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 Snowy 2.0 Main Works 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; and • temporary access roads.
Disturbance area	The disturbance area is the extent of construction works required to build Snowy 2.0. The maximum disturbance area is about 1,680 hectares (ha), less than 0.25% of the total area of KNP. Parts of the disturbance area will be rehabilitated and landformed and other parts will be retained permanently for operation (operational footprint).

Table 2.1 Overview of Snowy 2.0 Main Works

Operational footprint	The operational footprint is the area required for permanent infrastructure to operate Snowy 2.0. The maximum operational footprint is about 99 ha. This is 0.01% of the total area of KNP.
Tunnelling and excavation method	The primary tunnelling method for the power waterway is by tunnel boring machine (TBM), with portals and adits using drill and blast methods. Excavation for other underground caverns, chambers and shafts will be via combinations of drill and blast, blind 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 (eg at accommodation camps). Water to be discharged (comprising process water, wastewater and stormwater) will be treated before discharge to the two existing reservoirs (Talbingo and Tantangara) as follows: • 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 (eg intakes and portal entrances).
Construction workforce	The construction workforce for the project 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	Construction 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 value	Estimated to be $4.6 billion.



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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
- Indicative rock emplacement area

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

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GDA 1994 MGA Zone 55
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Snowy 2.0 project elements

Snowy 2.0
Paleozoic geodiversity report
Main Works
Figure 2.1

snowy 2.0

EMM creating opportunities

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 Figures 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 is proposed as part of a modification to the 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 Tumut 3 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); • Domestic sewer (wastewater); and • Construction site stormwater (stormwater).	Utility pipelines generally follow access roads. Water treatment plants (drinking water) will be needed for the accommodation camps and will be located in proximity. 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.

Table 2.2 Snowy 2.0 construction elements

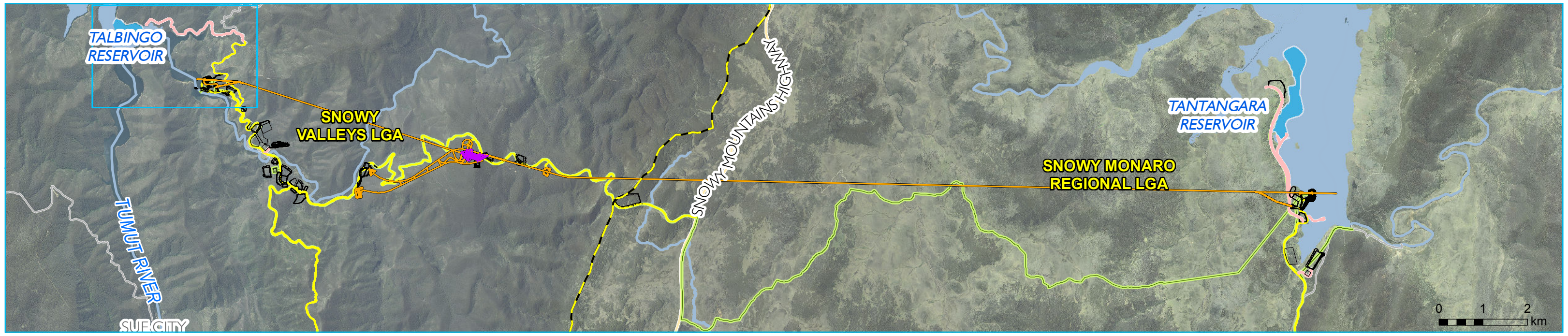
Construction element	Purpose	Location
Temporary and permanent access roads	Access road works are required to: • provide for the transport of excavated material between the tunnel portals and the excavated rock emplacement areas; • accommodate the transport of oversized loads as required; and • facilitate 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 Main Works will require the establishment of barge launch facilities on Tantangara Reservoir to enable these similar works (removal of the intake plug).	Barge launch sites are shown on Figure 2.2 and Figure 2.6.
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

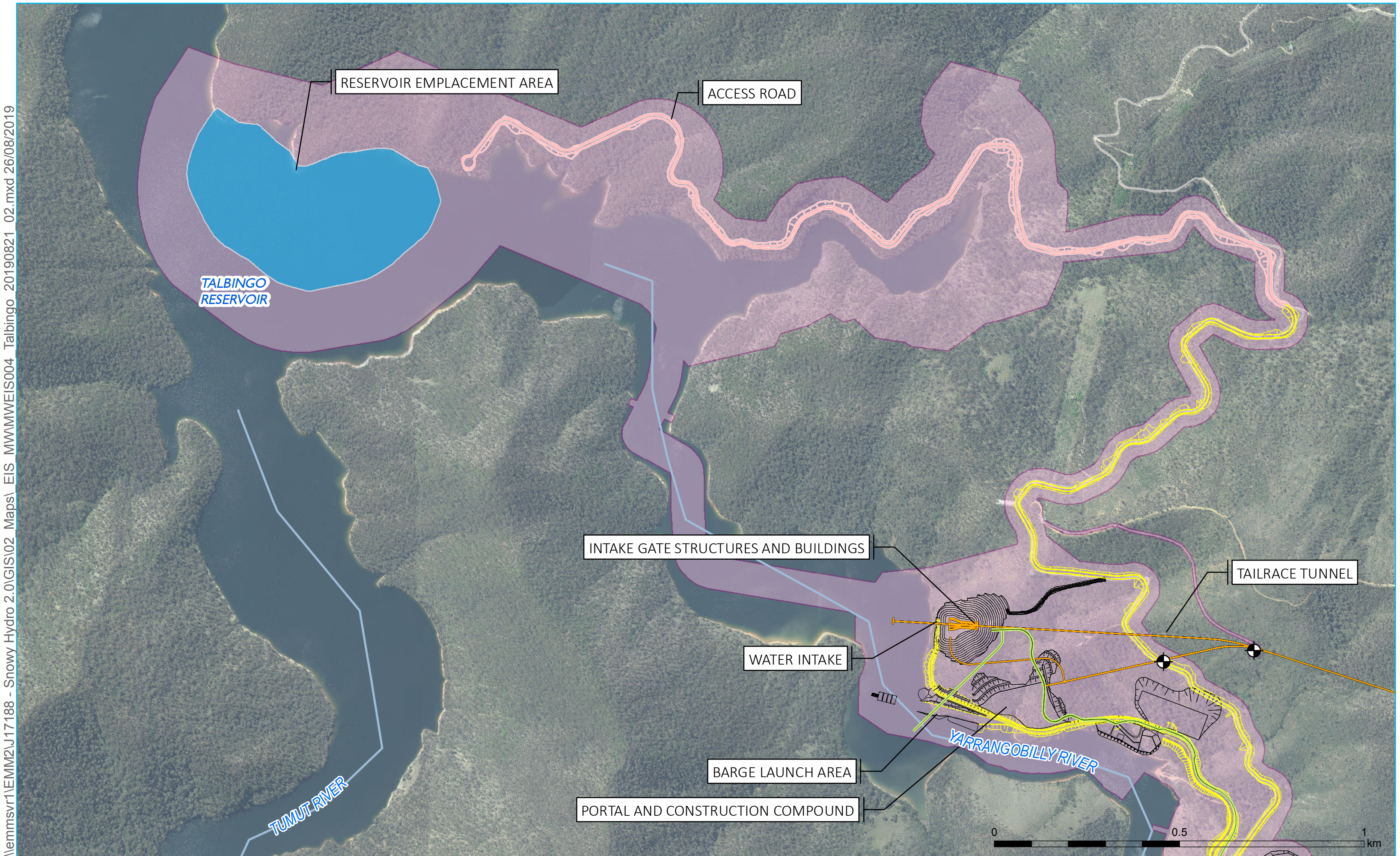
The key areas of construction are shown on Figure 2.2 to Figure 2.8 and can be described across the following locations:

- 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 are shown in Figure 2.8 with further detail on construction methods provided at Appendix D of the EIS.





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

GDA 1994 MGA Zone 55

N

KEY

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

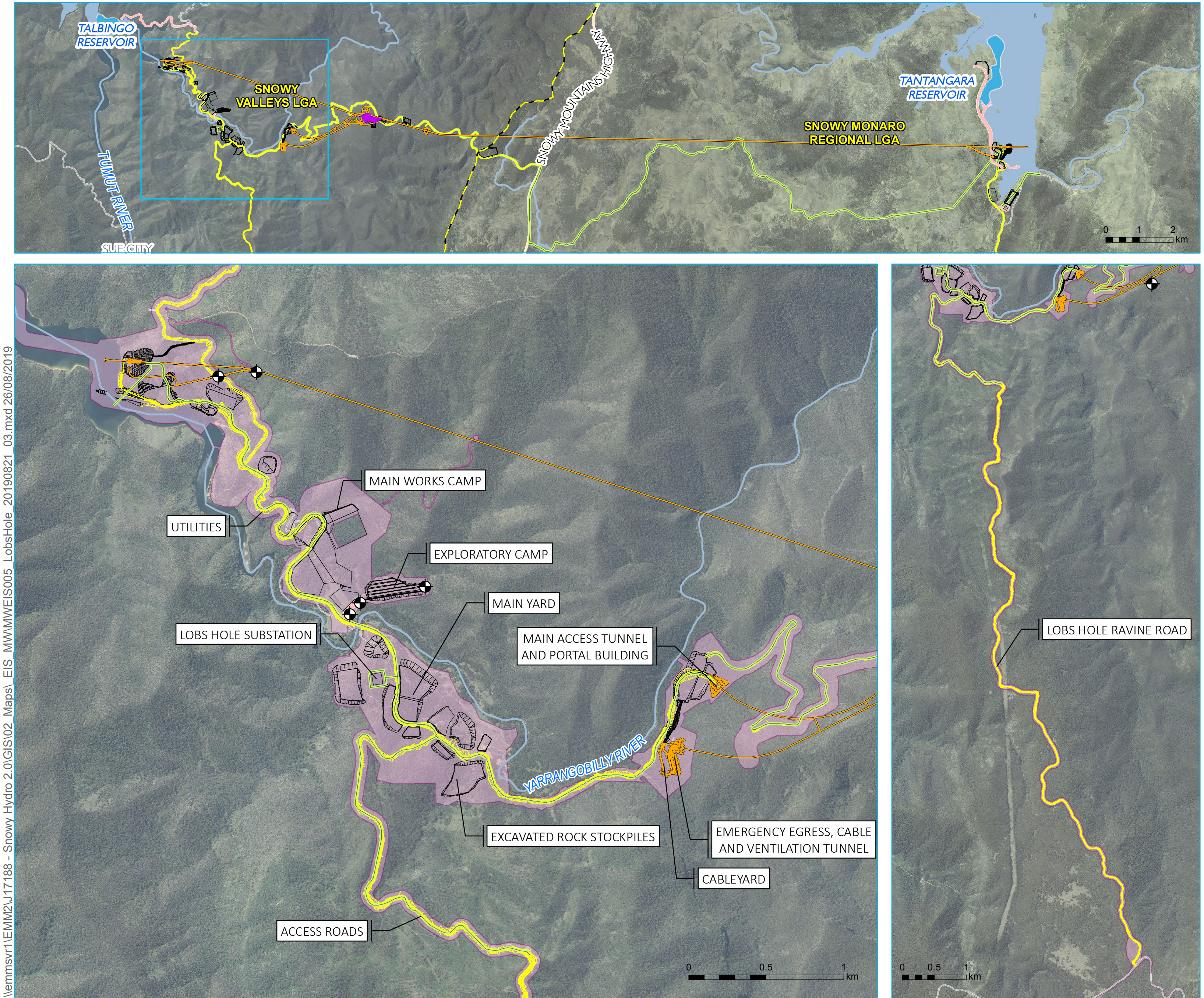
Snowy 2.0 Main Works operational elements
- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

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.

Talbingo Reservoir - project elements, purpose and description

Snowy 2.0
Paleozoic geodiversity report
Main Works
Figure 2.2



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.

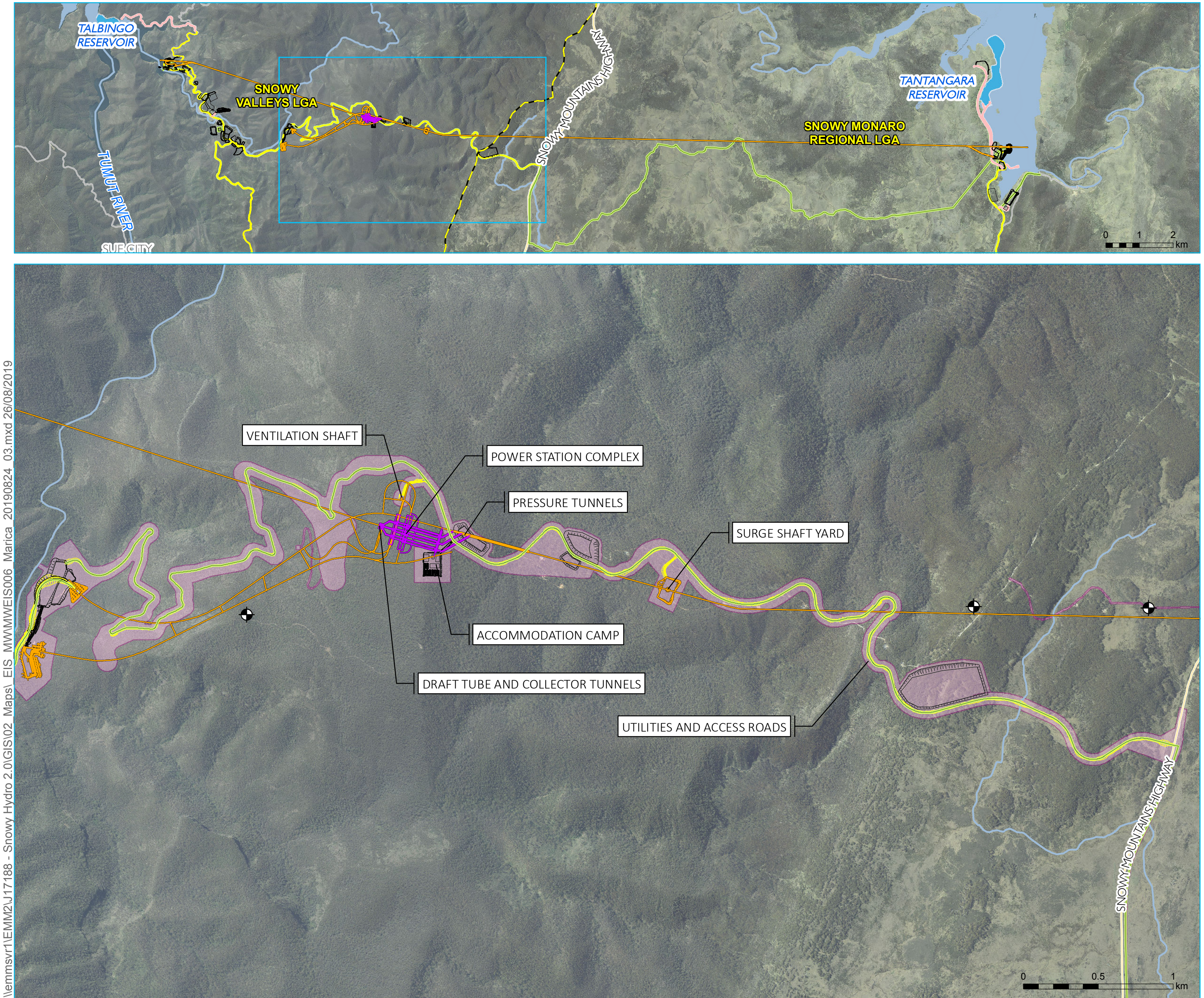
Lobs Hole - project elements, purpose and description

Snowy 2.0
Paleozoic geodiversity report
Main Works
Figure 2.3

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

GDA 1994 MGA Zone 55

N



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

GDA 1994 MGA Zone 55

N

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*

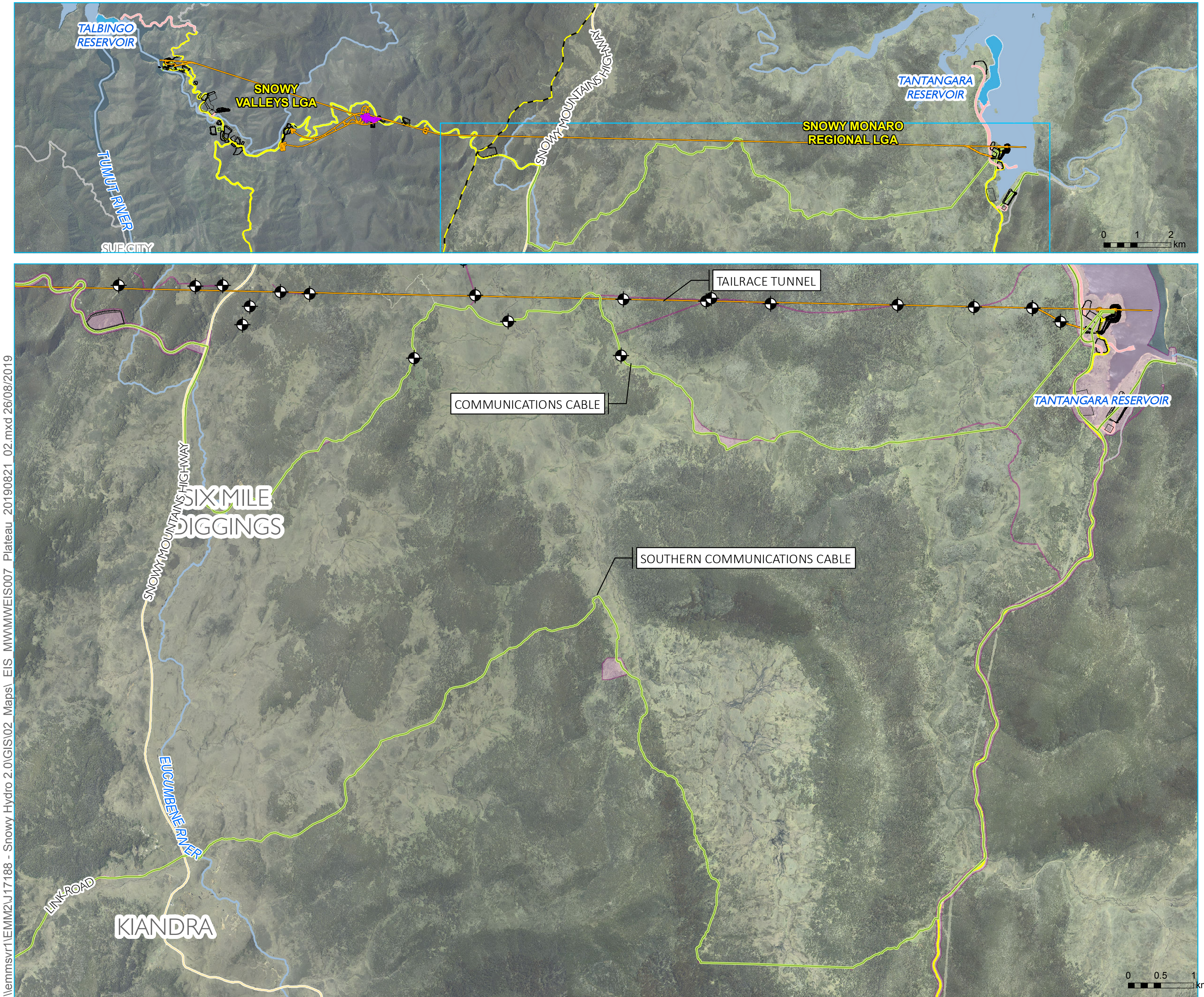
Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during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

Marica - project elements, purpose and description

Snowy 2.0
Paleozoic geodiversity report
Main Works
Figure 2.4

snowy 2.0

EMM creating opportunities



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*

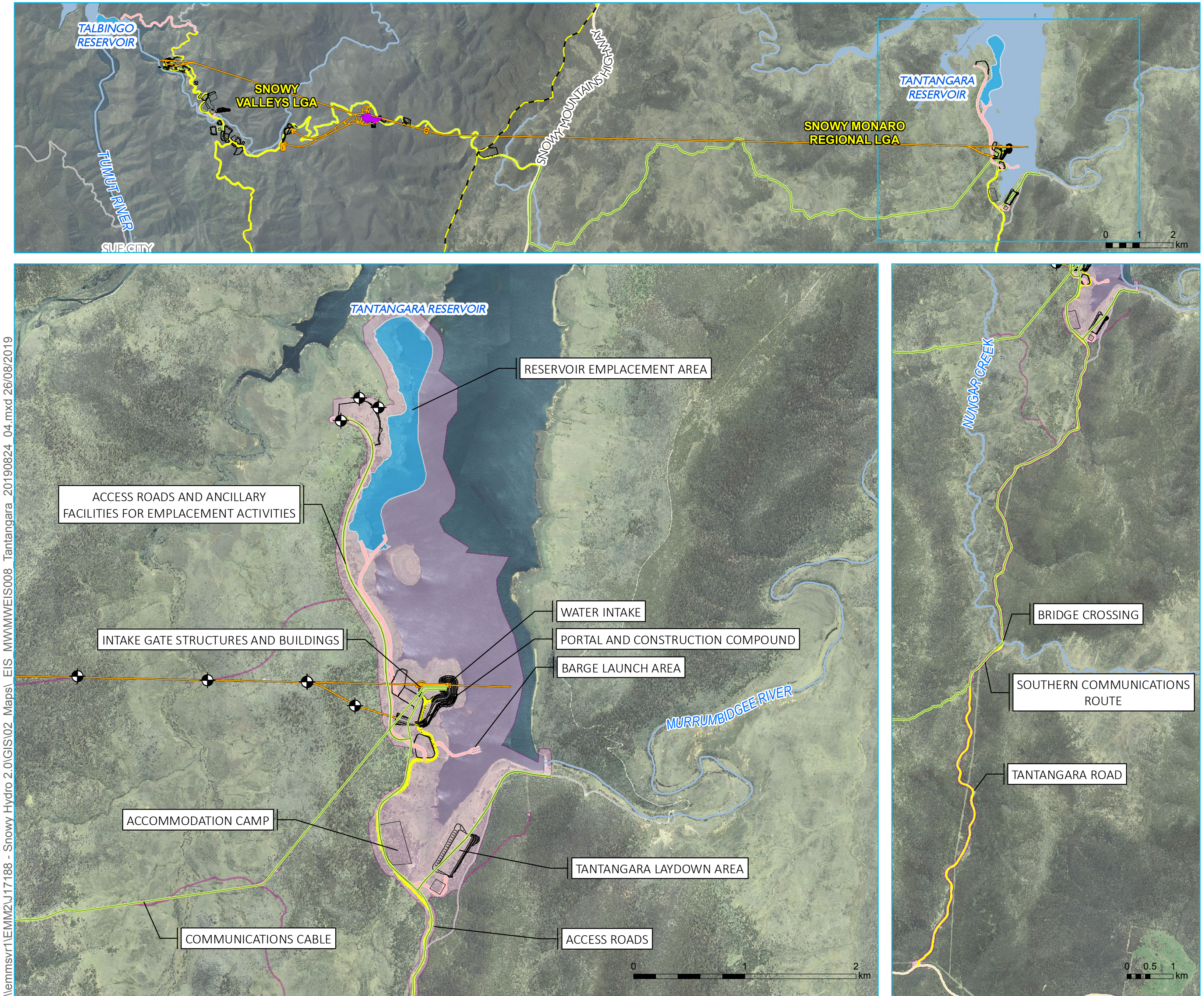
Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during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

Plateau - project elements, purpose and description

Snowy 2.0
Paleozoic geodiversity report
Main Works
Figure 2.5

snowy 2.0

EMM creating opportunities



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.

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

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Tantangara Reservoir - project elements, purpose and description

Snowy 2.0
Paleozoic geodiversity report
Main Works
Figure 2.6

snowy 2.0

EMM creating opportunities

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

GDA 1994 MGA Zone 55

N

KEY

Existing environment

- Main road
- Local road
- Watercourse

Snowy 2.0 operational elements

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

Snowy 2.0 contruction elements

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

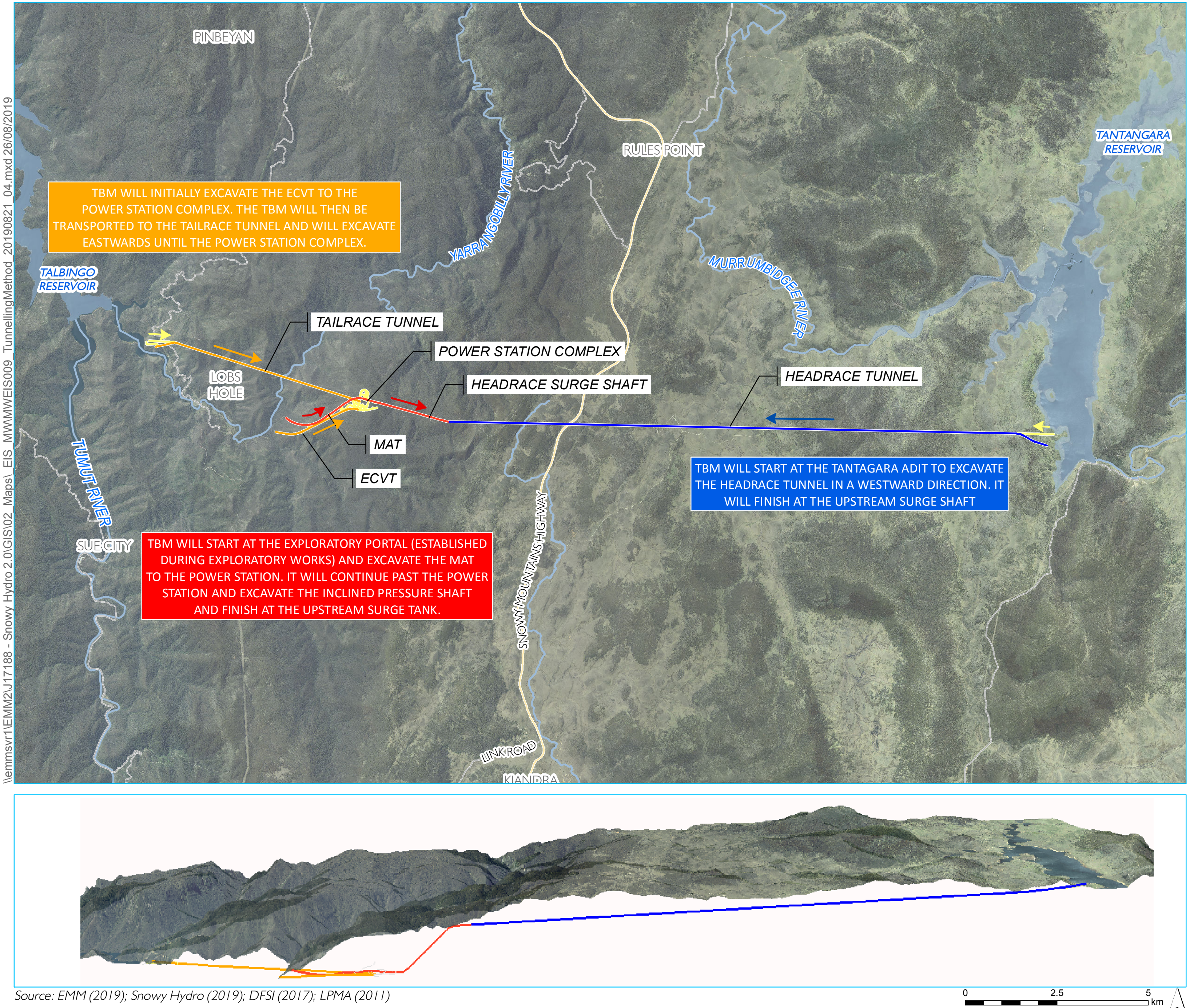
Note: the disturbance area is the extent of construction works required to build Snowy 2.0. It has been identified to allow an assessment of impacts for the EIS, and represents a defined maximum extent where construction works will be carried out. The area will be minimised as much as possible during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

Rock Forest - project elements, purpose and description

Snowy 2.0
Paleozoic geodiversity report
Main Works
Figure 2.7

snowy 2.0

EMM creating opportunities



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

KEY
Tunnelling method
- Drill and blast
- TBM 1
- TBM 2
- TBM 3
- Tunnelling direction

Existing environment
- Main road
- Local road
- Watercourse
- Waterbodies

Primary excavation methods – drill and blast and tunnel boring machine

Snowy 2.0
Paleozoic geodiversity report
Main Works
Figure 2.8

snowy2.0

EMM creating opportunities

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 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 Tumut 3 power station.

Due to its historic relationship to both the upstream Tumut 2 Power Station and downstream Tumut 3 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 (FSLs). 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.

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, water 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. For some roads, permanent access by Snowy Hydro will require restricted public access arrangements.

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).

2.4 Rehabilitation and final land use

A Rehabilitation Strategy has been prepared for Snowy 2.0 Main Works and appended to the EIS.

It is proposed that all 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.

3 Geological context

3.1 Regional setting

The Snowy 2.0 Main Works Project Area is located within the south-east portion of the Lachlan Orogen (Fold Belt) of NSW. The Lachlan Orogen comprises a suite of Ordovician (485 million years) to Devonian (359 million years) sedimentary, igneous and metamorphic rocks that have developed during multiple orogenic periods associated with extensive faulting forming major geotectonic structures throughout the area.

The geology of the broader assessment area comprises Ordovician to early Devonian granites, volcanics, occasionally fossiliferous sedimentary rocks and metamorphosed sedimentary sequences that have formed faulted, stepped ranges at the point where the South Eastern Highlands (part of the Lachlan Orogen) in NSW transition west into Victoria (NPWS 2003). The region was uplifted during the Middle Devonian Tabberabberan Orogeny and no further sedimentary deposition or igneous activity occurred until the Neogene Period, when basalts extruded over the exposed and eroded landscape, burying river valleys and lakes. During the Pleistocene epoch (2.6 Ma to 12 thousand years ago), the Australian Alps Bioregion was the only part of the Australian mainland to have been affected by glaciation, resulting in a variety of unique glacial and periglacial landforms above 1,100 m altitude (NPWS 2003). The general structural trend in this bioregion is north-south and the topography strongly reflects this (NPWS 2003).

Outcropping and subcropping Ordovician to Devonian units of the region are commonly extensively weathered, with widespread development of residual soils and colluvium. Weathered Neogene basalt deposits are erosional remnants of Early Miocene lava flows, and mostly occur capping ridges and plateaus. In some areas basalt is underlain or interbedded with unconsolidated fluvial and lacustrine deposits of a similar age.

The Snowy 2.0 Main Works Project Area extends across two major structural blocks, separated by the regional north-south trending Long Plain Fault. These are the Tumut Block in the west (composed of predominantly Silurian rocks) and the mainly Ordovician Tantangara Block in the east. Folding is well developed throughout much of the Project Area as a consequence of significant tectonic activity and east-west compression across the Tumut and Tantangara geological blocks. The Main Works Project Area comprises two distinct geomorphological terrains (incised ravine area and plateau area), separated by an escarpment caused by movement on the Long Plain Fault. The incised ravine area is situated on the western side of this fault structure whereas the plateau area is to the east.

A detailed synthesis of the regional Palaeozoic geology is presented in Appendix A. Troedson (2019) provides a companion report that assesses the Cenozoic (Neogene Period and Pleistocene Epoch) Geodiversity of the region.

3.2 Review methods, data and approach

This section provides an assessment of impacts to Palaeozoic geodiversity features from the Snowy 2.0 Main Works.

In order to thoroughly investigate the Palaeozoic geodiversity of the Snowy 2.0 Main Works project area an extensive literature review has included a review of the following sources:

1. Relevant environmental management documents for KNP including the KNP Plan of Management (PoM) (NPWS 2006), the KNP Geodiversity Action Plan 2012-2017 (KGAP) (OEH 2012) and appendices to that plan.

2. DIGS (Digital Imaging Geological System), the Geological Survey of NSW online repository of geological and mining reports, maps and other documents (https://digsopen.minerals.nsw.gov.au/digsopen/).

3. Geoscience Australia online report and data repository.

4. Relevant scientific literature relating to the geology of the project area and surrounding region, and assessment of geodiversity and geoheritage criteria in New South Wales and Australia.

5. Reports produced for the project including geological studies supplied by EMM, SMEC and Snowy Hydro.

The primary focus of this assessment is (1) to address whether work within the Main Works disturbance areas will directly or indirectly impact known sites and features of geodiversity significance, (2) to identify the significance of impacts to those sites, and (3) to propose recommendations mitigating potential impacts.

The introductory sections of this chapter includes some material taken directly (with permission) from an accompanying report by Dr Alexa Troedson on Cenozoic Geodiversity Features of the Snowy 2.0 Main Works project area. That information has been modified as appropriate. The most obvious distinction between the present report on Palaeozoic geodiversity and that on Cenozoic geodiversity features (Troedson 2019) is that most of the latter sites were previously identified as being of scientific significance and had been brought to the attention of NPWS and OEH. For the Palaeozoic geology and its geodiversity features, previous research had a greater regional focus with relatively few sites being studied in any detail. The assessment of Palaeozoic geodiversity impacts is divided into two sections, a review of known geodiversity sites within KNP and a review of additional sites with Palaeozoic geodiversity potential within the Main Works project area.

The list of known sites within KNP was obtained by reference to the KNP PoM (NPWS 2006) and the KGAP (OEH 2012) previously referred to. Those sites (10 in all) that occur within (or in the case of the Black Perry Mountain site, immediately adjacent to) the Snowy 2.0 Main Works project area, are listed and briefly described in Table 3.1.

Looking at the geographic distribution of these sites (Figure 3.1) and their coverage of geological features known to be present in the northern KNP, it was apparent that there was a concentration on karst and caves in areas of limestone outcrop and a smattering of other, widely scattered rock types, minerals and fossils that did not fully represent the wider geodiversity of the region. It was possible, therefore, that the construction phase of the Snowy 2.0 project might impact a site whose existence was unknown, or potentially damage a feature that had considerable significance at a local, regional of national level but was largely undocumented. Identifying such sites, determining their significance, and assessing whether they might be impacted by construction or disturbance zones, is the secondary focus of this report. The considerable variety of ages and lithologies recognised as constituting the overall geodiversity of the region argues for building a stratigraphic and intrusive unit-focussed database, specifically indicating identified and potential geodiversity features that might be encountered in the project area. This approach also includes a brief assessment of geodiversity features that lie peripheral to the major construction zones if they are of direct relevance to geological units that continue into the project area.

3.3 Geodiversity assessment and management within KNP

Management of geodiversity within KNP is addressed in the Plan of Management (NPWS 2006) and the KNP Geodiversity Action Plan 2012-2017 (OEH 2012). The PoM includes an objective to protect rocks, landforms and geological processes at risk of disturbance. It also specifies the most significant geodiversity features identified in the park. The KGAP provides a more detailed conservation strategy for geodiversity in KNP. Geodiversity assessment was undertaken previously for the Snowy 2.0 Exploratory Works EIS (EMM 2018b; Percival 2018; Opdyke 2018).

Geodiversity conservation and management in KNP is undertaken within the scope of the KNP PoM (NPWS 2006) and the KGAP and its appendices (OEH 2012). These issues were addressed after wide stakeholder consultation identified that geodiversity features of the park are 'significant and highly regarded by the community for their aesthetic, rarity, scientific, educational, socio-economic and recreational values'.

The PoM outlines policies and actions to protect and manage geodiversity features. These include providing maximum protection to features that are deemed to be of national significance and sensitive to disturbance, prohibiting developments that are likely to significantly impact on the integrity of such features, assessing potential impacts on geodiversity values during approval processes for proposed developments, and rehabilitating disturbed sites. Additional objectives are to enhance visitor appreciation and understanding of the geodiversity of the park, and to facilitate research on geodiversity. The PoM separately outlines a Karst Management Strategy (Section 6.4) that provides a framework for protection of karst areas, which have specific management issues.

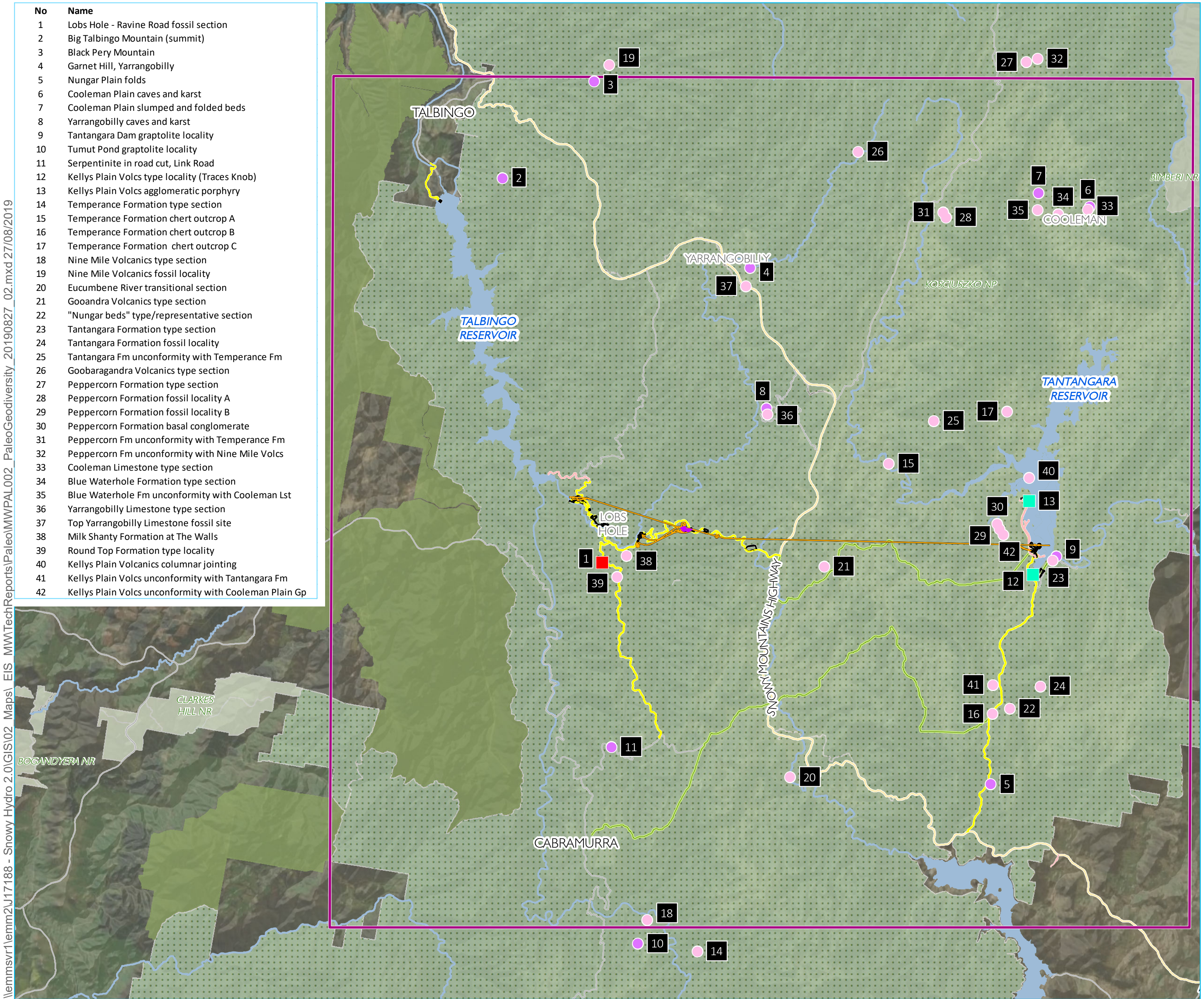
The PoM identifies geological and geomorphological features with national, state or regional significance that occur within the park. These include: numerous features within the Ordovician to Devonian rocks of the Lachlan Fold Belt; several 'Tertiary' geological features associated with Miocene basalt and sedimentary deposits; and glacial and periglacial features associated with Pleistocene glaciations. The most significant geodiversity features are listed in Schedule 1 of the PoM, with Table S1.9 relating to rocks and landforms, and Table S1.10 listing karst features.

A Geodiversity Action Plan (KGAP) was subsequently developed for the park, effective from 1st July 2012 (OEH 2012). The plan applies to the significant geological and geomorphological features identified in Schedule 1 of the PoM and a limited number of additional features. The main purpose of the plan is to outline actions required to ensure these features are protected, conserved and promoted. Some key sites, including several within the Snowy 2.0 Main Works project area, are the subject of ongoing monitoring as documented in Appendix 1 of the KGAP. The basis for this monitoring is outlined in Appendix 2 of the KGAP, which describes the KNP Geodiversity Monitoring Program (KGMP).

The KGAP identifies poorly designed or located infrastructure amongst a range of activities that pose a potential threat to geodiversity sites within KNP, with possible impacts including complete or partial loss of an element of geodiversity, physical damage, interruptions to natural land forming processes, impeded or lost access to significant sites, changes in erosion rates and water pollution.

KNP is within the Australian Alps National Parks and Reserves, which is a listed National Heritage Place. Some of the geodiversity features and values of the KNP may contribute to the heritage values of the Australian Alps National Parks and Reserves. An assessment of impacts to National Heritage Places from the Snowy 2.0 Main Works is provided in the Snowy 2.0 Main Works Historic Cultural Heritage Assessment Report (NSW Archaeology 2019).

Geodiversity features listed in the PoM and KGAP were identified on the basis of institutional knowledge within NPWS and literature review. Other significant Palaeozoic geodiversity features are known to exist within KNP but are undocumented in the KGAP, increasing the potential for their loss or damage due to human activity (OEH 2012, Appendix 3). One of the important outcomes of the present report has been to identify and document 30 additional Palaeozoic geodiversity sites in the northern part of KNP, thereby quadrupling the previously known number of sites (Figure 3.1). By undertaking this thorough analysis it has been possible to determine which of those newly recognised sites will potentially be impacted by Snowy 2.0 Main Works.



No	Name
1	Lobs Hole - Ravine Road fossil section
2	Big Talbingo Mountain (summit)
3	Black Pery Mountain
4	Garnet Hill, Yarrangobilly
5	Nungar Plain folds
6	Cooleman Plain caves and karst
7	Cooleman Plain slumped and folded beds
8	Yarrangobilly caves and karst
9	Tantangara Dam graptolite locality
10	Tumut Pond graptolite locality
11	Serpentinite in road cut, Link Road
12	Kellys Plain Volcs type locality (Traces Knob)
13	Kellys Plain Volcs agglomeratic porphyry
14	Temperance Formation type section
15	Temperance Formation chert outcrop A
16	Temperance Formation chert outcrop B
17	Temperance Formation chert outcrop C
18	Nine Mile Volcanics type section
19	Nine Mile Volcanics fossil locality
20	Eucumbene River transitional section
21	Gooandra Volcanics type section
22	"Nungar beds" type/representative section
23	Tantangara Formation type section
24	Tantangara Formation fossil locality
25	Tantangara Fm unconformity with Temperance Fm
26	Goobaragandra Volcanics type section
27	Peppercorn Formation type section
28	Peppercorn Formation fossil locality A
29	Peppercorn Formation fossil locality B
30	Peppercorn Formation basal conglomerate
31	Peppercorn Fm unconformity with Temperance Fm
32	Peppercorn Fm unconformity with Nine Mile Volcs
33	Cooleman Limestone type section
34	Blue Waterhole Formation type section
35	Blue Waterhole Fm unconformity with Cooleman Lst
36	Yarrangobilly Limestone type section
37	Top Yarrangobilly Limestone fossil site
38	Milk Shanty Formation at The Walls
39	Round Top Formation type locality
40	Kellys Plain Volcanics columnar jointing
41	Kellys Plain Volcs unconformity with Tantangara Fm
42	Kellys Plain Volcs unconformity with Cooleman Plain Gp

KEY

Project area

Geodiversity sites
- Known site likely to be impacted
- New sites likely to be impacted
- Known sites
- New sites not likely to be impacted

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

Existing environment
- Main road
- Local road
- Watercourse
- Waterbodies
- Kosciuszko National Park
- NPWS reserve
- State forest
- State boundary

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

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Overview of Paleozoic geodiversity sites

Snowy 2.0
Paleozoic geodiversity report
Main Works
Figure 3.1

snowy 2.0

EMM creating opportunities

3.4 Previously known geodiversity sites and features within KNP

An assessment of impacts to Palaeozoic geodiversity sites within the Main Works disturbance area and listed in the KNP PoM (2006) and KGAP (2012) was undertaken and is provided in this section. Table 3.1 lists significant Palaeozoic geodiversity sites and features within KNP identified in the KNP PoM (NPWS 2006) and KGAP (OEH 2012), along with their geographic extent and geological context. Key sites singled out for monitoring in the KGAP are noted. The potential impact (direct and/or indirect) of disturbance associated with the Snowy 2.0 project construction phase on each of these sites is discussed in Section 3.5. Only one of the previously identified geodiversity sites listed in Table 3.1 – fossiliferous Devonian age Lick Hole Formation exposed in cuttings along Lobs Hole Ravine Road – will be impacted during the construction phase of the Main Works.

Other geological and geomorphological features in KNP that were identified in the KNP PoM (NPWS 2006) and KGAP (OEH 2012) as being of geodiversity significance, but are distant from the Snowy 2.0 Main Works project area, are listed below. Because they are irrelevant to the project they are not further discussed in this report.

- Geehi Valley: metamorphic rocks with abundant garnets, staurolite and amphibolite;
- Thredbo Valley: the dominant and well-defined Crackenback Fault;
- Byadbo area: graptolite fossils;
- The Pilot and Byadbo areas: Ordovician hard, green platey quartzite;

Main Range: three types of granitoid rocks.

Table 3.1 Summary of Palaeozoic geodiversity features within Main Works project area listed in PoM & KGAP

No.	Feature type	Location relative to project disturbance boundary	Direct or indirect impacts of Snowy 2.0 construction	Geographic extent	Geological context and age	Subject to NPWS monitoring
1	Devonian shallow-water sediments	Road section is within disturbance boundary	Directly impacted by road widening	Lobs Hole Ravine Road, Ravine Basin	Only precisely age-dated Lower Devonian fossiliferous rocks in KNP	No (only overlying tufa deposits are monitored)
2	Devonian lava flows forming cliffs	Not within project disturbance boundary	Neither directly nor indirectly impacted	Big Talbingo Mountain	Spectacular geomorphological feature of Early Devonian age	No
3	Skarn rock with garnets, occurrence of babingtonite	Not within project disturbance boundary	Neither directly nor indirectly impacted	Black Perry Mountain	Devonian intrusion and alteration (babingtonite is a mineral found in only a few other localities worldwide)	No
4	Skarn rock (limestone altered by igneous intrusion)	Not within project disturbance boundary	Neither directly nor indirectly impacted	Garnet Hill, Yarrangobilly	Devonian(?) sill intruded and altered Silurian limestone; abundant garnets	Yes
5	Folding of Bowning tectonic episode	Not within project disturbance boundary	Neither directly nor indirectly impacted	Nungar	Evidence of Bowning tectonic episode at end of Silurian Period	No
6	Silurian limestone caves, karst, fossils	Not within project disturbance boundary	Neither directly nor indirectly impacted	Cooleman Plain area	One of two major deposits of fossiliferous Silurian limestone in KNP	Yes (under Karst Management Strategy)
7	Slump bed folding	Not within project disturbance boundary	Neither directly nor indirectly impacted	Cooleman Plain area	Slump bed in Blue Waterhole Formation with limestone blocks containing microfossils	No
8	Silurian limestone, caves, karst, fossils	Not within project disturbance boundary	Neither directly nor indirectly impacted	Yarrangobilly	One of two major deposits of fossiliferous Silurian limestone in KNP	Yes (under Karst Management Strategy)
9	Graptolite fossils	All 3 sites located outside disturbance boundary	Neither directly nor indirectly impacted	Tantangara, Kiandra and Tumut Pond areas	Evidence of Late Ordovician age, important for geological correlation	No

Table 3.1 Summary of Palaeozoic geodiversity features within Main Works project area listed in PoM & KGAP

10	Serpentinite along major faults with nickel and chromium	Not within project disturbance boundary	Neither directly nor indirectly impacted	Cutting on Link Road near Cabramurra	Serpentinite & mineralisation in Tumut Serpentinite Province	Yes

3.5 Assessment of impacts on known Palaeozoic geodiversity sites within KNP

This section provides an assessment of impacts to known Palaeozoic geodiversity sites within the Main Works project area. As previously mentioned, only one of the previously identified geodiversity sites – fossiliferous Devonian age Lick Hole Formation exposed in cuttings along Lobs Hole Ravine Road – will be impacted by the Main Works.

i Site 1: Devonian shallow-water fossiliferous sedimentary rocks of the Lick Hole Formation exposed in cuttings along Lobs Hole Ravine Road

a Summary

The Lick Hole Formation road cutting section along Lobs Hole Ravine Road was designated as a geodiversity site in the KNP PoM (NPWS 2006) on the basis of being the only fossiliferous rock unit of Devonian age known in the entire Park. The fossiliferous rocks are not subject to monitoring by KNP staff under the KGAP program (OEH 2012), whereas the overlying and much younger tufa deposits are. The geoheritage significance of the site was first documented by Percival (1979). It is the only geodiversity site identified in the KNP PoM that will be directly impacted by work (road widening) in the construction phase of the Snowy 2.0 project. The site is described below, based on an initial report (Percival 2018) and a subsequent update (Percival 2019) following a site visit to inspect outcrops in cuttings along Lobs Hole Ravine Road.

b Geological setting and context

The Lobs Hole–Ravine valley and its surrounding elevated ridges is composed of rocks of the Byron Range Group that consists of three conformable units. The lowermost of these is the Milk Shanty Formation (170 m thick), a thick to massive-bedded fining upwards succession of clastic rocks devoid of fossils. It passes gradationally upwards into the Lick Hole Formation – consisting of blue-grey fossiliferous limestone, often nodular and interbedded with siltstones and shales, with a total thickness of approximately 488 m measured by Flood (1969) along Lobs Hole Ravine Road. The limestone disappears up sequence and is replaced by fossiliferous quartzite containing undescribed lingulide brachiopods at the base of the Round Top Formation that forms the capping of Round Top Trig.

The first fossils to be described from the Lick Hole Formation were tentaculitids (small conical shells of unknown affinity), published by Sherrard (1967). Two genera and species were recognised: *Tentaculites chapmani* Sherrard and *Nowakia* aff. *acuaria* (Richter). Subsequently detailed geological mapping and palaeontological sampling of the Lobs Hole–Ravine area was undertaken by P.G. Flood and his colleagues from the University of New England in 1967. Results of this study, published two years later (Flood 1969), include a measured section through the Lick Hole Formation from which Flood obtained approximately 1,300 identifiable well-preserved conodont elements from the acid digestion of about 200 kg of limestone. Among 14 form species of conodonts identified by Flood, the most important is the index microfossil *Polygnathus dehiscens* Philip & Jackson. This conodont, which is indicative of the early Emsian Stage in the later part of the Early Devonian Period, has been widely recognised in other Devonian limestones in southeastern Australia, including the Cavan Limestone and lower part of the Taemas Limestone at Burrinjuck Reservoir, and the Buchan Caves Limestone in the Gippsland region of Victoria. Mawson & Talent (2000) reviewed the evidence for the precise age of the conodonts obtained from this unit (citing an unpublished study by one of their students) and concluded that it could span the *dehiscens* and overlying *perbonus* zones of the lower Emsian.

The most abundant macrofossils found in the measured section are shells of brachiopods, less common corals, pelecypod molluscs and bryozoa. Only some of these fossils have been formally described. The brachiopods *Spinella yassensis ravina* Flood and *Uncinulus australis* Flood, described in Strusz et al. (1970) and Flood (1973) respectively, are closely allied to species recognised in the Taemas Limestone in the Burrinjuck Reservoir area. Flood (1973) also identified (but did not describe) the brachiopods *Parachonetes* sp. nov., *Athyris waratahensis* (Talent), *Howittia multiplicatus* (de Koninck), *Howellella* sp., and *Globithyris* sp. nov. Pedder (1971) described three new species including the corals *Tropidophyllum hillae* and *Chalcidophyllum discorde giandarrense*, and the bryozoan *Heterotrypa rapinae*.

Fossils in the Lick Hole Formation are only known from its type section, which is a series of artificial exposures in road cuttings. It is certain that fossils will be present in the limestone and siltstone beds that extend above and below the road, but they will only be exposed there on bedding planes. The likelihood of new or previously undescribed species being present is considered to be very high.

c Significance

The first assessment of the geodiversity of the Lobs Hole–Ravine area, specifically focussing on the fossils in the Lick Hole Formation, was undertaken in 1978 by the current author and documented in an unpublished report prepared for the Australian Heritage Commission and the Planning & Environment Commission of NSW the following year as part of an initial statewide study of geological heritage in NSW (Percival 1979). In that report (p.98) the major risk to the site was identified as "unauthorised removal of the fossils". To highlight the significance of the fossil site it was included in the KNP PoM and listed in Schedule 1 along with other significant geodiversity sites. However, in order to minimise pilfering of the fossil shells, the site has not been publicised.

The site is **locally and regionally significant** for the following reasons:

1. It is the only fossiliferous limestone of Devonian age in KNP, and so represents an important part of the geological history of the Snowy Mountains region in NSW.

2. It contains microfossils (conodonts) and macrofossils (mainly brachiopods and corals) that enable precise correlation with strata of identical age (early Emsian Stage of the Early Devonian) and depositional environment (shallow marine conditions in a subtropical to warm temperate setting) elsewhere in southeastern Australia.

3. The fossiliferous rocks exposed in the road cuttings are the type locality for several fossil species, including at least two brachiopods, two corals and a bryozoan.

In a statewide or national context, the palaeontological significance of the Lick Hole Formation is actually quite low. There are far more extensive outcrops of Early Devonian limestones in the Burrinjuck area to the north and the Buchan Caves Limestone to the south in Victoria that were deposited over a much greater time interval; these exposures are far more spectacular and are very much richer in fossil diversity and abundance. Hence the Murrumbidgee Group limestones around Burrinjuck Reservoir have been the focus of far more palaeontological research (summarised in Percival & Zhen 2017) and accordingly are much better known.

d Risks, sensitivities and opportunities

The major risk to the site as it stands continues to be the unauthorised removal of fossils, particularly the brachiopod shells that weather out from the siltstones forming the middle part of the road section. The weathered siltstones are susceptible to further crumbling and deterioration of the road cuttings. Similar to the findings of the previous assessment of impacts from the Exploratory Works (Percival 2019), removal of weathered rock from the cuttings would benefit scientific research as well as potentially providing a safe and interesting geotourism site. That report highlighted the opportunity to move the weathered spoil material off-site to geoscientific institutions where research can be carried out on the fossils without causing threats to the safety of scientists collecting from the existing road cuts on the narrow winding road.

e What is the likely impact of Snowy 2.0 Main Works?

This site is directly affected by widening of Lobs Hole Ravine Road as part of the Snowy 2.0 Main Works construction. A detailed report on the impact of the roadworks during Exploratory Works was prepared (Percival 2019) and found that the amount of road widening proposed under Exploratory Works would not detrimentally affect the site. That widening is expected to contribute positively to retaining the significance of the site by exposing fresh, relatively unweathered fossiliferous rock. The proposed road boundary changes during Main Works construction which will involve further widening (of variable width, but potentially with a disturbance zone of up to 20-30 m in some places) and realignment of Lobs Hole Ravine Road to accommodate movements of very large vehicles and pieces of machinery as well as improving safety of the road, will have both positive and negative effects on the Ravine fossil site.

Following is a summary of the expected positive and negative impacts due to the full extent of road widening associated with the Main Works.

The **positive effects** may include (but are not limited to) the following:

1. ‘Freshening up’ of the site by removing weathered and crumbling strata and creating relatively fresh exposures in new cuttings situated further into the hillside, without the lichen and algae overgrowth that obscures the appearance of fossils on bedding plane and vertical surfaces. The heights of the existing road cuts are likely to be substantially increased, maximising the extent of the visible fossiliferous outcrops. Increasing the width of rock removed from the upslope side of the road will likely result in largely pristine (i.e. almost wholly unweathered) rock being exposed, compared to the existing cuttings. It is difficult to be certain that no minor weathering zones or channels will be present, as the entire land surface was probably exposed to chemical leaching for much of the past 395 million years and certainly since the Miocene basalts were extruded approximately 20 million years ago. However, there can be no doubt that the stability of the cuttings will be improved with the appropriate angle of batter, so that the faces of the cuttings will not need to be covered with shotcrete or other stabilising materials.

2. The potential to find new genera and species of fossils in strata that are known to be fossiliferous but which have only been studied in detail in a series of four papers published 45-50 years ago, all of which described only half a dozen fossil species from road cuts that have not changed in extent up to the present time.

3. The possibility of incorporating sufficient space into the widened road and its verges to allow for places for the public to safely stop and view the fossils in situ, assisted by interpretative signage. This would markedly benefit the educational aspects of the geodiversity site.

Negative effects may include:

1. The proposed road works are not expected to have a significant negative impact on the fossiliferous rocks. The key impact to be avoided is the complete removal of all fossiliferous rocks during the process of road widening. However, this possibility is regarded as so unlikely, given the extent of the Lick Hole Formation into the ridge adjacent to the road, that it can be readily dismissed. All fossiliferous layers that are presently exposed will be intersected by the new road alignment. The shallow dip of the strata (about 7° towards the SW) combined with the downhill gradient of the road will ensure that a continuous section through the formation remains intact. Reference to Figures 3.3 and 3.4 shows that formation is far more extensive than the relatively minor footprint of the disturbance zone.

2. Making the fossils potentially more susceptible to pilfering by increasing access to the outcrop. However, this possibility is mitigated by the fact that whole fossils are less likely to be easily removed from fresher rock. Certainly it is apparent that over 40 years considerably fewer specimens of the larger, more obvious shells remain at the locality, but this is largely because these fossils weathered out of the eroding siltstones and shales and were available to be easily gathered. Sending off bulk samples of the weathered faces of the road cuttings (recommended during the Exploratory Works) will ensure that further fossil specimens will be curated into museum and university collections where they can be studied by palaeontologists, rather than being collected by the general public merely for display as curiosities.

ii Conclusions

1. The Lobs Hole Ravine Road fossil site is an artificial exposure. Had the road not cut through and exposed the fossiliferous beds, the site and its geodiversity significance as the only known example of Early Devonian fossiliferous strata in KNP would have remained out of public view. Thus widening the exposure of the fossiliferous strata – provided it is done in a sympathetic manner to allow for future access by the public and palaeontological research workers – should not be detrimental. In fact, there are more positives than negatives.

2. Given the observed distribution of fossils in the road cuttings at present, excavation of a wider (up to 20-30 m) strip of rock (within a maximum disturbance corridor of 80 m) into the ridge on the upside of the road will not materially affect the distribution nor abundance of fossils in the new road cuttings.

3. The proposed road widening will result in an improvement in site conditions, not only in terms of road safety and access for the general public once the Snowy 2.0 construction works conclude, but also in access to the fossiliferous layers. It is critical that the fresh exposures be left to weather naturally over many years, and not be obscured by shotcrete or other means.

4. Opportunities to learn more about the geodiversity significance of the site will result from the proposed road widening and exposure of fresh rock surfaces. More varieties of fossils, as yet undescribed from this locality, will be revealed which will increase the scientific knowledge of the site. Another opportunity is for public education, which will also benefit from safe access. The site could become part of a geotrail after construction ceases, with interpretative signage.

iii Recommendations

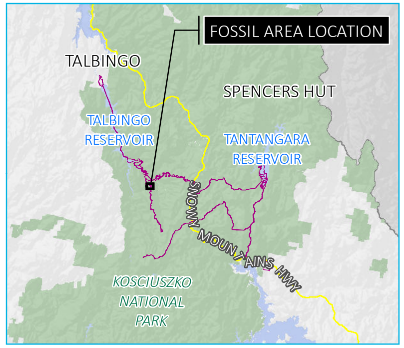
1. The excavated rock faces in the new cuttings will be higher than at present, and so it will be necessary to ensure that they are stable by ensuring a suitable angle of batter.

2. A stepped design for the new cuttings, instead of a single slope, would also be acceptable as this would allow access to bedding planes along benches.

3. The construction works should avoid any use of shotcrete, or vegetation seeding that would cover the new exposures. The new road cuttings must be allowed to naturally weather as the present ones have done (though this will take many decades).

Tufa deposits of Recent age that develop on the Lick Hole Formation (and are derived by dissolution and redeposition of carbonate from the limestone) are also a known geodiversity feature in the immediate vicinity of the type section of the Lick Hole Formation. These deposits are described in detail by Troedson (2019).

Figure 3.2 Current state (April 2019) of Lobs Hole Ravine Road, showing single lane unsealed road flanked by weathered and crumbling fossiliferous beds of the Lick Hole Formation.



KEY

- Main Works disturbance footprint
- Indicative fossil area
- Indicative road design
- Local road
- Named watercourse

Source: EMM (2019); Snowy Hydro (2019); FGJV (2019); DFSI (2017); GA (2015); LPMA (2011)

0 150 300 m

GDA 1994 MGA Zone 55

N

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Lobs Hole Ravine Road upgrade near Ravine Fossil Beds

Snowy 2.0
Main Works
Paleozoic Geodiversity Assessment Report

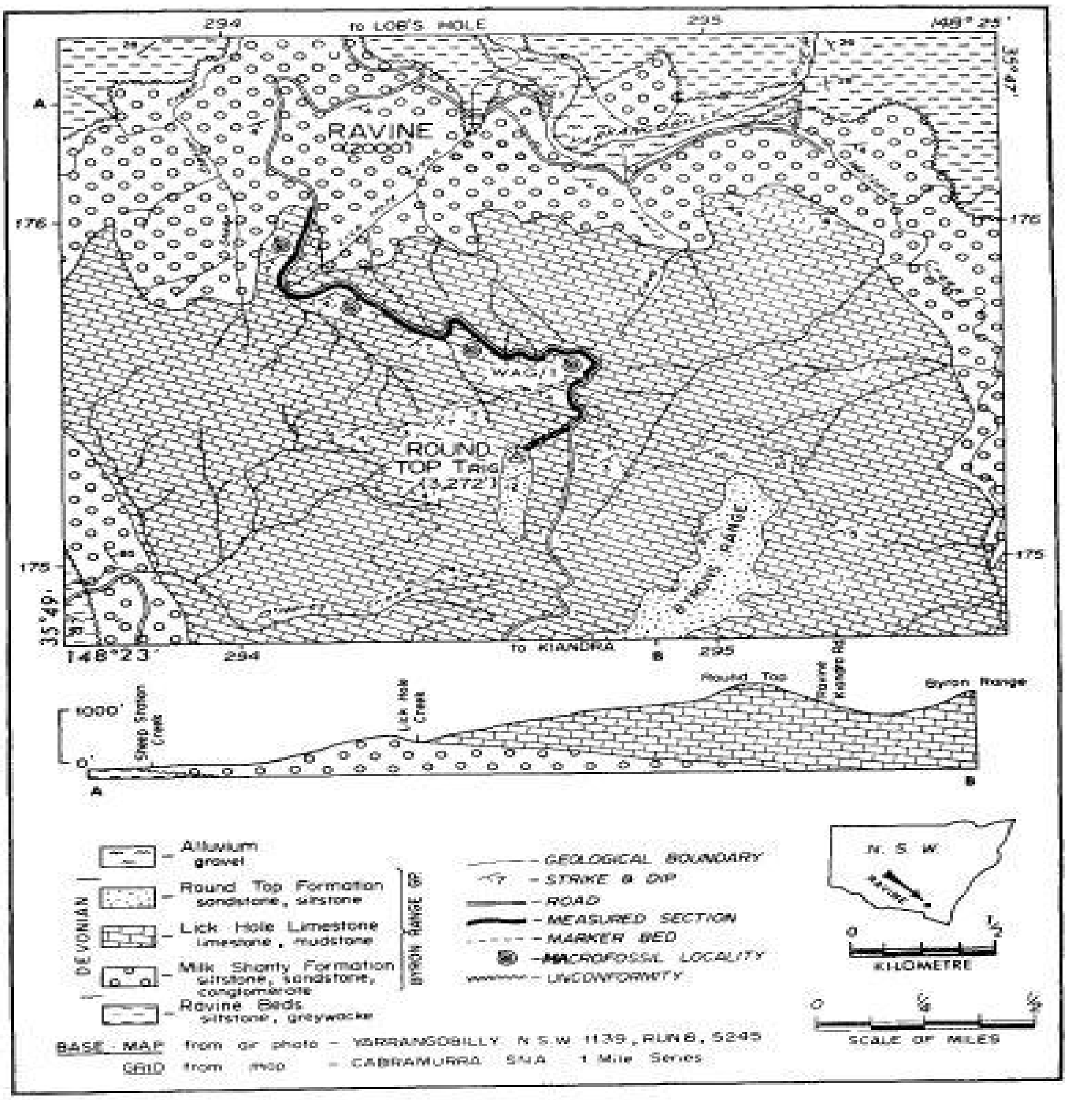


Figure 3.4 Geological map of the Ravine area, showing section measured along Lobs Hole Ravine Road through the type sections of the Lick Hole Formation and overlying Round Top Formation (Flood 1969). Note the extent of the Lick Hole Formation – termed Lick Hole Limestone at the time of this map both upslope (to the west of the road) and downslope (to the east).

iv Site 2: Devonian lava flows forming cliffs on Big Talbingo Mountain

a Summary

The cliff-forming unit on Big Talbingo Mountain was identified as a Geodiversity site in the KNP PoM (2006). It is not specified in the PoM as to which of the five formations comprising the Boraig Group is the cliff-forming unit – as the summary of the geological setting (below) indicates, all five contain resistant layers of volcanic or sedimentary rocks – but most likely this is the Cumberland Rhyolite, which caps the mountain. The resistant beds in the underlying formations of the Boraig Group may also contribute, so it is simplest to define the whole of Big Talbingo Mountain as one geodiversity site, where all the component units of the Boraig Group are exposed. The Big Talbingo Mountain site is not listed as a monitored site in the KGAP (OEH 2012).

b Geological setting and context

The Boraig Group (Moye et al. 1969) comprises five formations – in ascending stratigraphic order, the **Buddong Volcanics** (approximately 1,060 m thick, consisting mainly of rhyolitic lavas with several distinct flows, and very minor tuff and agglomerate beds); **Saddle Tuff** (the lower 90 m composed largely of pink to brown rhyolitic tuff, tuffaceous breccia and agglomerate, overlain by 180 m of volcanic conglomerate with waterworn pebbles in a tuffaceous matrix); **Landers Creek Formation** (mainly consisting of alternating beds of andesitic tuffs and more resistant indurated quartzose sandstone); **Talbingo Basalt** (an andesitic basalt 450 m thick on Big Talbingo Mountain but rapidly diminishing in thickness to the south); and **Cumberland Rhyolite** (a resistant cliff-forming rhyolite 240 m thick, capping Talbingo Mountain). Mapping by Wyborn et al. (1990) shows the outcrop of the Boraig Group to be largely restricted to the ranges surrounding Talbingo Reservoir, particularly on its eastern side. Talbingo Mountain is located towards the northern end of the reservoir on its eastern side, behind the town of Talbingo.

Significance: local/regional. The site is a spectacular geomorphological feature, best viewed at a distance from the adjacent valley around Talbingo, or along the Snowy Mountains Highway passing around its northeastern side. A rough track (suitable for 4WD or walking) off the highway provides access to the summit and passes through the sequence of rocks forming the Boraig Group.

Impacted by Snowy 2.0 construction zone: No – within project area but not affected by construction directly or indirectly. Big Talbingo Mountain is approximately 16 km N of the Talbingo tunnel portal.

v Site 3: Skarn rock at Black Perry Mountain

a Summary

Black Perry Mountain is situated 7 km east of Talbingo and lies on the periphery of the Snowy 2.0 Main Works project area, adjacent to (and immediately outside) its northern margin. It is included in this survey of features identified as a Geodiversity site in the KNP PoM (2006) but is not listed as a monitored site in the KGAP (OEH 2012). The reason for its inclusion as a geodiversity site within KNP is that it is one of only two skarn deposits located in the national park (the other is Garnet Hill at Yarrangobilly, described below). Skarns are calcium-rich mineralised zones formed by alteration of limestone or other carbonate rocks due to contact metamorphism by igneous intrusive rocks. They are characterised by the presence of unusual mineral assemblages that result from the interaction of heat or hot fluids from the intrusion interacting with calcium and other minerals present in the limestone. In the case of Black Perry Mountain, this site is one of only a handful of occurrences of the rare mineral babingtonite known in the world.

Geological setting and context

The occurrence is a Ca-Fe-Si skarn that is widespread over Black Perry Mountain, having formed where the Early Devonian Bogong Granite intruded country rocks (mapped as Ravine beds of Late Silurian age), metamorphosing limestones in the Ravine beds to marble and altering their mineralogy. New minerals produced in the alteration zones include andradite garnet, vesuvianite and wollastonite. Babingtonite is mostly restricted to the skarn-granite contact about 2 km northeast of Black Perry Mountain peak with an additional small outcrop about 1 km due north of the peak (MINDAT website; see Figure 3.5 from Gole 1981). The Ca-Fe-Si skarn bodies are enclosed by thin epidote-rich skarn zones. The resistant peak of Black Perry Mountain is due to the outcrop of the skarn deposit.

Significance: Regional. The site is one of only two recognised in KNP and contains a different mineral assemblage to the other site at Garnet Hill at Yarrangobilly.

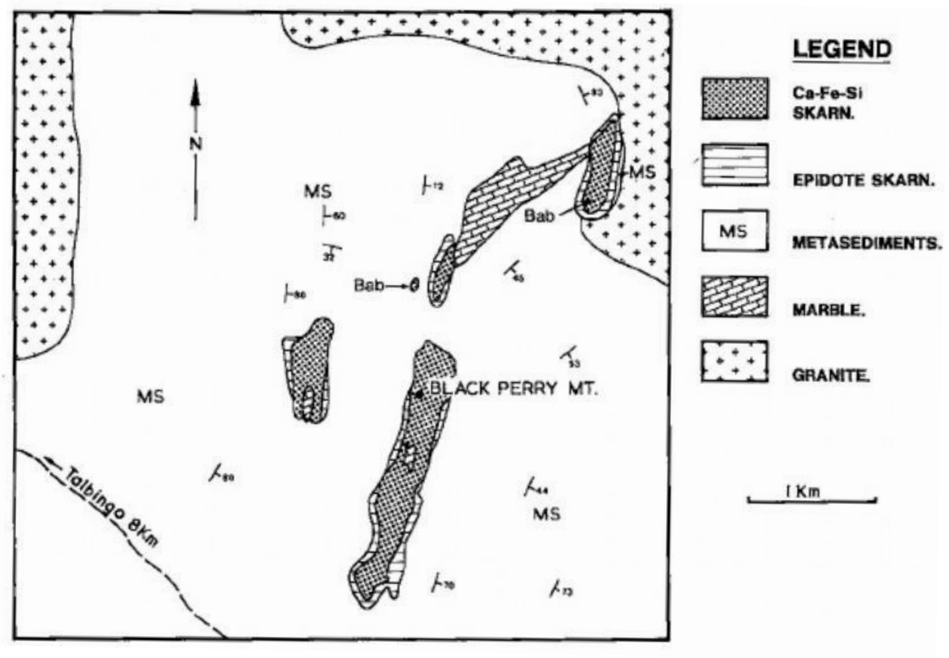


Figure 3.5 Location and geological setting of Black Perry Mountain skarn deposit (from Gole 1981).

Impacted by Snowy 2.0 construction zone: No – the site is peripheral to the northern margin of the project area (the very southern extremity of the skarn may just extend into the project area) and is not affected by construction directly or indirectly.

vi Site 4: Skarn rock at Garnet Hill, Yarrangobilly

a Summary

Garnet Hill is situated 1.4 km east of Yarrangobilly village and forms a small hill on the south side of the Yarrangobilly River. It was identified as a Geodiversity site in the KNP PoM (2006) and additionally is listed as a monitored site in the KGAP (OEH 2012). The reason for its inclusion as a geodiversity site within KNP is that it is one of only two skarn deposits located in the national park (the other is Black Perry Mountain east of Talbingo, described above). Skarns are calcium-rich mineralised zones formed by alteration of limestone or other carbonate rocks due to contact metamorphism by igneous intrusive rocks. They are characterised by the presence of unusual mineral assemblages that result from the interaction of heat or hot fluids from the intrusion interacting with calcium and other minerals present in the limestone. Garnets are particularly common in the skarn at Garnet Hill, hence its name. This site differs from the Black Perry Mountain site is being due to interaction between an intrusive sill and the Yarrangobilly Limestone, rather than a granite batholith intruding limestone lenses within the Ravine beds.

b Geological setting and context

The skarn at Garnet Hill consists of massive andradite garnet, with minor lead, zinc and limonite mineralisation. At the surface the Bogong Granite is about 4 km away, so while this large intrusive body may have contributed to regional metamorphism of the northern part of the Yarrangobilly Limestone outcrop, it is unlikely to have formed a single small skarn deposit restricted to Garnet Hill. Possibly a sill (or dyke) associated with the batholith has caused a localised contact metamorphism of the limestone.

Significance: Regional. The site is one of only two recognised in KNP and contains a different mineral assemblage to the other site at Black Perry Mountain.

Impacted by Snowy 2.0 construction zone: No – the site lies within the Snowy 2.0 Main Works project area but is distant from the Main Works disturbance footprint and is not affected by construction either directly or indirectly.

vii Site 5: Folding of Bowning tectonic episode, Nungar

a Summary

As listed in Schedule 1 of the KNP PoM (2006) it is not clear what exactly this feature refers to, nor where it is precisely located. The site is not monitored under the KGAP program (OEH 2012). It is taken to represent an area where sedimentary rocks that were laid down horizontally were subject to deformation (tilting and folding) during the Bowning 'tectonic episode' – usually referred to in the scientific literature as the Bowning Orogeny. This event spanned a few million years at most across the Silurian-Devonian boundary (centred on 419 Ma). The locality 'Nungar' presumably indicates the Nungar Plain south of Tantangara Reservoir. This area comprises outcrops of two sedimentary rock formations, the former Nungar beds (now Warbisco Shale) of Late Ordovician age, and the Tantangara Formation of earliest Silurian age, both of which predate the Bowning deformation. Owen & Wyborn (1979b) note that the region between the Tantangara Fault and the Cotter Fault (to the east), that includes the Nungar Plain, is marked by intense meridional cleavage-forming deformation.

b Geological setting and context

The timing of the Bowning deformation is usually interpreted to be of latest Silurian or earliest Devonian age, based on a famous unconformity at Bowning in the Yass district of southern NSW between the Elmside Formation (dated by fossils as latest Pridolian to earliest Lochkovian) and the overlying Sharpeningstone Conglomerate (inferred to be of late or latest Lochkovian age). Fergusson (2017, p.5) recently advocated usage of the term Bindian Orogeny in place of Bowning Orogeny; the effects of the Bindian Orogeny (named after Bindi in NE Victoria) are more intense, but the dating of the orogenic episode is less constrained than in NSW. As the Nungar region of KNP is about halfway between Bindi and Bowning, either term will suffice. On the Tantangara 1:100,000 geological map, Owen & Wyborn (1979b) depict an area in the 'Nungar beds' south of Nungar Creek and east of Tantangara Road that is strongly deformed. Wyborn et al. (1979c, p.16, fig. 4) illustrate intense folding in rocks of this unit exposed in a road cut on the Snowy Mountains Highway, between Providence Portal and Adaminaby township.

Significance: Regional. The site is representative of the intense folding developed in sedimentary rocks in the Bowning/Bindian Orogeny.

Impacted by Snowy 2.0 construction zone: No – the Nungar Plain site lies within the Snowy 2.0 Main Works project area but is not within the Main Works disturbance footprint and is not affected by construction either directly or indirectly. Tantangara Road, situated 400-500 m to the west of the westernmost limit of the site, is sufficiently distant that any road upgrade will not impact the geodiversity site.

viii Site 6: Silurian limestone caves, karst & fossils, Cooleman Plain area

a Summary

One of the two Silurian karst and caves geodiversity areas in the northern KNP and also located entirely within the Snowy 2.0 Main Works project area, this site was identified in the KNP PoM (NPWS 2006) and is also closely monitored in the KGAP program for its karst and cave features (OEH 2012). The site consists of several geodiversity phenomena that overlap in their distribution and local extent. The surface karst, which is a relatively modern feature (i.e. forming over the past few million years where limestone is exposed to chemical weathering in subaerial and shallow subsurface environments), is widespread over Cooleman Plain and in the immediate vicinity of the Cooleman Caves, and extends north of Coolamine homestead, occupying an area about 5-7 km in diameter. Separately identified in the KGAP monitoring program (OEH 2012, Appendix 3) are four general access caves – Murray, Left and Right Cooleman, and Barbers caves – adjacent to or very near Caves Creek. Though considerably older than the surface karst features it is not clear when these caves first formed (although this would probably not have happened until the Kosciuszko Uplift). Both the surface karst and the caves are therefore post-Palaeozoic features. Fossils of Late Silurian age are briefly mentioned in the monitoring program as part of the caves site, and a photograph of in situ fossils in limestone at the entrance to one of the caves is shown in the Cooleman caves site monitoring documentation (see Figure 3.6). No further details of the fossils are provided in that document, so additional information is provided below.

Figure 3.6 Fossil megalodont bivalves (large shells forming layer in centre of image) and pentameride brachiopods (smaller shells above and below this layer) near the entrance to Murray Cave at Cooleman Caves (source: Karst & Geodiversity unit, OEH, reproduced in KGAP Appendix 1).

b Geological setting and context

Throughout of the Cooleman Limestone, in spite of widespread recrystallisation, fossils are abundant and fairly well preserved in places. Brachiopods including *Kirkidium* sp. and ?*Pentamerus* generally dominate the fauna, though corals, stromatoporoids (*Actinostroma* sp.), gastropods, bivalves, crinoids, bryozoans, and ostracods also occur. Among the corals identified from this formation (Hill 1954, Owen & Wyborn 1979c) are *Favosites gothlandicus*, *Heliolites daintreei*, *Parastriatopora* sp., *Phaulactis shearsbyi*, *Tryplasma lonsdalei* and *Pycnostylis* sp. A large (100-mm wide) thick-walled megalodont bivalve (presently unidentified) is distinctive at some levels (Figure 3.6), and algal balls (oncolites) are also present. The age of this fauna is late Wenlockian to Ludlovian.

Significance: **Regional** – the site is one of two Late Silurian limestones with caves and karst features within the northern area of KNP (the other is Yarrangobilly). These limestones provide an important record of continued Silurian shallow water carbonate sedimentation in the region, linking the KNP area to the Yass Basin and the Quidong Basin. The majority of the fossils found in the limestone are well known and typical of other Late Silurian limestones in NSW. However, the unidentified large megalodont bivalve is interesting and significant as a comparable fossil is known from the Molong Limestone in central NSW.

International – Cooleman Caves and surrounding karst is the most closely studied karst area in Australia, with research conducted over many decades (initially by Professor Joe Jennings and continued by Andy Spate) being considered of international importance (Spate and Baker 2018).

Impacted by Snowy 2.0 construction zone: No – the site lies within the Snowy 2.0 Main Works project area but is distant from any disturbance zones and is not affected by construction either directly or indirectly. Of particular importance to these karst sites is the preservation of the existing hydrology regime. The hydrology of the Cooleman Caves area is complex and not fully understood (OEH 2012), but is not connected with the main watercourses traversing the area between Tantangara and Talbingo reservoirs. The Cooleman Caves area is at least 18 km north of the Tantangara portal construction zone, and so will not be subject to any vibration or other disturbance from tunnelling work.

ix Site 7: Slumped bed folding, Cooleman Plain area

a Summary

Few details of this site were provided in the KNP PoM where it was identified in the list of known geodiversity sites for the KNP PoM (NPWS 2006). It is not monitored as part of the KGAP program, so is not shown on a map in that document (OEH 2012). However, the site is relatively well known in the scientific literature (Owen & Wyborn 1979c). It is part of the Blue Waterhole Formation that generally overlies the Cooleman Limestone, and is particularly significant in incorporating allochthonous blocks of Cooleman Limestone that have been redeposited into younger sedimentary deposits.

b Geological setting and context

Limestone in the Blue Waterhole Formation is confined to a slumped horizon [Locality A on fig. M19 of Owen & Wyborn 1979c] containing allochthonous blocks of limestone that have yielded Ludlovian age conodonts identical to those obtained from the underlying Cooleman Limestone, which is interpreted as the source of these allochthonous blocks. This site is significant as it provides the best indication of the age of the Cooleman Limestone, that generally is too recrystallised to yield identifiable conodont microfossils. The mention of folding in the description of this site in the KNP PoM possibly refers to the deformation of sediments in the slumped bed when the blocks of Cooleman Limestone fell down slope into unconsolidated mud of the Blue Waterhole Formation.

Significance: The site is of local and regional significance in demonstrating that lithified blocks of the Cooleman Limestone were redeposited into sediments of the younger Blue Waterhole Formation. There are several ways that this could happen, but the most likely is that the Cooleman Limestone (which is a massive shallow water carbonate deposit) gradually subsided as the limestone accumulated in the photic zone, perhaps forming a coral reef. The silt and mud-rich deposits of the Blue Waterhole Formation were deposited on the drowned reefal rocks of the Cooleman Limestone, part of which remained at a higher elevation like a modern-day reef front. Blocks of the older limestone rock were dislodged from the edge of the reef-front cliffs and tumbled down slope into the accumulating soft muds of the Blue Waterhole Formation, leading to the slumped bed as those limestone blocks deformed the unconsolidated muds.

Impacted by Snowy 2.0 construction zone: No – the site lies near the northern extremity of the Snowy 2.0 Main Works project area; it is remote from the Main Works disturbance footprint and is not affected by construction either directly or indirectly.

x Site 8: Silurian limestone caves, karst & fossils, Yarrangobilly

a Summary

This is one of the two main Silurian karst and caves geodiversity areas identified in the KNP PoM (NPWS 2006) in the northern KNP (the other is the Cooleman site, Geodiversity Site 6, described above). Yarrangobilly is also monitored in the KGAP program (OEH 2012) for its karst and cave features in the four publicly-accessible show caves (Figure 3.7). The site consists of several geodiversity phenomena that overlap in their distribution and local extent. The surface karst, which is a relatively modern feature (i.e. forming over the past few million years where limestone is exposed to chemical weathering in subaerial and shallow subsurface environments), is widespread around Yarrangobilly Caves, extending in a NW-trending belt between the Yarrangobilly River and the Snowy Mountains Highway, crossing the highway south of Yarrangobilly village. The northern extent of the main outcrop of Yarrangobilly Limestone is at Garnet Hill (Geodiversity Site 4, described above). Yarrangobilly Caves first formed subsequent to the Kosciuszko Uplift. Both the surface karst and the caves are therefore post-Palaeozoic features. Fossils of Late Silurian age found in the limestone are only briefly mentioned as part of the caves site, so additional information is provided below.

b Geological setting and context

The Yarrangobilly Limestone consists of massive limestone 500-600 m thick. It is of Late Silurian (Ludlovian) age, with that age well constrained (at least in the middle and upper parts of the formation) by conodont microfossils. These range from the *Polygnathoides siluricus* Zone of the middle Ludlovian (at a level 180 m above the base of the formation) to the *Ozarkodina crispa* Zone of uppermost Ludlovian age at the top of the limestone. Corals (both rugose and tabulate varieties) have been described from the upper beds of the limestone (Hill 1954) including the youngest in situ assemblage of halysitid (chain) corals known from Australia (Hamada 1957, 1958; Pickett 1982, p.23). The corals identified include *Tryplasma delicatulum*, *Halysites* sp. cf. H. *lithostrotionoides* (= *Schedohalysites yarrangobillyensis* of Hill), *Heliolites daintreei*?, *Propora*? sp., *Favosites gothlandicus*, *F. forbesi*, *F*. sp. cf. *F. tripora*, *Striatopora* sp., *Alveolites* sp. and *Coenites seriatopora*. Also present, occasionally abundantly is the brachiopod *Conchidium knighti*. Though these macrofossils occur throughout the outcrop area of the limestone, particularly in its upper part, they are commonly found along the banks of the Yarrangobilly River downstream from the Thermal Pool.

Figure 3.7 Yarrangobilly Limestone outcrop opposite entrance to Jillabenan Cave, showing massive bedded appearance and karstification (incipient solution and cave formation) typical of the limestone.

Significance: Regional – the Yarrangobilly site includes one of two Late Silurian limestones with caves and karst features within the northern area of KNP (the other is Cooleman Plain and Cooleman Caves area). These limestones provide an important record of continued Silurian shallow water carbonate sedimentation in the region, linking the KNP area to the Yass Basin and the Quidong Basin. The majority of the fossils found in the limestone are well known and typical of other Late Silurian limestones in NSW.

National/International – Yarrangobilly Caves and surrounding karst is one of the most closely studied karst area in Australia, with research conducted over many decades (Spate and Baker 2018), though it has not been as intensively monitored as the Cooleman Limestone at Cooleman Plain and caves.

Impacted by Snowy 2.0 construction zone: No – the site lies within the Snowy 2.0 Main Works project area but is distant from the Main Works disturbance footprint and is not affected by construction either directly or indirectly. The type section described here will not be affected by secondary impacts due to its remoteness from the Main Works construction areas. Of particular importance to the karst at Yarrangobilly is the preservation of the existing hydrology regime. As documented in the Main Works Water Assessment (EMM 2019) there is no potential for impacts to water in proximity to this site. None of the disturbance zones or construction work associated with the Snowy 2.0 project (further to the south) can potentially impact the hydrology regime that influences karst and cave formation. Yarrangobilly Caves area is at least 4 km north of the underground tunnel, and hence any vibration or other disturbance from tunnelling work will be negligible or non-existent.

One additional geodiversity site listed in the KNP PoM (NPWS 2006) that is shown as occurring in the immediate vicinity of Yarrangobilly Caves is referred to as the Trilobite site. Talent et al. (1975) cited the discovery of the trilobite *Denckmannites* by Vidas Labutis during his Honours thesis mapping project as evidence for a late Silurian age for rocks assigned to the upper part of the Tumut Pond Group near the boundary with the Yarrangobilly Limestone. However, subsequent study by Lesley Wyborn (cited in Pickett 1982, p.45) indicates that the trilobite occurs in the Ravine beds that are partly laterally equivalent to the Yarrangobilly Limestone, or alternatively comes from a mudstone facies of the Yarrangobilly Limestone. The exact location of the trilobite occurrence has not been cited in the published literature, nor has it been publicised by KNP management in any publicly accessible report (presumably as a strategy to keep the site secure).

xi Site 9: Graptolite fossils, Tantangara, Kiandra and Tumut Pond areas

a Summary

Four localities from which Late Ordovician graptolites are known are listed in the KNP PoM (NPWS 2006) as sites of geological significance. They include sites in the Tantangara, Tumut Pond, Kiandra and Byadbo areas. Of these, only the Tantangara and Kiandra sites are located within the Snowy 2.0 Main Works project area. The Kiandra site was unable to be identified from the literature. The Tumut Pond site lies to the south of the project area, but as it contains the most diverse graptolite assemblage it is documented below. Although the stratigraphic context is not given in the KNP PoM (NPWS 2006), these fossils are almost certainly preserved in Warbisco Shale, based on numerous other occurrences throughout southeastern NSW. Details of the exact location of these sites are lacking, but some coincide with graptolite localities described in Sherrard (1954, 1962) which are assigned at best to the antiquated Parish and County land title system, and Fletcher (1955) who provides sketch maps of many sites.

b Geological setting and context

The Tantangara site was identified during the construction of Tantangara Dam, when poorly preserved graptolites were found in a black pyritic slate cropping out in the foundation of the northern half of the dam site (Crook *et al*. 1973, p. 120, fig. 3). One specimen was identified as *Orthograptus calcaratus* var. *tenuicornis*, which ranges through the Gisbornian and Eastonian stages of the Late Ordovician (Owen & Wyborn (1979c, p.M58). At the time of discovery the strata containing these fossils was named the Nungar beds, but it is certain that – given the description of the lithology, and the age indicated – that the black pyritic slate can be assigned to the Warbisco Shale. The Tantangara site is very restricted in extent and is not located within the Snowy 2.0 disturbance zone, as it is situated NW of the dam wall.

The Tumut Pond locality (Owen & Wyborn 1979c, fig. M5) is outside (just to the south of) the Snowy 2.0 Main Works project area. The graptolites occur in a black slaty shale near the top of the Nine Mile Volcanics in its type section, close to the Long Plain Fault. A diverse fauna listed by Sherrard (1954) includes *Dicellograptus divaricatus* var. *salopiensis*, *Climacograptus scharenbergi*, *Mesograptus multidens*, *Glyptograptus teretiusculus*, *Amplexograptus arctus*, ?*Retiograptus geinitzianus*, *Lasiograptus mucronatus*, and *L. mucronatus* var. *bimucronatus*. Sherrard derived a Gisbornian (early Late Ordovician) age for this fauna, but these specimens are poorly preserved and their identifications are in need of reassessment – most likely they are slightly younger (Eastonian, or middle Late Ordovician) in age.

Significance: Local/Regional. The Late Ordovician graptolite sites recognised in the KNP PoM are representative of the occurrence of fossils in rocks of this age in the Park. In many graptolite sites in the Warbisco Shale occurring throughout southern NSW, preservation of the fossils is much better than at the Tantangara site. Preservation there has been detrimentally affected by the pervasive regional metamorphism caused by granite batholiths underlying much of KNP.

Impacted by Snowy 2.0 construction zone: No – the Tantangara site lies within the Snowy 2.0 Main Works project area but is well outside any disturbance zones associated with upgrades to Tantangara Road and is not affected by construction in the vicinity of the Tantangara tunnel portal (or associated infrastructure) either directly or indirectly. Although the Kiandra site cannot be determined accurately from the published literature, this area is distant from any construction or disturbance zones that are part of the Snowy 2.0 project.

The Tumut Pond graptolite locality is outside (just to the south of) the Snowy 2.0 Main Works project area, on Tumut Pond Creek immediately upstream from where it flows into the eastern side of Tumut Pond Reservoir, south of Cabramurra.

xii Site 10: Serpentinite along major fault with nickel and chromium, Link Road

a Summary

Serpentinite is a metamorphic rock caused by the hydrous alteration of ultramafic igneous rocks to produce a characteristic suite of minerals (mainly antigorite, lizardite and chrysotile, the latter including some forms of asbestos). Typically it has a greasy feel due to talc mineralisation and a greenish colour (sometimes resulting from chlorite), and may break with a sharp-edged conchoidal fracture when fresh. Often the rock weathers rapidly and can become soft and easily eroded. Most commonly serpentinite occurs along major faults and shear zones. In KNP it is found along the Tumut Fault Zone (continuous further north as the Gilmore Fault Zone).

b Geological setting and context

The most accessible example in KNP of serpentinite is a man-made exposure in a roadside quarry (now abandoned) on Link Road between Mount Selwyn and Cabramurra (Figure 3.8). The serpentinite is brecciated in part, with rotated clasts of ultramafic rock (metapyroxenite and hornblende amphibolite) embedded in a dark chloritic matrix, reflecting tectonic movements along the fault zone. The age of the serpentinite is controversial, as is the means of its emplacement. Stuart-Smith (1991) interpreted the age as Cambrian-Ordovician, suggesting its derivation from the basement rocks of the region (which would make it the oldest rock known in KNP) while others have suggested an Early Silurian age (on the basis of isotopic dating). Pods of chromitite, a dense layered ultramafic rock composed mainly of the mineral (an iron-chromium oxide spinel group) of the same name, are found in association with the serpentinite.

Significance: Regional. The site is representative of an unusual rock type which is restricted in NSW to major shear zones, the main ones being the Great Serpentinite Belt in the western part of the New England region, and the Coolac Serpentinite and the Gilmore Fault Zone in southern NSW. In KNP, the southern extremity of the Gilmore Fault Zone is the Tumut Fault Zone, that terminates just south of Cabramurra. This site is listed as a geodiversity site in the KNP PoM (NPWS 2006) and is monitored under the KGAP program (OEH 2012).

Impacted by Snowy 2.0 construction zone: No – the site lies within the Snowy 2.0 Main Works project area but is not close to any disturbance zones and is not affected by construction either directly or indirectly. No roadwork is proposed on Link Road near this site.

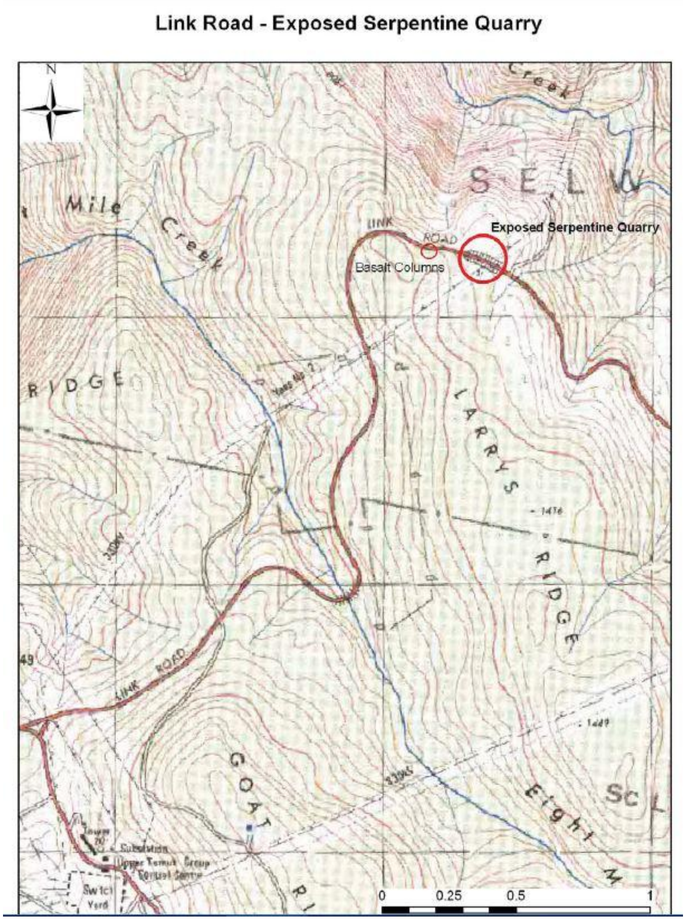


Figure 3.8 **Location of serpentinite quarry (now exposed in cutting on Link Road, approximately 3 km NE of Cabramurra and about 2.5 km west of intersection with Lobs Hole Ravine Road. No roadworks associated with Snowy 2.0 are anticipated to impact this site. (Source: KGAP Appendix 1)**

3.6 Newly recognised Palaeozoic geodiversity sites in the Main Works Project Area

It is readily apparent by reference to Table 3.1 that the majority of geodiversity sites previously identified as occurring within KNP are located within the northern sector of the park; most also lie within or in close proximity to the Snowy 2.0 Main Works project area. To ensure that no other sites of geodiversity significance were present within the disturbance or construction zones of the project area, a thorough literature review of all Palaeozoic geological features in the region was conducted. This resulted in identification of 30 areas with potential for geodiversity significance that are not currently recognised within the KNP PoM or KGAP. These additional sites were assessed according to their stratigraphic unit, based on geodiversity values that are documented below. Of these newly recognised sites, only two localities in the Kellys Plain Volcanics, in the vicinity of the Tantangara portal construction area, were found to be within the Main Works disturbance area and therefore likely to be impacted by construction works. Recommendations are provided to mitigate the impacts identified as are opportunities to enhance the geodiversity and geotourism potential of these two sites.

Because the great majority of geodiversity sites identified in the assessment process are not affected by Snowy 2.0 works, their documentation is included in an Appendix to this report. These new sites should be considered and evaluated by KNP for opportunities to enhance the management of geodiversity values through research and to increase geotourism potential of the Park. Recognition of these opportunities is a positive outcome of the Snowy 2.0 geodiversity assessment.

3.6.1 Method for identification and assessment of geodiversity potential

The review of additional Palaeozoic geodiversity sites report utilises a quick and practical guide to the documentation of geodiversity features (original to this Report) that is based on a succinct categorisation of sites determined by the 5 Rs – **Rarity**, **Reference**, **Representation**, **Relationships**, and **Research** potential and values. These five categories are not necessarily mutually exclusive as several may be present at the one locality, section or outcrop. This approach is supplemented by assessment of their geological significance as local, national or international.

Rarity of geodiversity features is a relative criterion that depends on the geographic context – what is locally rare in KNP may be a relatively common feature on a national or global scale. Occurrence of a particular mineral or fossil, or a specific sedimentary (depositional) or igneous (intrusive or extrusive) may be limited to one or two places in KNP, but could be common elsewhere in the state, or in Australia. Rarity also depends on what minerals and rock types (and their ages) are present in the region. Rare geodiversity features may be safeguarded by affording them no publicity, or if they are large scale and robust, they might be suitable to be publicised as a major geotourism attraction.

Reference sections or localities include formally-defined type sections of a formation, or type areas of an igneous suite, that embody the standards on which knowledge of the lithological, mineralogical or palaeontological characteristics of that unit are based. Type sections, localities and areas provide details and criteria against which other occurrences of the same formation or suite are judged, thereby forming the basis of local and regional geological correlation.

Representative features are those that characterise the variation within a rock unit, whether it be depositional (sedimentary or volcaniclastic) or intrusive/extrusive. Particular metamorphic features may also be representative. They may be unique to, or characteristic of, a particular formation or rock suite, but are not necessarily rare. Examples could include graded bedding or the clast composition of conglomerates in sedimentary rocks, or cooling features such as hexagonal columns in volcanic rocks. In terms of the representative geomorphic expression of a geological formation or igneous suite, such areas are more widespread geographically and are less formally defined.

Geological relationships between adjacent rock units are of great value in determining the regional geological history. Boundary relationships such as unconformities, or erosional or karstified surfaces, are especially significant in this regard, as they are important in conveying an appreciation of the forces of deformation, uplift and erosion that take place over geological time. Intrusive relationships have added significance if the intrusive body has been isotopically dated, as this provides an age relationship to the rock that it intrudes.

Geodiversity sites and features may have high potential for **research** purposes. Type sections and areas fall into this category, as do rare features (which are often identified or interpreted through research). Depending on their rarity and fragility, access to some geodiversity sites may need to be restricted to those undertaking approved scientific research – for example, via a scientific sampling/collecting permit system such as occurs in KNP under the PoM (NPWS 2006). At other geodiversity sites which are suitable for public inspection and education, scientific research may provide the basis for interpretative signage on site, or for publicity at visitor centres or via books and other media.

Brocx & Semeniuk (2007) provide a useful framework for the assessment of geoheritage significance which may equally be applied to geodiversity as the concepts are similar. In their scheme, significance can be evaluated on the basis of how common a feature is within a particular scale of reference (local/regional/national/international), and how important it is intrinsically or culturally. In this report, only the assessment of relative commonality is taken to be an appropriate guide to significance.

3.6.2 Newly recognised geodiversity sites impacted by Snowy 2.0 construction work

i Kellys Plain Volcanics

Of the 30 geodiversity features newly identified in this report, two sites in the Kellys Plain Volcanics on the western shore of Tantangara Reservoir (Figure 3.9) are assessed as likely to be directly impacted by construction during the Snowy 2.0 project. Specific measures are proposed for both sites that will mitigate potentially detrimental effects of disturbance or proximity to construction or associated infrastructure.

a Kellys Plain Volcanics Type Locality (category: Reference site)

Owen & Wyborn (1979c, p.M166, fig. M11) proposed the large disused quarry at Traces Knob (1500 m southwest of Tantangara Dam) as the type locality of the Kellys Plain Volcanics (Fig. 3.9). About 25 m of fresh massive dark bluish quartz-feldspar porphyry, typical of much of the Kellys Plain Volcanics in the southern part of its outcrop, is exposed in this quarry. It is the only artificial exposure of the Kellys Plain Volcanics, and is also one of the few localities where unweathered rock is exposed.

b *Significance*: Local/regional

Impacted by Snowy 2.0 construction zone: Yes – the disused quarry is located adjacent to Quarry Trail Road and the Tantangara accommodation camp and might be directly impacted by road or camp construction.

Recommendations: During construction, ensure that the exposed rock faces are not permanently covered and that the quarry is not used for disposal of excavated rock or other waste.

This and nearby sites exhibiting various features of the Kellys Plain Volcanics has potential for geotourism and could be enhanced through the installation of an interpretative sign outlining a local geotrail connecting all five sites, though it will not be feasible to investigate this potential until all construction work has finished. It should be noted that at present the quarry walls are regarded as unstable and so public access is currently unavailable.

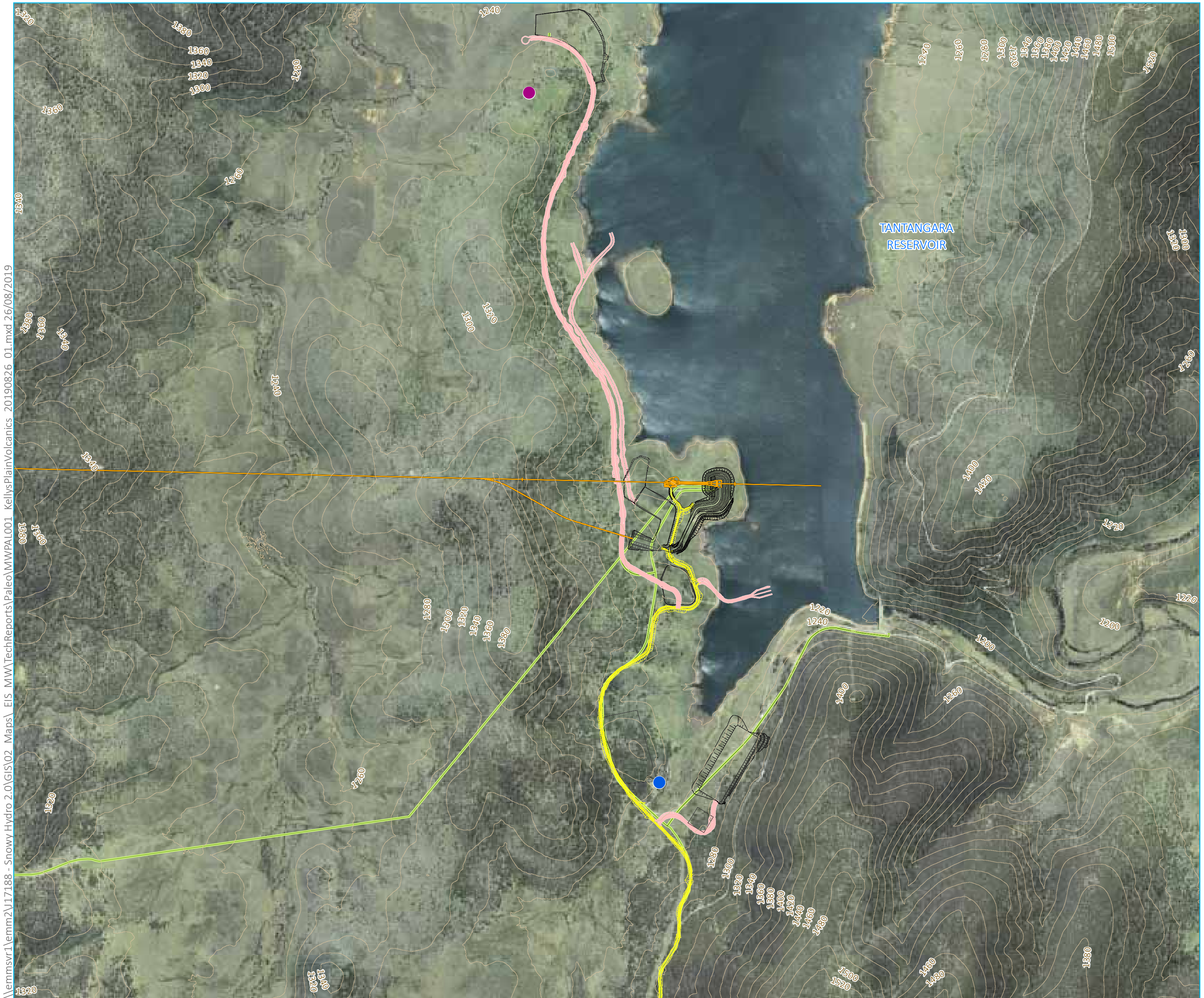
ii Kellys Plain Volcanics agglomeratic porphyry (category: Representative lithological site)

According to Owen & Wyborn (1979c, p.M169), an excellent example of agglomeratic porphyry is exposed on the western shore of Tantangara Reservoir due east of the confluence of Nungar Creek with the reservoir, where rounded to angular fragments of quartz-feldspar-biotite porphyry 10 to 500 mm in diameter are enclosed in a porphyry with similar phenocrysts but darker matrix.

Significance: Local/regional – a spectacular and representative example of the characteristic lithology of the Kellys Plain Volcanics, suitable for scientific, educational and geotourism purposes.

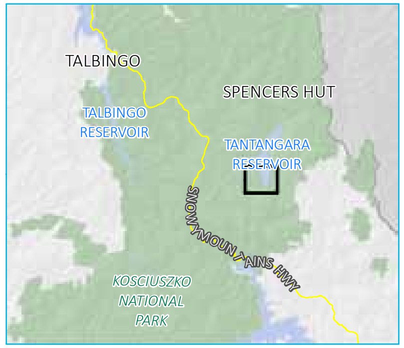
Impacted by Snowy 2.0 construction zone: Potentially yes – the outcrop is adjacent to (and probably just northwest and southwest of) the Tantangara excavated rock emplacement area. Excavated rock emplacement will need to be carefully monitored to ensure that adequate and representative examples of the agglomeratic porphyry are available for public inspection away from the disturbance zone once construction is finished. Aerial photographs of the site (Figure 3.9) indicate that large areas of outcrop are present outside the areas required for site and road establishment. Hence it is regarded as unlikely that the boundaries of the excavated rock emplacement area will require modification, but it would be appropriate for geologists to confirm this with a field inspection as per the following recommendation.

Recommendation: Appropriately qualified geologists should identify the outcrops of agglomeratic porphyry prior to construction and ensure that the best examples are not covered by the excavated rock emplacement. After construction is completed, public access should be maintained to enable representative examples of this rock type to be viewed outside the excavated rock emplacement area.



Source: EMM (2019); Snowy Hydro (2019); PhotoMapping (2018); FGJV (2019); DFSI (2017); GA (2015); LPMA (2011)

GDA 1994 MGA Zone 55



KEY

- Kellys Plain Volcanics agglomeratic porphyry
- Tantangara Quarry – Kellys Plain Volcanics
- 10 m contours

Snowy 2.0 Main Works operational elements

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

Snowy 2.0 Main Works construction elements

- Temporary construction compounds and surface works
- Temporary access road

Kellys Plain Volcanics potential geodiversity sites

Snowy 2.0
A review of Palaeozoic geodiversity feature within the Snowy 2.0 Main Works project
Main Works

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4 Management of geodiversity sites

4.1 Impact of construction on Palaeozoic geodiversity sites discussed in this study

4.1.1 Previously known geodiversity sites

Ten geodiversity sites located on outcrops of Palaeozoic rocks had previously been identified as occurring within, or immediately adjacent to, the Snowy 2.0 Main Works project area (Table 3.1). Of these only one – fossiliferous strata of the Lower Devonian Lick Hole Formation exposed along the Lobs Hole Ravine Road – will be directly impacted by construction associated with the project. The Lick Hole Formation was determined to be sufficiently laterally and vertically extensive to cope with the proposed Main Works road widening, which might also have positive outcomes in terms of exposure of fresh, relatively unweathered rock, potential discovery of additional fossil species, and possible opportunities for additional scientific research and public education (Table 4.1).

The Lick Hole Formation in the Ravine area was one of three karst areas identified within KNP (Spate & Baker 2018), all of which are located within the Snowy 2.0 Main Works project area. All three are subject to NPWS monitoring under the KGAP program (OEH 2012). The other two areas are much more extensive and include thick deposits of massive limestone, and in both cases are of Late Silurian (Ludlovian) age. These include the well-known caves and karst areas at Yarrangobilly and Cooleman. Neither of these areas will be impacted directly or indirectly by the Snowy 2.0 construction works zones. Of particular importance to these karst sites is the preservation of the existing hydrology regime.

The Water Assessment prepared for the Main Works EIS (EMM 2019) conducted groundwater modelling to predict impacts to water drawdown resulting from underground works for Snowy 2.0. The results of this study across the Snowy 2.0 tunnel alignment reveals two major concentrations of water drawdown, one immediately west of the Tantangara portal, and the other centred on the area where the tunnel passes under the Snowy Mountains Highway at considerable depth.

The western shore of Tantangara Reservoir consists of an extensive area of Kellys Plains Volcanics abutting Cooleman Plains Group limestones in the adjacent Nungar Creek Valley. That area is not listed in the KNP PoM for karst features, and is not in continuity with limestones 15-16 km north at Cooleman Caves, so there will be no possible impact on the Cooleman karst.

The water drawdown maxima underlying the Snowy Mountains Highway in the vicinity of Mt Gooandra lie within Ordovician Kiandra Group rocks on the eastern side of the Long Plain Fault zone. As detailed in the Main Works EIS Water Assessment (EMM 2019) drawdown from proposed underground works at this location will have negligible effects on the hydrology of the Yarrangobilly karst area.

In order to complete a thorough, up-to-date review of geodiversity within the Snowy 2.0 Main Works project area, most of the other previously known sites listed in Table 3.1 were documented in varying detail, dictated largely by the amount of information that could be gleaned from an extensive literature survey supplemented by field visits by the writer to two sites (Ravine and Yarrangobilly).

Table 4.1 provides recommended mitigation measures for those geodiversity sites within the Snowy 2.0 Main Works project area that will be directly impacted by construction works, including the previously known Lick Hole Formation fossiliferous section on the Lobs Hole Lobs Hole Ravine Road, and the two newly identified sites in the Kellys Plains Volcanics on the western shore of Tantangara Reservoir.

4.1.2 Potential geodiversity sites

Several areas along roads that will be upgraded as part of Snowy 2.0 Main Works may potentially provide significant new discoveries and increase knowledge of Palaeozoic geodiversity sites within the Snowy 2.0 Main Works project area. The main risk posed by the project to such features is the possibility that they might not be recognised by construction personnel and may be unwittingly damaged or destroyed by construction activities. However, the roadworks also provide opportunities for new discoveries to be made by exposing fresh rock in road cuttings and infrastructure excavations. Two main areas have been identified in this study, where it would be beneficial for geologists to closely examine new cuttings during and after construction work.

Tantangara Road, leading from the Snowy Mountains Highway north to Tantangara Dam, passes through small areas mapped as Nungar beds (now Warbisco Shale). Black shale in this formation is likely to contain graptolites of Late Ordovician age. If found, these should be carefully collected and the locality details recorded.

Marica Road and **Marica Road West**, providing access from the Snowy Mountains Highway west to Lobs Hole, and **Lobs Hole Road** leading to Talbingo portal, will be upgraded during the Snowy 2.0 construction phase. These routes cross areas where the geology is poorly known (in the case of the Ravine beds and Boraig Group on the western side of the Long Plain Fault Zone) or contentious (such as the belt mapped as Kiandra Group on the east side of the Long Plain Fault Zone. No geodiversity sites have been suggested along the course of these access roads, solely due to the lack of detailed information available. It will be particularly important to have geologists check any fresh cutting along these routes, especially for fossils which are very rare in the Ravine beds and Boraig Group.

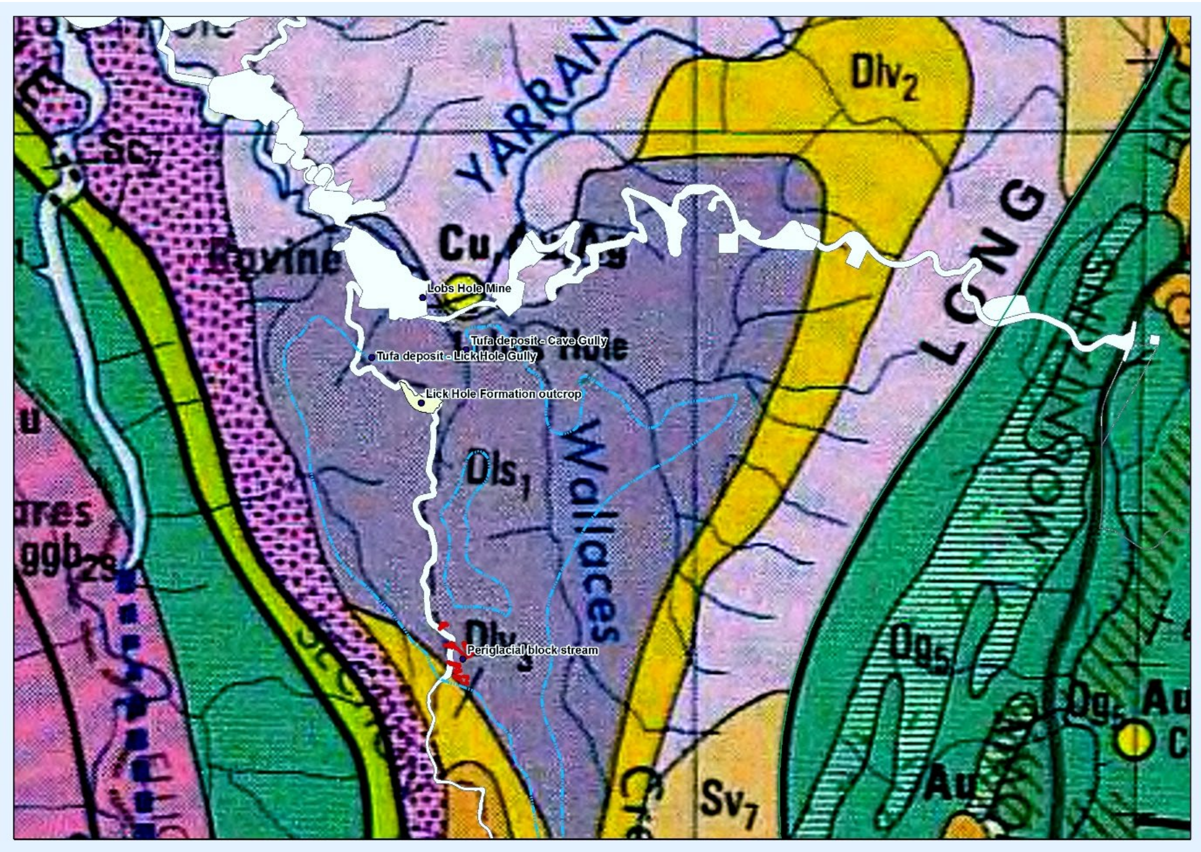

Figure 4.1 Roadworks and associated infrastructure (shown in white)

Roadworks and associated infrastructure (shown in white) as part of Snowy 2.0 Main Works, superimposed on geological map of Wyborn et al. (1990). Marica Road, commencing at the Snowy Mountains Highway, initially traverses Ordovician Kiandra Group (shown in green) before intersecting Ravine beds (pink) and Boraig Group (orange). Marica Road west passes mainly through Byron Range Group and Ravine beds east of Lobs Hole. Lobs Hole Road crosses Byron Range Group and Ravine beds on its way to Talbingo portal. There are opportunities for potential new discoveries and new geodiversity features and sites to be found during the upgrades of these roads, as all these rock units are relatively poorly known. Map of roadworks courtesy of EMM/Snowy Hydro.

4.2 Risks and sensitivities relating to impacted Palaeozoic geodiversity sites

Risks and sensitivities relating to the three Palaeozoic geodiversity sites (Lobs Hole Ravine Road fossil site, and two sites in the vicinity of the Tantangara Reservoir portal and associated infrastructure) identified in this study as being directly impacted by Snowy 2.0 construction are summarised in Table 4.1.

For the fossil site on Lobs Hole Ravine Road, road widening during the Main Works phase is unlikely to remove more than a small fraction of the available rock resource, which occupies most of the hill upslope from the road. The proposed widening and minor realignment will primarily have the effect of excavating weathered rock from the surface of the cuttings, with plans in place to distribute representative samples of the fossil-bearing spoil to palaeontologists in state and federal geological surveys to enable further specialist study of undescribed fossils. Any new discoveries may potentially increase the geodiversity significance of the site. Removal of weathered rock surfaces and exposure of fresh rock faces will not affect the fossiliferous nature of the rock, other than preventing loose fossil specimens being taken from the cuttings. Creating a wider road, possibly with pull-over bays on the verge of the road, will increase safety for visitors to the site. In the future, after completion of construction, it might be possible to enhance the site with interpretative signage organised by KNP.

For the two sites in the Kellys Plain Volcanics, on the western shore of Tantangara Reservoir, the risks to both involve covering up existing rock exposures and preventing access to the sites after construction work is complete. One site, the disused Traces Knob quarry near the southern-most point of the reservoir, is adjacent to Tantangara Road and Quarry Road, and may potentially be impacted by road construction or site establishment at Tantangara accommodation camp. The other site, north of the Tantangara portal, is adjacent to the spoil heap for storage of rock spoil excavated from the tunnel. It is recommended that the area immediately surrounding the proposed spoil emplacement area be investigated by a geologist to ascertain that sufficient representative examples of the agglomeratic porphyry remain accessible outside the area to be covered by spoil. This is a judgement that can only be made by a geologist on site before construction commences. Both sites could potentially be incorporated into a geodiversity suite (including three other sites in the vicinity that are not likely to be directly impacted) once construction is finished, so it is important to retain public access to these rock exposures. There are potential safety issues concerning unstable rock walls at the Traces Knob quarry, which currently is closed to the public. This will need to be addressed after the conclusion of construction work and hence is not a concern during the construction phase.

Indirect impacts arising from construction during the Snowy 2.0 project were considered for all sites documented in this report, including potential changes to hydrological regime and possible damage from vibration during excavation and associated plant movement. A buffer zone of no less than 80 m laterally was considered sufficient where roadworks were involved to guard against damage to adjacent sites. Wherever possible and appropriate, distance from major construction works was calculated and noted in documentation of each site (summarised in Appendix Table 1). No indirect impacts were identified to any sites in this Table.

4.3 Opportunities for increased awareness of Palaeozoic geodiversity in KNP

The Snowy 2.0 Main Works development presents opportunities for substantially enhancing the appreciation of Palaeozoic geodiversity within KNP in relation to research and public education.

4.3.1 Scientific research opportunities

Geological studies in KNP substantially lag behind biological studies, and hence the number of geodiversity sites is relatively small. Only in terms of karst studies, and to a lesser extent, research into Pleistocene glaciation and its effects on geomorphology in the vicinity of the high elevations around Mt Kosciuszko, has substantial progress been made towards a relatively complete documentation of geological features and history in these fields. Recent mapping has demonstrated that the reconnaissance mapping undertaken 40-50 years ago is due for revision and reassessment.

Investigation and construction activities associated with Snowy 2.0 Main Works, including geotechnical testing, excavations, new road cut exposures along existing roads and road development in previously untracked areas, will undoubtedly reveal previously undocumented geodiversity features. In terms of Palaeozoic geodiversity covering the Ordovician, Silurian and Devonian periods, it is likely that new fossil discoveries will lead to greater precision in correlation of sedimentary rock formations locally and regionally. Artificial exposures such as road cuts and quarries are often good sources of new discoveries in fresh rock. It is strongly recommended that a geologist closely examine any new rock exposures excavated during the construction phase in order to capture the potential for new discoveries.

4.3.2 Public education and geotourism opportunities

Awareness by the public of geodiversity leads to a wider appreciation of our natural heritage. This study, focussing on only a small region of KNP, has demonstrated that many new geodiversity sites are waiting to be documented and brought to the attention of visitors to KNP. As suggested in the KGAP (Key Action 5.2 and Appendix 1 of that report), this and similar studies will help fulfil two of the aims of the KGAP, i.e. to promote opportunities for increasing visitation to interesting and/or significant geological sites, and to increase awareness, appreciation and understanding of the geodiversity of KNP (p.5). To maximise the opportunity for geotourism, it is recommended that liaison be established and maintained with the Geological Survey of NSW which has an active public awareness and outreach program centred around the establishment of geotrails in some of the state's most spectacular scenic landscapes.

Table 4.1 Key recommendations for management of Palaeozoic geodiversity sites likely to be impacted during construction

Geodiversity site/category	Likely impact of construction	Recommendations for management	Current status	Risk/ sensitivity/ opportunity
Lick Hole Formation Type Section and fossil locality (Reference site and Representative fossil site)	Widening of Lobs Hole Ravine Road will completely remove weathered face of cuttings containing fossils, but will reveal fresh fossiliferous rock.	Mitigation of impact of road widening for Exploratory Works involved weathered spoil being sent to experts for study. Additional widening for Main Works will reveal fresh fossiliferous rock. Widening expected to benefit safety, research and public education about the site by allowing sufficient safe space for stopping. Final road design should incorporate interpretive signage and safe stopping space within the proposed road and disturbance footprint where practical.	Included in KNP PoM as a geodiversity site, being the only accurately-dated fossiliferous Devonian rocks known in KNP. Not monitored under KGAP. Fossils currently visible on outcrop. Unsealed road is barely one lane wide, passing through entire thickness of Lick Hole Formation. Plenty of additional outcrop is present higher and lower on hillside.	No risk of depletion of fossiliferous rock. Opportunity for research and public education on site – potential for site improvement with interpretative signage.
Kellys Plain Volcanics Type Locality (Reference site)	Disused Traces Knob quarry could potentially be directly impacted by construction works on Quarry Trail and Tantangara accommodation camp.	During construction phase, ensure that the quarry is not in-filled. After construction phase, consult with NPWS regarding opportunities to enhance the geotourism potential of impacted sites. An opportunity that could be considered in consultation with NPWS is a geotrail for the Kellys Plain Volcanics linking five geodiversity sites in this formation in nearby vicinity, complementing the engineering works.	Not previously listed as a geodiversity site in KNP PoM. Type locality is the abandoned quarry at Traces Knob which is located adjacent to Quarry Trail Road leading to the eastern tunnel portal construction site. This site provides the standard against which other occurrences of this geological unit are compared and is an essential component of the potential Kellys Plain Geodiversity geotrail.	Risk of loss of access after construction if quarry is infilled with rubbish. Safety concerns about unstable quarry walls currently limit or prevent public access. Opportunity for KNP to showcase type section and provide access after works if these safety issues can be addressed.
Kellys Plain Volcanics agglomeratic porphyry (Representative lithological site)	Outcrop could potentially be covered by spoil which making it inaccessible to the public; possible damage by excavation machinery.	Identify outcrops of agglomeratic porphyry prior to construction of Tantangara portal. Spoil placement should leave some of the best examples of agglomeratic porphyry exposed. After construction phase, consult with NPWS regarding opportunities to enhance the geotourism potential of impacted sites. An opportunity that could be considered in consultation with NPWS is a geotrail for the Kellys Plain Volcanics linking five geodiversity sites in this formation in nearby vicinity, complementing the engineering works.	Spectacular and representative example of lithology forming most of the Kellys Plains Volcanics in the Nungar Creek valley and Kellys Plain near Tantangara Reservoir. Best site is located north of Tantangara portal, adjacent to the Tantangara spoil storage site	Risk of damage from being partly covered by spoil heap and loss of access. However, outcrops of this rock type are likely to extend outside area of spoil emplacement. Opportunity for KNP to include site in future Kellys Plain geodiversity suite.

Table 4.2 Key recommendations for management of Palaeozoic geodiversity features potentially encountered during construction

Geological unit	Likely impact of construction	Recommendations for management	Current status	Risk/ sensitivity/ opportunity
Temperance Formation & Nine Mile Volcanics	Widening or upgrading of Marica Road may potentially reveal fresh exposures of rock.	Following construction of Marica Road, a geologist should investigate any new exposures in cuttings made during the road upgrade, with emphasis on finding fossils that would assist in age determination of the rock units. An excavated material management plan will be prepared and will included measures for management of unexpected geological finds.	The eastern-most part of Marica Road, commencing at its junction with the Snowy Mountains Highway opposite Mt Gooandra, initially traverses a narrow belt of Ordovician rocks mapped as Kiandra Group.	Opportunity to sort out contentious mapping interpretation.
Warbisco Shale (graptolite fossils)	Upgrading of Tantangara Road may reveal well preserved graptolites on bedding planes in black shale.	Following construction of Tantangara Road, a geologist should investigate new exposures of black shale along Tantangara Road should be investigated for graptolite fossils. Any specimens of graptolites that are found should be carefully collected to prevent damage, and provided to a relevant specialist. An excavated material management plan will be prepared and will included measures for management of unexpected geological finds.	Potential locations for Warbisco Shale to be encountered are confined to Tantangara Road, particularly in areas mapped by Owen & Wyborn (1979b) as the former 'Nungar beds'.	Opportunity to increase limited number of sites with graptolite fossils previously identified in KNP PoM and KGAP.
Tantangara Formation (chert outcrop)	None - It is unclear whether this site falls within the Snowy 2.0 construction zone or not, but this appears to be unlikely.	It would be useful to sample this chert as it may help resolve the age of the rocks in the vicinity. This sampling should be done prior to works commencing only if the site is found to fall within the disturbance footprint. Otherwise, sampling as part of a research project can take place after construction concludes.	In Appendix D (Section 5.2.2 of the SMEC Geological Reconnaissance Report dated July 2018) an isolated occurrence of chert in the Tantangara Formation is noted in Nungar Creek valley (although the exact locality is not given, it is recorded Placemark 547 in the Appendix of SMEC Geological Field Notes).	Opportunity for new geodiversity site if the extremely fine grained, grey-green chert at this locality is found to contain identifiable microfossils.
Ravine beds	West of the Long Plain Fault Zone this unit is traversed by both Marica Road West and Lobs Hole Road leading to the	Any fossils that are found during widening of either road, or in any other excavations, should be carefully collected and brought to the attention of a relevant specialist.	Relative to many of the other Palaeozoic stratigraphic formations that are mapped in the KNP, the Ravine beds is poorly known. It is an informal unit, without a type section, and seems	Opportunity for new discoveries in a stratigraphic unit in

Table 4.2 Key recommendations for management of Palaeozoic geodiversity features potentially encountered during construction

Geological unit	Likely impact of construction	Recommendations for management	Current status	Risk/ sensitivity/ opportunity
	Talbingo portal. Upgrading of either road may create new exposures of Ravine beds with potential for new discoveries.	An excavated material management plan will be prepared and will included measures for management of unexpected geological finds.	(with one possible exception – a trilobite that may belong to another formation and whose location is unknown) to lack fossil evidence of its age. (Figure 3.7).	which fossils are almost unknown
Boraig Group (fossil locality)	The Landers Creek Formation is most likely to be found in the western part of the area, between Lobs Hole and the Talbingo portal. Upgrading of the Lobs Hole Road may reveal fossils.	Any fossils that are found during widening of the road, or in any other excavations, should be carefully collected and brought to the attention of a relevant specialist. An excavated material management plan will be prepared and will included measures for management of unexpected geological finds.	Sandstones and siltstones interpreted to be lacustrine deposits (containing fragmentary fossils of early land plants) were reported from the Lobs Hole region in rocks of the Boraig Group (Moye et al. 1969, p.144). The formation and locality details are not given (the Landers Creek Formation is most likely. Early land plants are relatively uncommon, and therefore it would be worthwhile to flag this as a potential Geodiversity site, pending further information.	Opportunity for new discoveries in a stratigraphic unit in which fossils are almost unknown

5 Summary and conclusions

This report presents a geodiversity review conducted for the Snowy 2.0 Main Works EIS. It includes:

- An updated overview of the record of Early Palaeozoic (Ordovician, Silurian and Devonian) geological history in KNP, based on the widely-known scientific literature on the region that culminated in the compilation of the Geological Map of Kosciuszko National Park (Wyborn et al. 1990), supplemented by recent mapping since the mid-2000s (in some instances unpublished) that has led to reassessment of some aspects of the Ordovician history of this area;

- A review of Palaeozoic geodiversity in the Snowy 2.0 Main Works project area within northern KNP, with a focus on features within the project disturbance area, leading to recognition and documentation of 30 newly recognised geodiversity sites, all but four of which are within the project area boundary;

- An assessment of the sensitivities, risks and opportunities associated with these features in the context of the project and recommendations for their management.

The work is based on a thorough literature review, and builds on personal knowledge of geodiversity sites and geoheritage values in the region accumulated over the past four decades. Two previous reports have been contributed on the Lobs Hole Ravine Road locality (Percival 2018, 2019).

Two key points result from this review of all Palaeozoic geodiversity features (both previously known and newly recognised) located within the Snowy 2.0 Main Works project area. Firstly, two sites in the vicinity of the Tantangara construction zone that were not listed in the KNP PoM were identified. Secondly, the thoroughness of the review in recognising 30 geodiversity sites in the project area additional to those listed in the KNP PoM gives confidence that no other significant sites are likely to be impacted, directly or indirectly, by construction associated with Snowy 2.0 Main Works.

Ten Palaeozoic geodiversity features previously identified in KNP management documents (e.g. the KNP PoM of 2006, and KGAP monitoring program 2012) occur within or close to the Snowy 2.0 Main Works project area. These are listed in Table 3.1. Some of these sites, specifically those covering the three karst areas of Cooleman, Yarrangobilly and Ravine, are closely monitored by NPWS as part of the KGAP (OEH 2012). Details of the other sites are variable, and available locality information for some was poor to almost non-existent. Several of these sites are documented in greater detail in this report. In the case of the karst areas of Cooleman and Yarrangobilly, aspects other than the caves and other karst features are identified, described and proposed as geodiversity sites to provide a more complete stratigraphic, sedimentological and palaeontological context to the development of karstification.

Geodiversity sites identified in this report are based on stratigraphic units, commencing with the oldest (Middle Ordovician, about 465 Ma) and ending with the youngest (Early Devonian, about 393 Ma). Twenty different stratigraphic formations of Early Palaeozoic age are recognised within the Snowy 2.0 Main Works project area, together with numerous granitoid igneous intrusions of Silurian – Devonian age. Geodiversity sites documented in this report are represented in 13 of those 20 units, ensuring that this report is as comprehensive as current knowledge (and the presence of reasonable outcrop) allows.

Geodiversity sites were assessed using five non-exclusive criteria: Reference sites (type sections or localities), Rarity of features, Representativeness (palaeontological or lithological), Relationships involving boundaries with adjacent or subadjacent units (especially unconformities), and Research potential. Significance was further attributed to each site in terms of local, regional, and national.

The likely impact of Snowy 2.0 Main Works construction and disturbance on each site was also assessed. Three of the documented geodiversity sites were found to be directly impacted by construction works. Other than the Lick Hole Formation impacted by widening of Lobs Hole Ravine Road, both the other affected sites are located on the western side of Tantangara Reservoir in the vicinity of Tantangara Road, or the spoil emplacement associated with excavation of the tunnel at the Tantangara end. Several other geodiversity sites are identified within this relatively small area, presenting a geotourism opportunity.

Recommendations suggested for management of the three Palaeozoic geodiversity sites impacted by Snowy 2.0 construction are presented in Table 4.1. Management measures for potential geodiversity finds during construction are outlined in Table 4.2. Geodiversity sites that have been identified but are not at risk (directly or indirectly) of impacts from construction works are documented in the Appendix – these sites (all of which are located within KNP) should be brought to the attention of KNP so that they can be listed in future Plans of Management and carefully monitored. Some geodiversity sites are Reference or Representative examples, comparable to plant community sites in biodiversity classifications. Rare geodiversity sites are analogous to rare and endangered biodiversity sites for plants and animals. Research potential sites need no explanation. The one type of geodiversity site that is not represented in biodiversity listings is the boundary Relationship site, as in most cases documented herein these sites show time relationships represented by unconformities. Such sites indicate where earth movements (termed orogenies) have uplifted rock strata, sometimes also deforming them by tilting and folding, before erosion of the exposed surfaces takes place over millions of years. Then new deposits accumulate generally horizontally on the eroded surfaces. Such sites, if spectacular, are particularly appropriate for public education and information.

There is some potential for further discoveries of geodiversity features to be made within the project area. Particular places where such sites may be encountered are along Marica Track and Marica Road West, which pass through several poorly known or contentious geological units. Roadworks along Tantangara Road could intersect outcrops previously mapped as Nungar beds that may contain Late Ordovician graptolites. The other area where new geodiversity features might potentially be encountered is Lobs Hole Road leading to the Talbingo Portal at the southern end of Talbingo Reservoir. This passes through the poorly known Ravine beds. Any unusual feature noticed in these rocks during the construction phase, especially any fossils, should be viewed as rare and worthy of further investigation. Artificial exposures such as road cuts or quarries are sometimes the source of significant discoveries because they enable fresh rock to be inspected. It is suggested that field assessment and monitoring by geologists is scheduled during the investigation and construction phases of the project to check for undocumented features such as fossil sites. The palaeontologist at the Geological Survey of NSW (Londonderry office) can assist in the identification of any fossils found.

The Snowy 2.0 Main Works project area includes a large number of previously unrecognised or undocumented representative and highly valued geodiversity features which occur within a national heritage-listed national park landscape. With careful design, construction practices and monitoring, impacts on geodiversity can be minimised and opportunities for education, research and public appreciation of geodiversity enhanced by the project.

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Annexure A

Geological context

A.1 Review of geological studies of the Snowy Mountains region

Early detailed geological studies in the Snowy Mountains were often focused on localities characterised by mineral deposits, e.g. Andrews (1901) on the gold at Kiandra, Carne (1908) on the copper deposits at Lobs Hole, and Carne & Jones (1919) on the limestone deposits at Ravine, Yarrangobilly and Cooleman Plain. As all these areas now are located within the boundaries of the Kosciuszko National Park, the impetus for mining and mineral exploration has been removed. However, they remain of interest as significant sites showcasing the geodiversity of the Snowy Mountains region.

A second major theme in the early days of geological research in the region was description and interpretation of the glacial features recognised in the high country in the vicinity of Mount Kosciuszko, e.g. David et al. (1901). The significance of this area was its identification as the only place on the Australian mainland that had been glaciated during the last Ice Age of the late Pleistocene. These pioneering studies have subsequently been expanded by detailed reappraisals of the Pleistocene glacial and periglacial features and climate history (e.g. Galloway 1963; Costin 1972; Barrows et al. 2001, 2004).

Modern geological investigations of previously unknown and largely inaccessible areas of the Snowy Mountains commenced with the inception of the original Snowy Mountains Scheme in 1949, culminating in a series of publications documenting the results of reconnaissance mapping that appeared in the Technical Reports series of the Geological Survey of New South Wales (GSNSW) between 1953 and 1962 (e.g. Hall & Lloyd 1954; Adamson 1957, 1958). This work was summarised by Moye et al. (1969).

Regional geological mapping of the Snowy Mountains and surrounding areas at the standard 1:100,000 scale commenced in the 1970s, when geologists from the Commonwealth Bureau of Mineral Resources, Geology & Geophysics (BMR), the GSNSW and the Geology Department of the Australian National University mapped the eastern side of KNP bounded to the west by longitude 148°30´. The resulting Brindabella and Tantangara sheets (Owen & Wyborn 1979a, 1979b, 1979c) and Berridale sheet (White, Williams & Chappell 1976) supplemented by the Tumut sheet (Basden 1990) covering the northeast corner of KNP and northwards to Tumut, greatly added to geological knowledge of the region. However, the Yarrangobilly, Kosciuszko and Jacobs River 1:100,000 geological maps remain unpublished. There was considerable focus on interpreting the complex igneous history of the area, with multiple phases of silica-rich intrusions occurring through the late Silurian and early Devonian involving the newly recognised S-type and I-type granites. Complementary palaeontological studies in the late 1960s and early 1970s concentrated on the Lower Devonian limestone of the Lobs Hole area (e.g. Flood 1969), with minor work undertaken on the Yarrangobilly Limestone (Cooper 1977). The rich fossil flora found within Cenozoic sediments in the Kiandra area were well studied during the mid 20th century (e.g. Cookson 1945, 1954; Gill & Sharp 1957), and a number of more recent palaeontological studies have also been published (e.g. Owen 1988; Paull & Hill 2003; Tarran et al. 2013).

Compilation of all geological mapping and thesis studies to the end of the 1980s resulted in the first geological map covering the entire extent of Kosciuszko National Park at 1:250,000 scale (Wyborn et al. 1990), which remains the best publicly-available hard copy geology map for the project area. However, there have been subsequent revisions in the digital geology data available for the area, as reflected in the Statewide Seamless Geology Digital Data, a compilation of the state's best available geological mapping data in an internally consistent format (Colquhoun et al. 2018). These revisions include greater detail in some Palaeozoic units to the east of the project area, based on data from the Eastern Lachlan Orogen Digital Data Set (Glen et al. 2007).

Little recent mapping of the area has been published, apart from a regional reassessment of Ordovician stratigraphy adjacent to the Long Plain Fault Zone (Quinn et al. 2014), with geology of some critical sites presented in a field guide (Quinn & Glen 2009). Detailed mapping at 1:10,000 scale along the tunnel alignment has recently been undertaken as part of the investigations for Snowy 2.0 but remains unpublished. This mapping was reviewed as part of the compilation of this geodiversity study.

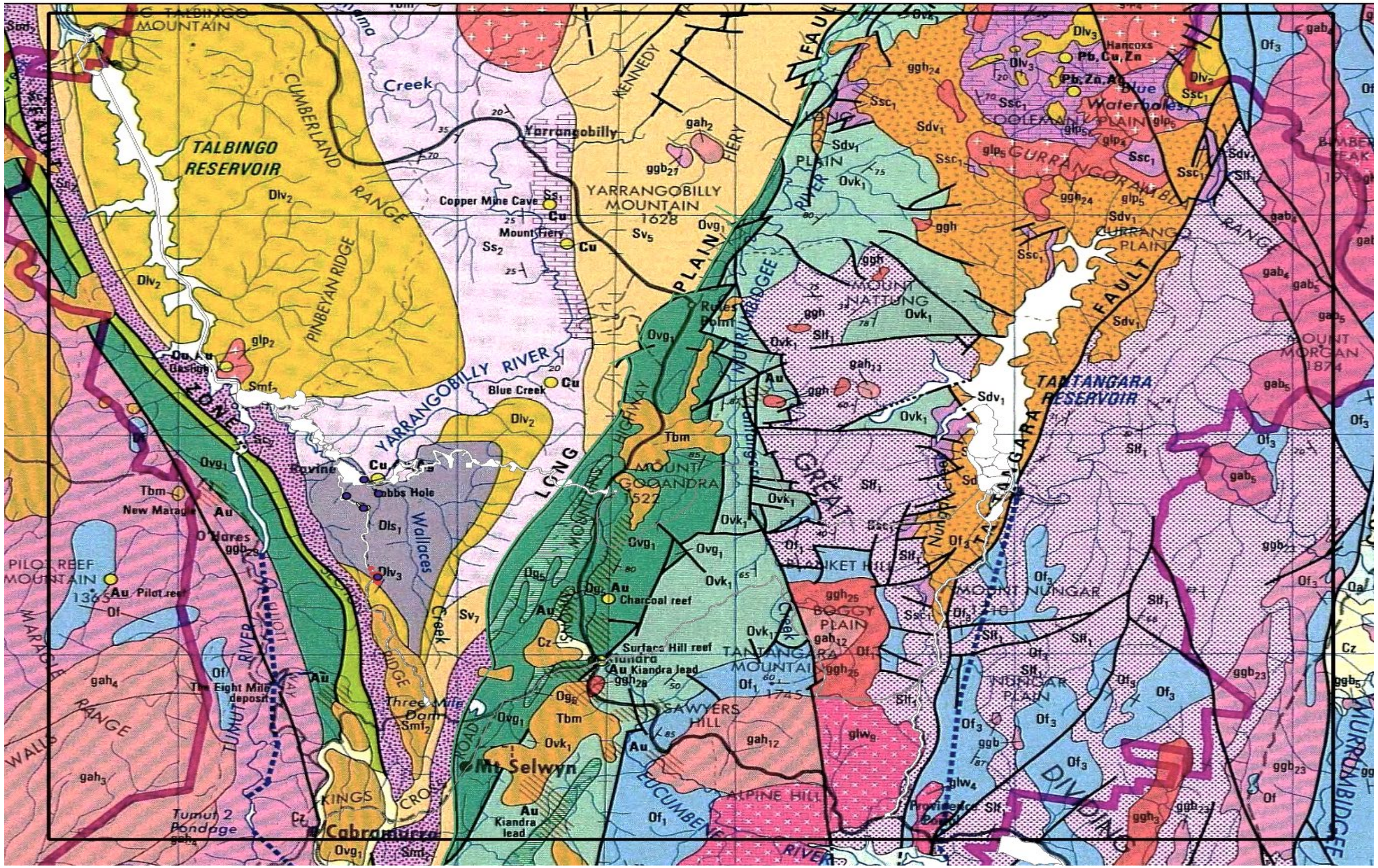

Figure A.1 Geological map (from Wyborn, Owen & Wyborn 1990) of the Snowy 2.0 Main Works Project Area (indicated by rectangle outlined in heavy black border), with Disturbance Area (shown in white) superimposed

The light and dark green belt trending NNE-SSW east of the Long Plain Fault Zone in the centre of the map are Ordovician volcanic rock units, including **Kiandra Group** (labelled Ovk) and **Gooandra Volcanics** (Ovg), associated with gabbroic intrusions (Og) SE of Mt Selwyn; another belt of Gooandra Volcanics extends between Cabramurra and the west side of Talbingo Reservoir. Light blue areas (Of) are Middle to Late Ordovician sedimentary rocks (**Adaminaby Group**) of deep-water turbiditic origin. The Lower Silurian **Tantangara Formation** (pink stippled pattern, Slf) crops out east of the Long Plain Fault Zone around Tantangara Reservoir and further south. Younger Silurian sedimentary rocks, including Ludlovian-age limestone at Yarrangobilly and the laterally equivalent **Ravine beds** (west of the Long Plain Fault Zone), and the **Cooleman Group** at Cooleman Plain (between the Long Plain Fault Zone and Tantangara Fault), are coloured light (Ss) and dark pink (Sc). Between Yarrangobilly and the Long Plain Fault Zone the Ravine beds extend around the closure of a major syncline, flanked by Silurian **Goobarragandra Volcanics** (Sv) and the **Tumut Pond beds** (purple spotted pattern, Smf), the latter cut off to the west by the Gilmore Fault Zone along which is emplaced the **Tumut Pond Serpentinite** (bright green, Sc). Early Devonian volcanic activity is represented by the **Kellys Plain Volcanics** (bright orange, SDv) that surround Tantangara Reservoir, and the **Boraig Group** (bright yellow, Dlv) west of the Long Plain Fault Zone and surrounding Talbingo Reservoir. These volcanics are genetically related to extensive Siluro-Devonian intrusive activity forming granite, granodiorite, adamellite, tonalite and other silica-rich plutons, shown in shades of pink, maroon and orange, variously labelled gab, ggb, and glw (S-type intrusions), and gah, glp and ggh (I-type). The axis of the syncline in the Ravine area is occupied by the Emsian age (Early Devonian) **Byron Range Group** (grey, Dls). The youngest rocks shown are basalts of Miocene age (orange colour, Tbm), capping plateaux and ridges (e.g. Mt Gooandra) or infilling palaeo-drainage in the vicinity of Kiandra where the basalt buried contemporary sediments (faint yellow, labelled Cz). Quaternary alluvium (Qa) is present in the valley of the Eucumbene River above its entry to Lake Eucumbene at Providence Arm. Note that this interpreted geology map does not show periglacial features nor relatively small areas of Recent calcrete/tufa deposition.

A.2 Palaeozoic geology of the Main Works Project Area

A.2.1 Overview of Ordovician stratigraphy

The oldest rocks, of Ordovician age, exposed in the Project Area crop out in two belts: (a) a larger and more complex NNE-SSW trending belt in the central and western parts of the Tantangara Block in the centre of the area, bounded to the west by the Long Plain Fault Zone, and (b) a much narrower zone confined to the western margin of the Tumut Block, trending NNW from Cabramurra along the western margin of the Gilmore Fault Zone west of Talbingo Reservoir. In comparison to the Silurian and Devonian units, details of the Ordovician stratigraphy exposed in KNP remain poorly understood.

A recent study (Quinn et al. 2014) redefined relationships between sedimentary rocks deposited in Ordovician turbidite environments and adjacent (in some cases, contemporary) volcanic rocks. Quinn et al. (2014) recognised a single outcrop belt of Ordovician volcanics, sandwiched between an older (late Middle Ordovician) turbiditic sedimentary succession including deep sea cherts, to the east, and a younger (Late Ordovician) shale-dominated succession including minor interbedded volcanic strata bounded to the west by the Long Plain Fault Zone. The turbiditic rocks belong to the **Adaminaby Group**, which now includes the **Temperance Formation** (formerly assigned to the Kiandra Volcanics by Owen & Wyborn 1979c), as well as informal stratigraphic units of localised extent such as those previously designated as the Boltons beds by Crook et al. (1973). Thin chert beds in the Temperance Formation generally cap graded-bed sequences commencing with thick sandstone units and grading upwards through increasingly finer beds of siltstone and shale. Conodont microfossils observed in thin sections of these cherts provide ages ranging from the middle to late Darriwilian stage to the earliest Gisbornian stage. Thickness estimates for the Temperance Formation range up to 5000 m (Owen & Wyborn 1979c) but are impossible to verify as all occurrences are in fault-bounded blocks. Quinn et al. (2014) documented volcaniclastic debris flows containing chert clasts where the Adaminaby Group and the Kiandra Group abut, implying an intergradational or transitional boundary, rather than a major faulted terrane boundary as was previously postulated. The locality of these debris flows is particularly important as this is the only known site in southern NSW where rocks of the volcanic arc are found in very close proximity to sediments deposited in the flanking ocean basin.

Volcanic and volcaniclastic rocks referred by Owen & Wyborn (1979c) and Wyborn et al. (1990) to the **Kiandra Group** (in which they included the Temperance Formation, Nine Mile Volcanics and Gooandra Volcanics) have generally been regarded as having been formed in an intra-oceanic arc environment. However, recent research has suggested that a back-arc setting adjacent to a continental margin is more likely for the cherts that elsewhere (e.g. in central NSW) flank both sides of the volcanics (Bruce & Percival 2014). In this model the volcanic rocks are inferred to have been extruded from a back-arc rift. Typical lithologies of the **Nine Mile Volcanics** include porphyritic basalt (high in potassium) and basaltic tuff, with accessory feldspathic sandstone, shale and minor chert, with a maximum thickness estimated to exceed 1000 m. These volcanic and volcaniclastic rocks are equivalents of more extensive calcalkaline and shoshonitic mafic volcanism of Gisbornian (early Late Ordovician) age, characteristic of the Macquarie Volcanic Province (formerly Macquarie Arc) in the central west of the state. Volcanic rocks in the Macquarie Volcanic Province were mostly erupted underwater, gradually building seamounts and islands with extensive fringing limestone deposits. Although no such *in situ* limestones are known from KNP, rare allochthonous blocks and clasts of limestone yielding the Late Ordovician conodont *Belodina* and a solitary rugose coral have been reported from near Peppercorn Creek, north of Cooleman Plain, in rocks assigned to the Nine Mile Volcanics (Owen & Wyborn 1979c).

A narrow NNE-SSW trending belt bounded to the west by the Long Plain Fault Zone, consisting of sedimentary rocks intruded by mafic to intermediate volcanic rocks, is interpreted as the youngest part of the Ordovician succession. The northern part of this belt was assigned by Wyborn et al. (1990) to the **Gooandra Volcanics**. Lithologies represented in this formation are predominately mafic volcanic rocks including basalt (some forming pillows), gabbro and andesite, associated with volcaniclastics, and minor sedimentary rocks such as feldspathic sandstone and siltstone, and chloritic schist. Lavas of the Gooandra Volcanics are geochemically distinct both from those of the Nine Mile Volcanics and from lava clasts in the Temperance Formation (Owen & Wyborn 1979c). A maximum thickness of 3000 m was estimated for this unit by Owen & Wyborn. However, Percival et al. (2011, p.26), citing unpublished mapping by Cam Quinn, restricted the extent of the Gooandra Volcanics to its type section around Gooandra Homestead. Quinn et al. (2014) reassigned the majority of the underlying volcaniclastic succession and siliceous clastic sedimentary rocks with debris flows to the Nine Mile Volcanics or to undifferentiated Kiandra Group, transitional with the Temperance Formation (of the Adaminaby Group).

In southeastern NSW and throughout northeastern Victoria, the **Bendoc Group** conformably overlies the turbiditic-dominated rocks of the Adaminaby Group. The lower part of this group consists of a thick succession of black shales, the **Warbisco Shale**, of Late Ordovician age. In the northern part of KNP these rocks were named the Nungar beds on early maps (e.g. Crook et al. 1973). The predominantly Eastonian (middle Late Ordovician) age of these black shales has long been known from graptolite fossils that have been recorded from at least four sites within the KNP (Sherrard 1954, 1962). Crook et al. (1973, p. 120) noted the occurrence of poorly preserved Late Ordovician graptolites in black shales at Tantangara Dam. Elsewhere in the region, such black shales are known to occasionally yield graptolites of late Gisbornian and early Bolindian age, although Eastonian faunas are most common. Wyborn et al. (1990) depict extensive areas mapped as Nungar beds (Of_3) east of the Tantangara Fault in a belt extending from the Brindabella Range to south of Lake Eucumbene; these rocks most likely equate to Warbisco Shale of current usage. Quinn et al. (2014) depict a band of black shales which presumably represent the Warbisco Shale, with minor interbeds of volcaniclastics, extending in a narrow tract from Mt Jagungal in a NNE direction adjacent to the Snowy Mountains Highway to Mt Gooandra. These rocks were previously mapped by Wyborn et al. (1990) as undifferentiated Kiandra Group south of Mt Selwyn, and as part of the Gooandra Volcanics north of there.

An overlying succession of dark green siltstone and conglomerate was mapped by Quinn et al. (2014) further west in this belt, extending from Mt Jagungal in the south, along the western side of Mt Selwyn, to the Long Plain in the north. No fossils have been recorded from these strata and hence there is no conclusive evidence for a Silurian age. Throughout much of the Lachlan Orogen, Ordovician deposition was terminated by the Benambran Orogeny that spanned the time of the Ordovician–Silurian boundary. Although Quinn et al. (2014) interpreted the boundary between these strata and the underlying black shale-dominated Upper Ordovician succession as conformable, an alternative explanation is that the conglomerate came from uplifted and eroded Ordovician rocks that were redeposited subsequent to the Benambran Orogeny.

A.2.2 Overview of Silurian stratigraphy

The distribution of Silurian stratigraphic units (including extrusive rock) in the KNP region is strongly controlled by major faults (the Long Plain and Tantangara Faults) that trend in a NNE-SSW direction. Lower Silurian (Llandovery and Wenlock series) sedimentary rocks in the Tantangara Block between these two faults are predominantly clastic. In the Tumut Block west of the Long Plain Fault Zone, equivalents of the lowermost unit present in the Tantangara Block are poorly constrained, whereas Upper Silurian facies can be more readily correlated across the faults.

The oldest Silurian unit in the Snowy 2.0 Project area (northern KNP) is the **Tantangara Formation**. Its early Llandoverian age is based in part on the discovery of fragmentary brachiopods identified as *Eospirifer*, associated with the coral *Tryplasma* (reported by Owen & Wyborn 1979c, p.M75) at the northern end of Nungar Plain. Confirmatory evidence for this age is provided by the presence in the unconformably-overlying Peppercorn Formation of late Llandovery conodonts. The Tantangara Formation is part of the **Yalmy Group**, which is widespread in northeast Victoria (where the group was first defined), where it unconformably overlies Upper Ordovician strata of the Bendoc Group. Lithologies found in the Tantangara Formation include graded beds of quartzose sandstone, siltstone and shale, typical of deposition by turbidity currents in a deep marine basin; in some areas a distinctive massive clean quartzite is present. As mapped by Wyborn et al. (1990), the Tantangara Formation mainly crops out east of the Tantangara Fault in the area immediately east of Tantangara Reservoir and extends south to Adaminaby and Providence Arm of Lake Eucumbene. Another band of Tantangara Formation is shown by Wyborn et al. (1990) west and south of Tantangara Reservoir, between the Tantangara and Long Plain faults. However, that interpretation differs significantly from more recent mapping of Quinn et al. (2014) who assign the more westerly outcrops to the Ordovician Adaminaby Group turbidites. Accordingly, the Tantangara Formation is restricted in the present report to the eastern belt, immediately east and south of Tantangara Reservoir. Note that Owen & Wyborn (1979c, p.M65) recognised that what they called Adaminaby beds (which are in fact a mixture of Abercrombie Formation of the Adaminaby Group and Warbisco Shale of the Late Ordovician Bendoc Group) "are similar lithologically to the Tantangara Formation, and distinguishing the two in the field is difficult in the absence of fossil evidence; so one may have been mapped for the other in places. The main difference between the two units is that black graptolitic shale is present in the Adaminaby beds, but absent from the Tantangara Formation".

Unconformably overlying the Upper Ordovician Nine Mile Volcanics of the Kiandra Group is the **Cooleman Plains Group** which is distributed between the Long Plain Fault and Tantangara Fault. The basal stratigraphic unit of the latter group, the **Peppercorn Formation**, is interpreted as having been deposited in more shallow water than the Tantangara Formation and is characterised by a distinctive basal conglomerate with rounded chert pebbles, passing upwards into sandstone, siltstone and shale with minor thin limestone lenses. Total thickness of the formation is about 600 m in its type section and may attain 1000 m elsewhere. The age range of the Peppercorn Formation is now regarded as most likely ranging from Telychian (late Llandovery) to Sheinwoodian (early Wenlockian) age, based on conodonts obtained from limestone near Coonbil Homestead, and reassessment of corals from that locality that were previously assigned a Wenlockian to early Ludlovian age.

The upper beds of the Peppercorn Formation may range into the latest Wenlockian or early Ludlovian, as they grade laterally into carbonate rocks of the **Cooleman Limestone**. This unit is also part of the Cooleman Plains Group, but entirely of Late Silurian (Ludlovian) age as evidenced by fossils including conodonts such as *Zieglerodina remscheidensis*. The Cooleman Limestone is massive to very thickly bedded, and variable in thickness – generally 500-700 m, but as little as 70 m is preserved in some places. Pervasive recrystallisation has largely obliterated all but the more robust macrofossils. Some of the more obvious fossils include large shells of an undescribed megalodont bivalve, thick-shelled pentamerid brachiopods, stromatoporoid sponges, and corals including the tabulates *Favosites*, *Heliolites* and *Parastriatopora*; and rugosans *Phaulactis*, *Tryplasma* and *Pyncostylus*. Outcrop of the Cooleman Limestone is restricted to the Cooleman Plain and Cooleman Caves area, north of Tantangara Reservoir.

Further complicating the stratigraphy is the **Pocket Formation**, consisting of quartzose sandstone, siltstone and limestone lenses, which generally underlies but also interfingers with both the Peppercorn Formation and the Cooleman Limestone. However, this formation is largely confined to the lower Goodradigbee River valley, to the northeast of Cooleman Plains and largely outside the KNP boundary. Hence because any outcrop of the Pocket Formation is well beyond the Snowy 2.0 Main Works Project Area, this unit will not be considered further in this report.

At the top of the Cooleman Plains Group is the **Blue Waterhole Formation**, comprising bedded grey and black chert or cherty siltstone, limestone and hornfels. This formation conformably overlies the Peppercorn Formation with a gradational boundary, but elsewhere (e.g. near Cliff Cave and east of Harris Hut, west of the Black Mountain Fault – Pickett 1982, p.62-63) it unconformably overlies the Cooleman Limestone which has a karstified surface (indicating an interval of subaerial exposure) immediately below the boundary. Limestone in the Blue Waterhole Formation is confined to a slumped horizon containing allochthonous blocks of limestone that have yielded Ludlovian age conodonts identical to those obtained from the underlying Cooleman Limestone, which is interpreted as the source of these allochthonous blocks. A variety of macrofossils are present in the siltstone beds of the Blue Waterhole Formation, including mainly corals with associated trilobites and atrypide brachiopods.

In the Tumut Block between the Long Plain Fault Zone and the Gilmore Fault Zone, mapping dating from the time of the original Snowy Mountains project suggests on stratigraphic grounds that the oldest Silurian rocks south and east of Talbingo Reservoir are represented by the **Tumut Pond Group**, which wraps around the closure of a major north-plunging syncline, centred on the Lobs Hole locality. The western limb of the syncline abuts the Gilmore Fault Zone along which serpentinite is emplaced. The eastern limb is cut off against the Long Plain Fault Zone. Lithologies typical of the Tumut Pond Group include rhythmically bedded grey sandstone (grading to quartzite) and grey slate (grading to phyllite). As well as undifferentiated Tumut Pond Group, Wyborn et al. (1990) depict separate bands of a constituent of the group, the **Kings Cross Formation**, a poorly defined unit consisting of green, purple and dark grey slate (grading to phyllite). Talent et al. (1975) cited the discovery of the trilobite *Denckmannites* by Vidas Labutis during his Honours thesis mapping project as evidence for a late Silurian age for rocks assigned to the upper part of the Tumut Pond Group. However, subsequent study by Lesley Wyborn (cited in Pickett 1982, p.45) indicates that the trilobite occurs in the Ravine beds, or alternatively comes from a mudstone facies of the Yarrangobilly Limestone, known to be of Ludlovian (Late Silurian age). L. Wyborn (pers. comm. in Pickett 1982) also regarded the shale in the Kings Cross Formation as being volcaniclastic. It is clear that the age and concept of the Tumut Pond Group and its constituent units, and its relationship to other formations west (and east) of the Long Plain Fault Zone, is open to question and would benefit from further detailed study.

Northeast of the syncline, abutting the Long Plain Fault Zone and extending west towards Yarrangobilly, is exposed a laterally extensive and very thick volcanic succession of the **Goobarragandra Volcanics** of predominantly felsic rocks. The dominant lithology is strongly porphyritic dacite of probable ignimbritic origin, together with siliceous volcaniclastic breccia. Isotopic dating (Rb/Sr) of this unit is poorly constrained at 429 ±16 Ma, implying most likely a Wenlockian age. The Goobarragandra Volcanics is interpreted as comagmatic with the Young Granodiorite, which has been isotopically dated (zircon analysis by SHRIMP) at 428.8 ±1.9 Ma, also indicating a Wenlockian age. Occasional strongly recrystallised limestone lenses and sandstone beds also occur in the Goobarragandra Volcanics, but these have not yielded any fossils except far to the north on the Yass 1:100 000 mapsheet where corals of Wenlockian to Ludlovian age have been identified. Field relationships observable along the Snowy Mountains Highway between the Goobarragandra Volcanics and the overlying Yarrangobilly Limestone and Ravine beds (Owen & Wyborn 1979c, M.136) seem to suggest intergradation of weathered tuff of the Goobarragandra Volcanics with volcaniclastic siltstone and green mudstone over a thickness of 10 m, culminating in a conformable boundary with green and purple mudstone equated by Owen & Wyborn with the Kings Cross Formation, that in turn is overlain conformably by the Yarrangobilly Limestone. These observations imply that the Goobarragandra Volcanics in this area is overlain by rocks assigned to the Tumut Pond Group. That relationship would suggest that the Tumut Pond Group may range from Wenlock to early Ludlow age.

Late Silurian (Ludlovian-age) sedimentary rocks include substantial thicknesses of limestones that provide evidence of prolonged deposition in warm shallow marine environments, e.g. the 840 m thick **Yarrangobilly Limestone** that correlates with the Cooleman Limestone in the Tantangara Block to the east. Conodont microfossils described from the Yarrangobilly Limestone by Cooper (1974, 1977) provide the basis for its Ludlovian age, ranging from the *Polygnathoides siluricus* Zone of the middle Ludlow (at a level 180 m above the base of the formation) to the *Ozarkodina crispa* Zone or uppermost Ludlovian at the top of the limestone. Corals (both rugose and tabulate varieties) have been described from the upper beds of the limestone (Hill 1954) including the youngest in situ assemblage of halysitid (chain) corals known from Australia (Hamada 1957, 1958; Pickett 1982, p.23). Also present in the uppermost part of the Yarrangobilly Limestone near the Snowy Mountains Highway is a shell bed layer composed of *in situ* trimerellide brachiopods [Figure A2] – the species represented in these beds is yet to be described scientifically, but is believed to be closely related to *Keteiodoros* from the Dripstone Formation of Wenlockian age in the Wellington region of central NSW (Strusz et al. 1998).

Figure A.2 Bedding plane in uppermost Yarrangobilly Limestone with shell bed of trimerellide brachiopods, the majority articulated and apparently in situ. Pen (15 cm) for scale.

Immediately to the west of Yarrangobilly Village, and west of the Yarrangobilly River, the Yarrangobilly Limestone grades laterally into, and is partly conformably overlain by, the **Ravine beds**. This informally named unit, estimated to be up to 2100 m thick, comprises shale, siltstone, slate and conglomerate. Internal evidence of its age is lacking, although it is assumed to be of Ludlovian to possibly earliest Pridolian (latest Silurian) age based on lateral stratigraphic relationships with the Yarrangobilly Limestone.

A.2.3 Overview of Devonian stratigraphy

The Bindian Orogenic phase affected deposition in NE Victoria, extending into the KNP region. Upper Silurian and older strata were relatively intensely deformed and uplifted in this tectonic episode, with basal Devonian strata overlying the eroded and folded Silurian rocks with pronounced angular unconformity (Fergusson 2017). As with distribution of the older rocks, the two main faults traversing the region NNE-SSW are major controlling factors on the distribution of the Devonian sedimentary and volcanic rocks.

In the Tantangara Block, bounded by the Tantangara Fault to the east and the Long Plain Fault to the west, the oldest Devonian formation is the **Kellys Plain Volcanics** which is restricted to the vicinity of Tantangara Reservoir. The formation, 300 m maximum thickness, consists of dacitic and rhyodacitic ignimbrite with S-type geochemical affinities, minor rhyolite, volcaniclastic tuff and agglomerate. It overlies the Cooleman Plains Group with a pronounced angular unconformity as a result of deformation in the Bindian Orogeny during the earliest Devonian (Fergusson 2017).

Disconformably overlying the Kellys Plain Volcanics is the **Rolling Grounds Latite**, consisting of porphyritic latite and minor andesitic lava with a maximum thickness of approximately 250 m. Only very minor patches of isolated and discontinuous outcrop are present on Cooleman Plain to the immediate north of the Snowy 2.0 Main Works project area. The formation is assigned a Lochkovian (Early Devonian) age on the basis of stratigraphic relationships and correlations with sedimentary units to the north in the vicinity of Burrinjuck Reservoir. Geochemistry of the latite suggests a compositional similarity with I-type intrusions of the Boggy Plain Suite.

The youngest Devonian stratigraphic unit exposed in the Tantangara Block is the **Mountain Creek Volcanics**, at the base of the Black Range Group. Rocks of this formation, including rhyolite lava, ignimbrite and tuff of I-type (Boggy Plain Suite) affinity with minor dacite, andesite, agglomerate, feldspathic sandstone, siltstone, and black shale, are present in restricted outcrops in the vicinity of Cooleman Caves where the formation unconformably overlies the Blue Waterhole Formation. Outcrops of the Mountain Creek Volcanics are much more extensive in the Goodradigbee River valley to the north, with the eastern margin of the unit controlled in part by the Goodradigbee Fault. The Rolling Grounds Latite and Mountain Creek Volcanics are geochemically identical and occupy closely comparable stratigraphic levels in the early Devonian. It is highly likely that in the Cooleman Plains area the two formations merely represent different volcanic facies of the same parent extrusive rock, and hence they might be best considered as part of the same stratigraphic unit.

In the Tumut Block west of the Long Plain Fault Zone, a slightly different Early Devonian stratigraphic succession is recognised. No equivalent of the Kelly Plains Volcanics is evident, but the **Boraig Group** includes geochemically-similar rocks to those of the Rolling Grounds Latite and the Mountain Creek Volcanics. Two main outcrop areas of Boraig Group are exposed, the largest as a basinal structure enveloping Talbingo Reservoir, forming the Pinbeyan Ridge, Cumberland Range and Big Talbingo Mountain east of the reservoir (Moye et al. 1969). Another, smaller, outcrop of Boraig Group rocks forms the eastern and southwestern limbs of the north-plunging syncline centred on Lobs Hole. Subdivision of the Boraig Group into five formations was proposed by Moye et al. (1969) in the area centred on Talbingo Reservoir. These are (in ascending order), **Buddong Volcanics** approximately 1,060 m thick, consisting mainly of rhyolitic lavas with several distinct flows, and very minor tuff and agglomerate beds; **Saddle Tuff**, the lower 90 m composed largely of pink to brown rhyolitic tuff, tuffaceous breccia and agglomerate, overlain by 180 m of volcanic conglomerate with waterworn pebbles in a tuffaceous matrix; **Landers Creek Formation**, predominantly consisting of alternating beds of andesitic tuffs and more resistant indurated quartzose sandstone; **Talbingo Basalt**, an andesitic basalt 450 m thick on Big Talbingo Mountain but rapidly diminishing in thickness to the south; and **Cumberland Rhyolite**, a resistant cliff-forming rhyolite capping Talbingo Mountain where it is 240 m thick, and thickening to 420 m on the Pinbeyan Ridge. Only the latter unit is readily recognisable away from the Talbingo Reservoir area. Moye et al. (1969) present a series of measured sections through the Boraig Group showing how it thins from about 800 m at Big Talbingo Mountain to almost nothing south of Lobs Hole. Much of the Group comprises felsic volcanics and associated volcaniclastic rocks, although sandstones and siltstones interpreted as lacustrine deposits (containing fragmentary fossil remains of early land plants) are known from the Lobs Hole region. An Early Devonian age is assigned to the Boraig Group purely on the basis of stratigraphic relations with the late Pragian? to Emsian Byron Range Group which overlies the former, as no age-diagnostic fossils are known from the Boraig Group.

The **Byron Range Group**, consisting of the Milk Shanty Formation forming the lower part, the Lick Hole Formation in the middle, and the Round Top Quartzite at the top, occupies the centre of the syncline in the Lobs Hole area. The **Milk Shanty Formation** is 170 m thick and consists of clastic rocks with a characteristic red colouration, including a basal breccia (with clasts derived from the underlying Ravine beds) and conglomerates in the lower 60-65 m, micaceous siltstones, and compact, resistant sandstones in the upper 105 m of the formation, that form the distinctive cliff-line known as The Walls above Lobs Hole. The **Lick Hole Formation** consists of thin bedded and nodular fossiliferous limestone, interbedded with siltstones and shales that predominate up-section, with a total thickness of 488 m measured along the Lobs Hole Lobs Hole Ravine Road (Flood 1969). Fossils described from the Lick Hole Formation, including conodonts (Flood 1969), brachiopods (Strusz et al. 1970, Flood 1973), corals and bryozoa (Pedder 1971) indicate an Emsian (late Early Devonian) for this formation, correlating with the Taemas Limestone in the Burrinjuck Reservoir and lower Goodradigbee River valley areas. The Lick Hole Formation is conformably overlain by fossiliferous quartzite at the base of the **Round Top Formation**. Early reports suggested the fossils in this basal unit were pelecypods, but subsequent study (Flood 1969) identified them as lingulate brachiopods, that have not been formally described. The Round Top Formation, 30 m thick, is formed mainly of interbedded reddish quartzite and siltstone. To the north the Byron Range Group unconformably overlies the Ravine beds; the relationship with the Boraig Group is less certain but is regarded as unconformable (Moye et al. 1969). In the Snowy 2.0 Main Works Project Area, equivalents of the Byron Range Group are unknown in the Tantangara Block east of the Long Plain Fault Zone.

A.2.4 1.2.4 Overview of Silurian and Devonian intrusive history

A substantial part of the Snowy Mountains region is underlain by felsic (largely granitoid) intrusions that range in age from middle Silurian to middle Devonian. Tectonically these intrusions can be assigned to five major batholiths within KNP. Within each of these are recognised (on the basis of geochemical differences) compositionally distinct suites and supersuites that reflect the sources of the parent magma. Further differentiation is made on the basis of the interpreted derivation of the parent magma, whether from melting of supracrustal (i.e. sedimentary) rocks in the mantle (S-type) or from purely igneous melting (I-type). Differentiation of these two types of granitoid rocks relies on mineralogical, geochemical, textural, and isotopic characteristics. S-type granites are over-saturated in aluminium, whereas I-type granites are silica-rich but undersaturated in aluminium. S-type granites never contain hornblende, whereas this mineral is typical of (and often common in) I-type granites. The original model of Chappell & White (1974) proposing these two igneous rock types has more recently been modified by the recognition of transitional and variable mineralogical responses to melting (see Chappell & White 2001).

S-type felsic intrusions of middle (Wenlockian) to Late Silurian (Ludlovian – Pridolian) age are composed of fine- to medium-grained, pale yellow-pink, two- mica leucogranite, leucomonzogranite and aplite, with some small porphyry and tonalite variants. Within the Snowy 2.0 Works Area, S-type intrusions are found in the block bounded by the Cotter and Tantangara faults east of Tantangara Reservoir (including the Mckeanhie Adamellite, Half Moon Peak Adamellite, and Happy Jacks Adamellite); the Snowy Mountains Highway traverses the Gang Gang Adamellite at Alpine Hill, west of Providence Portal, and the Wullwye Granodiorite occupies much of the area immediately west of Cabramurra.

I-type intrusions generally record younger ages, within the Early Devonian, based on Rb-Sr and Ar-Ar radiometric dates with fairly imprecise error margins. Within the Snowy 2.0 Main Works project area, I-type intrusions are most commonly exposed in the Tantangara Block between the Tantangara Fault and the Long Plain Fault Zone, particularly in the Coolamine area (Coolamine Igneous Complex, Jackson Granite, and Gurrangorambla Granophyre) and at Boggy Plain (Boggy Plain Granitic Complex – adamellite and granodiorite phases). West of the Long Plain Fault Zone, I-type intrusions are represented by the extensive Bogong Granite, and much smaller outcrops of the Lobs Hole Adamellite (on the eastern shore of Talbingo Reservoir, north of the Talbingo portal) and the Starvation Point Adamellite, north of Yarrangobilly Mountain.

The Boggy Plain Granitic Complex is a zoned high-temperature intrusion (Wyborn et al. 1987) which can be related geochemically to its extrusive components (including the Kelly Plains Volcanics and the Rolling Downs Latite), all forming part (along with contemporary and geochemically/mineralogically similar intrusives and extrusives extending further north for 500 km in the central Lachlan Fold Belt) of the Boggy Plain Supersuite (Wyborn et al. 1987; White et al. 2001).

None of these intrusive bodies are intersected by any Snowy 2.0 Main Works construction. The effects of their intrusion on older sedimentary rocks in KNP is pervasive, with widespread low-grade regional metamorphism affecting particularly more fine-grained clastic rocks such as shales and mudstone. Contact metamorphic effects and metasomatism (chemical alteration of surrounding rocks by hydrothermal fluids emanating from the intrusion) are prominent in some areas, especially where granitic magmas intrude close to limestones. At Black Perry Mountain and Garnet Hill, skarn deposits with abundant garnets form in the contact zone between the Yarrangobilly Limestone and such fluids. Both sites are listed in the KGAP (OEH 2012). The Kosciuszko Batholith, forming the Main Range in the Kosciuszko region of the southern KNP, is included in the KNP PoM (2006) as a listed geodiversity feature.

Annexure B

Newly recognised geodiversity sites not affected by Snowy 2.0 construction work

The following section provides a review of sites with geodiversity potential in the Snowy 2.0 project area but located outside the Main Works disturbance footprint (see Figure 3.1 for overview of site locations). A description of the sites, their significance and a discussion of potential for impacts is provided for each site.

B.1.1 Ordovician stratigraphic units

i **Temperance Formation** (Adaminaby Group)

a Temperance Formation Type Section (category: Reference site)

Owen & Wyborn (1979c, fig. M5, table M3) described the type section for the Temperance Formation on Temperance Creek, a tributary of the Tumut River flowing into Tumut Pond Reservoir. The section commences on the south side of Temperance Creek, 1100 m SE of Skeleton Creek and runs parallel to Temperance Creek in a downstream direction to the end of the section), 400 m east of Frenchmans Creek, opposite the mouth of an unnamed creek that flows into Temperance Creek from the northeast.

Significance: Regional – the Temperance Formation is extensively distributed east of the Long Plain Fault zone where it is one of the oldest sedimentary rock units.

Impacted by Snowy 2.0 construction zone: No [this type section lies approximately 6 km due south of Mt Selwyn, and about 5.5 km SE of Cabramurra and so is just beyond the southern margin of the Snowy 2.0 Main Works project area, but is included in this report for completeness and reference, as the formation extends north into the Main Works project area where several other sites are proposed].

ii **Temperance Formation chert outcrop A** (category: Representative lithological site and Research potential site)

Prominent outcrops of chert in the Temperance Formation were identified in Appendix D fig. 5.4 of the SMEC Geological Reconnaissance Report (July 2018) as occurring immediately east of Tantangara Creek (the exact locality is not given in the report but should be available from SMEC). Reference to the Tantangara 1:100,000 Geological map (Owen & Wyborn 1979b) shows an outcrop of bedded Temperance Formation chert at the confluence of Tantangara Creek and the Murrumbidgee River, situated between the western side of Tantangara Reservoir and the Snowy Mountains Highway.

Significance: Local/regional – chert is characteristic of the Temperance Formation and this is a particularly good outcrop. There is a possibility that the chert may contain conodont microfossils.

Impacted by Snowy 2.0 construction zone: No – within the project area, but as this site is several kms outside the Main Works disturbance area it is not affected directly or indirectly by construction.

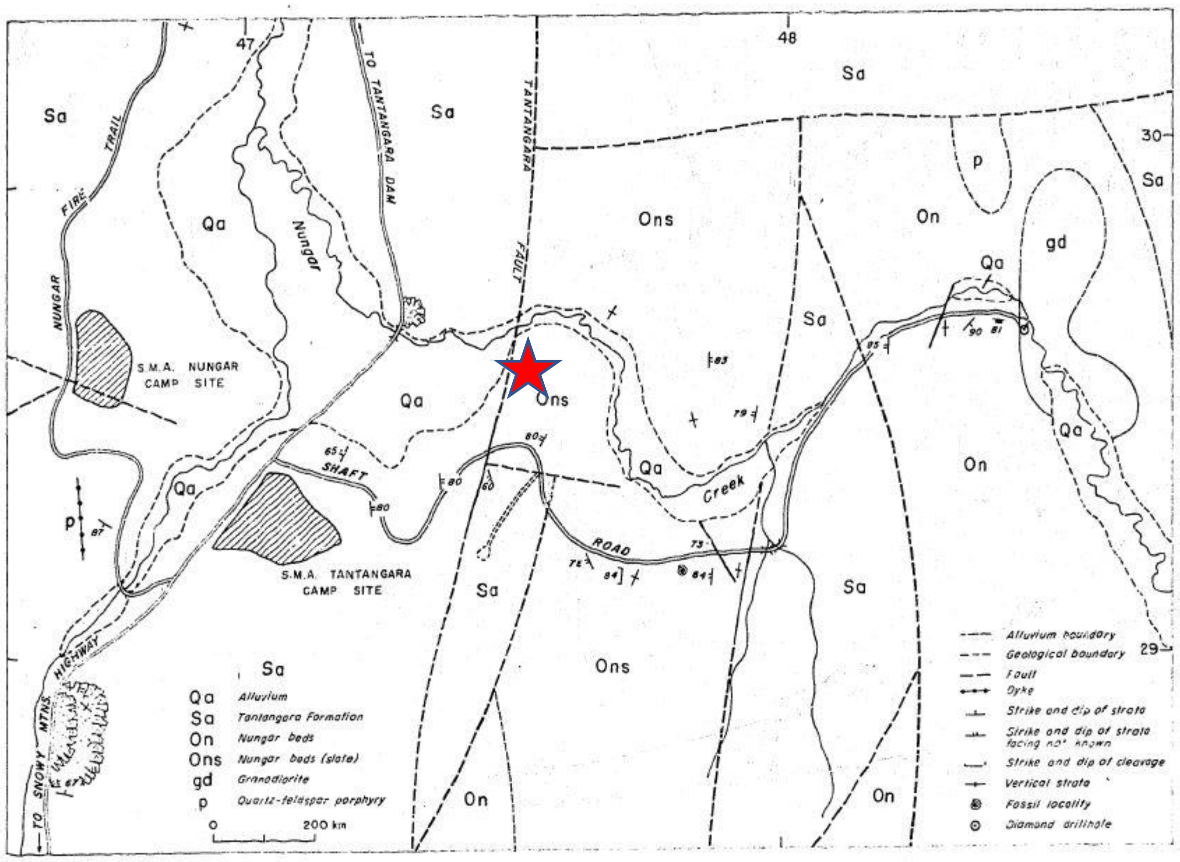

Fig. M8 Type locality of the Nungar beds 155/A16/10794

Figure B.1 Map (from Owen & Wyborn, 1979c) showing locality of geodiversity site 3 (red star), between Shaft Road and Nungar Creek, adjacent to east side of Tantangara Fault, in rock unit labelled Ons (centre of map).

iii Temperance Formation chert outcrop B (category: Research potential site)

Owen & Wyborn (1979c, p.M57, fig. M8) record an isolated sequence 10 m thick of well-bedded chert, in beds 5-20 cm thick, at the western edge of the type locality of the 'Nungar beds' on Nungar Creek, 7 km south of the southern tip of Tantangara Reservoir (grid ref. 476295). Crook et al. (1973) provide details of this site as extending along Shaft Road on the south side of Nungar Creek, east of the road to Tantangara Dam. Owen & Wyborn (1979c) remark on the similarity to chert in the Temperance Formation. If conodont microfossils are found in this chert, identical to those previously identified from the Temperance Formation, that would conclusively demonstrate that the mapping is incorrect and this outcrop may be previously unrecognised Temperance Formation. Being so close to the type locality of the 'Nungar beds' (now Warbisco Shale) it is important to resolve this question.

Significance: Local – this site may help resolve a local stratigraphic uncertainty.

Impacted by Snowy 2.0 construction zone: No – this site (Figure A3) is 300 m east of Tantangara Road leading to the dam, and so is not expected to fall within the Main Works disturbance footprint.

iv Temperance Formation chert outcrop C (category: Rare fossil site)

According to Owen & Wyborn (1979c) only one fossil occurrence is known from the Temperance Formation. Crook et al. (1973) reported the occurrence, in chert (then referred to the Nungar beds) on Mufflers Creek at Dairymans Plain (midway between Mt Nattung and the western side of Tantangara Reservoir), of three poorly preserved inarticulate brachiopods referred to the family Obolidae. Although numerous other microfossil localities are now known from the Temperance Formation (e.g. those that preserve the conodonts illustrated in Figure 2.4 of this report), those sites are predominantly in the Far Bald Mountain and Happy Jacks Pondage area just south of the Snowy 2.0 Main Works project area.

Significance: Local/regional - this locality on Mufflers Creek is presently the only macrofossil site known in the Temperance Formation.

Impacted by Snowy 2.0 construction zone: No – the site is within the project area but not affected by construction in the area of the Tantangara portal, which is situated at least 5 km away.

B.1.2 Nine Mile Volcanics (Kiandra Group)

i **Nine Mile Volcanics Type Section** (category: Reference site)

The type section of the Nine Mile Volcanics is located on the Tumut River immediately upstream from where it flows into Tumut Pond Reservoir (the type section of the Temperance Formation, previously described, is located along Temperance Creek immediately to the east). Both type sections are located just south of the southern boundary of the Snowy 2.0 Main Works project area, but as is the case with the Temperance Formation, the Nine Mile Volcanics trends NNE into the Project Area where it is crossed by the Tantangara to Talbingo tunnel.

The type section of the Nine Mile Volcanics was examined by Owen & Wyborn (1979c, fig. M5, table M4, p. M11) when Tumut Ponds Reservoir was low. The base of the Nine Mile Volcanics commences where lavas and volcaniclastic tuff become dominant over chert and cherty tuff of the underlying Temperance Formation and ends to the west at the Long Plain Fault Zone. The total thickness of the section through the Nine Mile Volcanics is estimated to be 1050 m. Repetition of the sequence by folding is not evident; all facing directions are to the west, and dips range from 65° west to vertical.

Significance: Regional - the Nine Mile Volcanics is extensively distributed east of the Long Plain Fault zone where it is one of the oldest sedimentary rock units.

Impacted by Snowy 2.0 construction zone: No [lies just outside Snowy 2.0 Main Works project area – details of this site are included in this report for completeness and reference, as the formation extends north into the Main Works project area].

ii **Nine Mile Volcanics fossil locality** (category: Rare fossil site and Research site)

The Late Ordovician age assigned to the Nine Mile Volcanics is based on one site near Peppercorn Creek, north of Cooleman Plain. Owen & Wyborn (1979c, p.M40) describe the site as follows: along the northwest side of Peppercorn Creek, allochthonous blocks and clasts of limestone crop out about 30 m west of a ferruginised zone. The only fossil found in the limestone is a conodont identified as *Belodina*. A poorly preserved solitary rugose coral has also been recorded in a nearby calcareous tuff.

Significance: Regional (Statewide). The site encompasses the only known limestone of Late Ordovician age in KNP. Further research into this site, involving selective sampling of the limestone and dissolution of those samples (2-3 kg is adequate to be separately collected from each major block), is imperative to try to find further conodonts enabling the age to be precisely constrained, and to determine where the limestone may have been originally deposited.

Impacted by Snowy 2.0 construction zone: No [the site is situated about 4 km north of the northern boundary of the Snowy 2.0 Main Works project area, and 4 km NE of Peppercorn Hill; it is included in this report for completeness and reference due to its considerable scientific significance].

iii **Transition between Kiandra Group volcanics & turbidites** (category: Relationship & Research site)

Detailed mapping of Ordovician rocks in the region between Mt Jagungal and Rules Point by C.D. Quinn resulted in a recent re-evaluation of relationships between the Kiandra Volcanics and flanking turbidite successions, assigned to the Adaminaby Group. One important locality at Sawyers Hill, east of Kiandra (within the Snowy 2.0 Main Works project area), demonstrates the presence of debris flows of volcaniclastic detritus intermingled with deep-water basinal turbidite deposits (Quinn & Glen 2009, pp.29-31). The site is reached by a 4WD track off the Snowy Mountains Highway at Sawyers Hill to access the Eucumbene River (see figure 6.4 in Quinn & Glen 2009, reproduced here as Figure A4). Another example of this relationship at Far Bald Mountain (Quinn et al. 2014, figs 3C & 4) lies just outside the Snowy 2.0 project area.

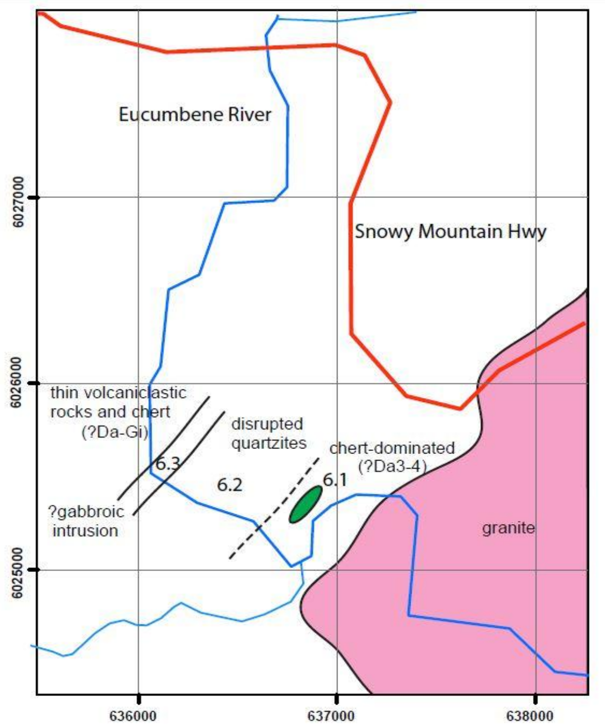

Figure B.2 Location of Geodiversity Site 7. Eucumbene River section near Sawyers Hill, showing location of debris flows of volcaniclastic rocks intermixed with chert, at transition between Kiandra Group volcanics and turbidite sediments of adjacent basin (from Quinn & Glen 2009, fig. 6.4)

Significance: Regional (Statewide) significance in demonstrating that the relationship between the volcanic 'arc' or rift is not a major terrane boundary as previously proposed, but more likely reflects an intra-basinal chain of sub-emergent active volcanoes within a back-arc basin infilled with turbidite deposits.

Impacted by Snowy 2.0 construction zone: No – the site lies within the project area but not affected by construction and is remote from any disturbance zones associated with the project.

B.1.3 Gooandra Volcanics (Kiandra Group)

i **Gooandra Volcanics Type Section** (category: Reference site)

The type section of the Gooandra Volcanics was originally designated by Owen & Wyborn (1979c, p.M11, fig. M2), commencing where the Kiandra Fault intersects an unnamed creek bed 1 km SE of Gooandra Homestead (approximately 10 km N of Kiandra), and ending 160 m W of Gooandra Creek. Quinn et al. (2014) restricted the extent of the Gooandra Volcanics to its type section around Gooandra Homestead, reassigning the majority of the underlying volcaniclastic succession and siliceous clastic sedimentary rocks with debris flows to the Nine Mile Volcanics or to undifferentiated Kiandra Group, transitional with the Temperance Formation (of the Adaminaby Group).

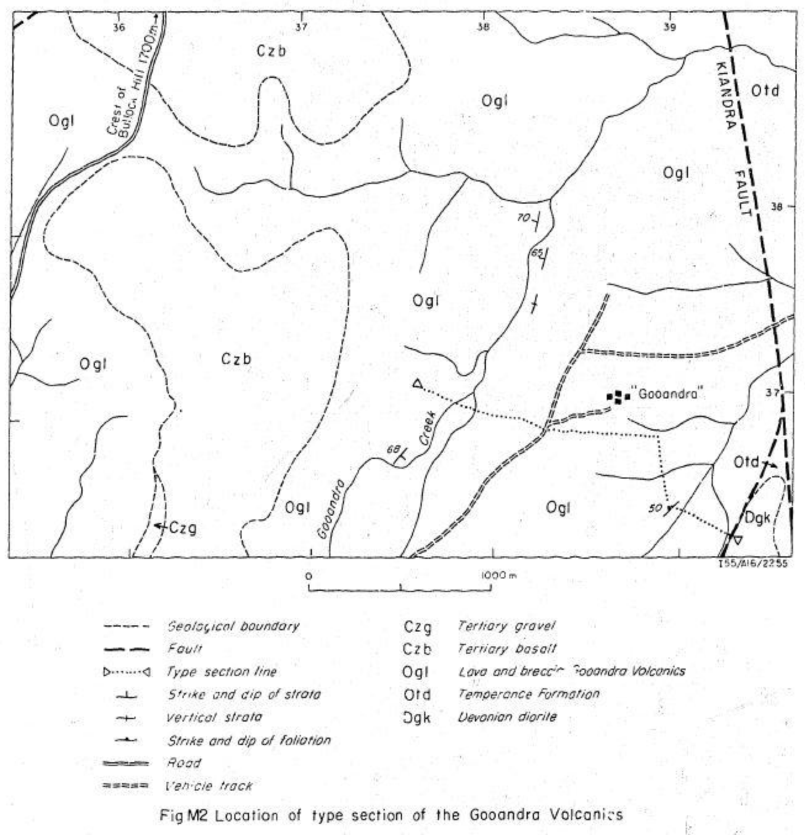

Figure B.3 Geodiversity Site 8: type section of the Gooandra Volcanics, south of Gooandra homestead, designated by Owen & Wyborn (1979c, fig. M2)

a Significance: Regional

Impacted by Snowy 2.0 construction zone: No – this reference site is within the project area but is not affected by construction or disturbance as it is remote from any proposed construction works.

B.1.4 **Warbisco Shale** (Bendoc Group)

i 'Nungar beds' Type/Representative Section (category: Reference site)

The common occurrence of Late Ordovician graptolites in black shales mapped as 'Nungar beds' has points to a probably synonymy of that informal stratigraphic named with the widespread and formally named Warbisco Shale. Owen & Wyborn proposed a revised type section for the 'Nungar beds' along Shaft Road, east of Tantangara Road and south of Nungar Creek (Owen & Wyborn 1979c, fig. M8 – see Figure A3 herein). The section is incomplete, and interrupted by two infaulted blocks of Tantangara Formation, but it does include the characteristic black shales. Accordingly, although the name 'Nungar beds' is superseded, this section remains a useful representative site within KNP for what is now Warbisco Shale.

Significance: Local/Regional. Other sites in KNP within what is now regarded as Warbisco Shale have graptolites preserved in black shales – it would be useful to have a palaeontologist check this reference site to determine whether graptolites are present here.

Impacted by Snowy 2.0 construction zone: No – within project area but not affected by construction. At its closest this site is 300 m east of Tantangara Road leading to the dam, and so is not expected to fall within the disturbance zone of any upgrading of this road. This site is adjacent to the newly recognised geodiversity site 3 (Temperance Formation) documented in this report.

B.2 Silurian stratigraphic units

B.2.1 Tantangara Formation (Yalmy Group)

i Tantangara Formation Type Section (category: Reference site)

Owen & Wyborn (1979c, p.M68, Fig. M11) show the location of the type section of the Tantangara Formation (and the nearby type locality of Kellys Plain Volcanics). This map is reillustrated here as Figure A6. The type section runs along the road-cutting on the south side of the Murrumbidgee River, east from the tunnel inlet valve station above Tantangara Dam to the bridge over the Murrumbidgee River, and continuing across a series of natural exposures along the hillside on the south side of Gulf Bend over a total distance of 2 km. The western part of the road-cutting exposes a continuous section of massive coarse dark sandstone with interbedded siltstone and shale; the eastern part has discontinuous exposures of softer fine brown sandstone.

Significance: Regional – the Tantangara Formation is the only unit of early Llandoverian age recognised in KNP, and this site provides the critical reference section for the formation.

Impacted by Snowy 2.0 construction zone: No – the site is within the project area but will not be affected by construction, as the western end of the type section is situated 1400 m NE of Tantangara Road where it passes the abandoned Traces Nob quarry. That is estimated to be the closest approach to the disturbance zone associated with upgrading Tantangara Road as part of the Snowy 2.0 project.

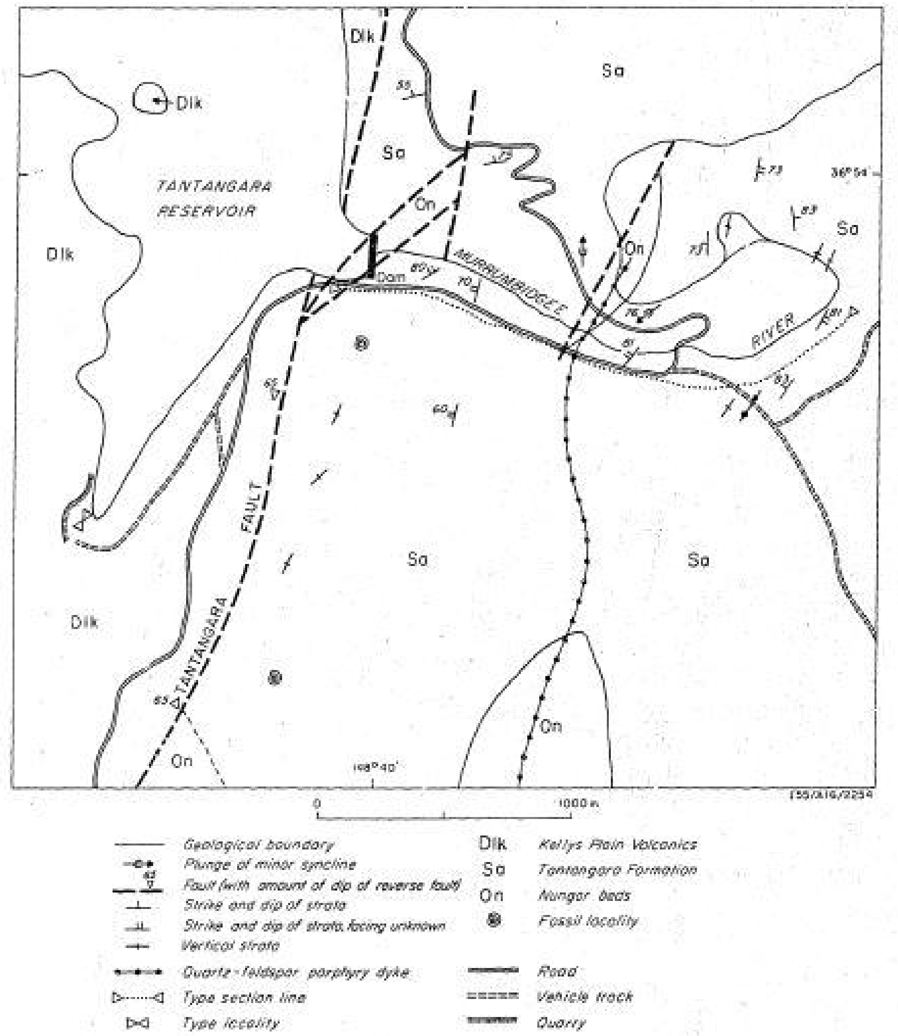

Fig M11. Location of type section of Tantangara Formation and type locality of Kellys Plain Volcanics

Figure B.4 Geodiversity Site 10: type section (shown as dotted line) of the Tantangara Formation (labelled Sa), along the Murrumbidgee River adjacent to and immediately downstream of Tantangara Dam, designated by Owen & Wyborn (1979c, fig. M11).

ii Tantangara Formation fossil locality (category: Rare fossil site)

Fossils are very uncommon to rare in the Tantangara Formation, with only one locality documented by Owen & Wyborn (1979c, p.M75). The early Llandoverian (Early Silurian) age assigned to this unit is based in part on the discovery of fragmentary brachiopods identified as *Eospirifer*, associated with the corals *Tryplasma* and *Angopora* at the northern end of Nungar Plain, 1 km north of Nungar Creek. This site is located just off the upper right hand margin of Figure A3 (=Map M8 of Owen & Wyborn 1979c) in the Tantangara Formation labelled Sa.

Two other fossil sites are shown by Owen & Wyborn (1979, Fig. M11) as occurring within the Tantangara Formation south of the type section of the unit (Figure A6 herein). No further details of these sites and their fossil content are provided. They would be worth resampling in case better preserved fossils compared to those from Nungar Plain are present – if so, they could be candidates for additional geodiversity sites in this formation.

Significance: Regional. As the Tantangara Formation is the only unit of early Llandoverian age recognised in KNP, it is important to date it precisely from its fossil content, as this will assist in tightly constraining the timing and extent of the Benambran Orogeny that took place immediately prior to deposition of the Tantangara Formation.

Impacted by Snowy 2.0 construction zone: No – The Nungar Plain site lies within the project area but is located 1500-1600 m east of any disturbance zones associated with the upgrading of Tantangara Road. The other fossil sites (yet to be investigated) mentioned above are 400-500 m east of Tantangara Road, so that distance should provide a sufficient buffer zone from any roadworks.

iii Tantangara Formation unconformity with Temperance Formation (category: Relationship site)

The angular unconformity between the Tantangara Formation and the underlying Temperance Formation is itself is not exposed, but at Dairymans Flat just north of Dairymans Creek the basal sandstone of the Tantangara Formation dips 34° northwest a few metres away from vertical Temperance Formation chert that strikes meridionally. This indicates an angular discordance of about 50° between the two formations (Owen & Wyborn 1979c, p.13).

Significance: Regional – this angular relationship records the effects of two orogenic episodes, firstly the Benambran Orogeny, which tilted the underlying Temperance Formation from its original horizontal level during deposition to being steeply dipping (though not vertical), prior to deposition of the Temperance Formation. A second earth movement, probably during the Bowning Orogeny, further tilted both formations, leaving the Temperance Formation vertical and the Tantangara Formation dipping at 34°.

Impacted by Snowy 2.0 construction zone: No – This site lies within the project area but not affected by construction as it is located well to the northwest of construction associated with the Tantangara portal which lies an estimated 9 km to the southeast.

B.2.2 Goobarragandra Volcanics (Douro Group)

B.2.3 Goobarragandra Volcanics Type Section (category: Reference site)

The type locality was defined by Owen & Wyborn (1979c, p.M128) as the hillside alongside the Yarrangobilly River 400 m southwest of Bucket Flat (Lat. 35°36′04″S, Long. 148°32′32″E). This is the best exposure of the formation in the KNP and consists about 2000 m^2 of 60-70% outcrop of a massive strongly porphyritic dacite with phenocrysts of plagioclase up to 20 mm and quartz up to 10 mm in a dark blue groundmass.

Significance: Regional – the Goobarragandra Volcanics has a widespread distribution in southern NSW, extending north to the area around Yass. The Type Section of this formation is therefore an important regional reference site.

Impacted by Snowy 2.0 construction zone: No – the site is just south of the northern margin of the project area in a remote locality 9 km NE of Yarrangobilly Village campground, and is not affected by construction.

B.2.4 Peppercorn Formation (Cooleman Group)

i Peppercorn Formation Type Section (category: Reference site)

The type section designated by Owen & Wyborn (1979c, p.M80, fig. M12), is in the valley of Little Peppercorn Creek. It starts about 250 m east of the creek crossing of an old disused track from Little Peppercorn Plain to Little

Peppercorn Hut (Fig. M12). From this point it extends northwest for about 800 m to the base of the overlying Kellys Plain Volcanics. The contact of the formation with the underlying Nine Mile Volcanics is not exposed in the type section, but mapping in the area has shown it to be an unconformity. The basal unit within the Peppercorn Formation is a coarse sandstone bed about 5 m thick, which contains reworked fragments of tuffaceous material from the underlying volcanics; this unit is not exposed in the type section, where it is present only as float. In the type section it is followed by 65 m of poorly bedded conglomerate which, being resistant to weathering, has formed good exposures along a ridge about 25 m high. The conglomerate is mainly composed of well-rounded chert pebbles up to 3 cm in diameter, and has interbeds of coarse sandstone and pebbly sandstone, particularly towards the top. Overlying beds of coarse to fine sandstone (about 25 m thick) and strongly cleaved brown siltstone, possibly more than 500 m thick, are poorly exposed.

Significance: Regional – the Peppercorn Formation is mainly exposed to the north of the Snowy 2.0 Main Works project area, but small outcrops are present in the valley of Nungar Creek west of Tantangara Reservoir and form the basis of several geodiversity sites there. It is important to include the Type Section of the formation as a reference site for comparison with these outcrops.

Impacted by Snowy 2.0 construction zone: No [the type section is located just north of the northern boundary of the Main Works project area].

ii Peppercorn Formation fossil locality A (category: Reference fossil site)

Hill (1954) described. corals from the limestone near Cooinbil homestead (off Long Plain Road) and identified *Halysites* sp. cf. *australis*, *H. brevicatenatus*, *Halysites* sp. indet., *Coenites* cf. *seriatopora*, and *Diploepora* sp. cf. *grayi*. This outcrop is the type locality for *Halysites brevicatenatus*. Hill reported a Wenlockian or Ludlovian age for this fauna. However, these limestone outcrops also yielded a rich conodont fauna, of which the main elements have been identified by Nicoll & Rexroad (1974). Significant species present include *Apsidognathus tubercalatus* and *Pterospathodus amorphognathoides*, indicating a Telychian age (late Llandoverian). Based on this information, Munson et al. (2001) reassessed the age of this limestone as Telychian to Sheinwoodian (i.e. entirely within the early Silurian).

Significance: Regional/national. This site is the type locality for a species of halysitid coral, and is the only place known to produce conodont microfossils that are important for age-dating of the Peppercorn Formation.

Impacted by Snowy 2.0 construction zone: No – this site is within the Snowy 2.0 project area but is not affected by construction work as it is remote from the disturbance zone around the Tantangara portal situated 18-19 km to the SSE.

iii Peppercorn Formation fossil locality B (category: Representative fossil site)

Fossils collected in the Nungar Creek valley (on the western side of Tantangara Reservoir) include a trilobite *Encrinurus* cf. *etheridgei*, a coral *Rhizophyllum* sp., and ?*Nucleospira* sp. (a brachiopod) (Owen & Wyborn 1979c, p.M85). The age assigned to this limited fauna is imprecise, ranging from Wenlockian to Ludlovian. The Tantangara 1:100,000 geological map (Owen & Wyborn 1979b) shows several fossil sites in this narrow faulted belt of Peppercorn Formation along the lower Nungar Creek valley.

Significance: Regional. This site is important because it contains a different suite of fossils, preserved in siltstone, compared to the coral-dominated fauna found in limestone of the Peppercorn Formation (e.g. Geodiversity site 14).

Impacted by Snowy 2.0 construction zone: No – reference to large scale mapping by SMEC geologists of the area between the western shore of Tantangara Reservoir and the lower Nungar Creek valley indicates that the closest outcrop of the Peppercorn Formation lies 1500 m to the west of the Tantangara tunnel portal and associated construction camp with a steep ridge intervening between the two. This site therefore lies outside the Main Works disturbance area.

iv Peppercorn Formation basal conglomerate (category: Representative lithological site; Research potential site)

The basal chert conglomerate is the most distinctive part of the Peppercorn Formation. Wherever it crops out it forms prominent tors and ridges, as in the lower Nungar Creek valley where outcrops are up to 10 m high. Detailed mapping by Jorg Bein (fig. 3 in Crook et al. 1973) shows the distribution of the conglomerate layer in what was then called the Currango Beds (now superseded by Peppercorn Formation). The conglomerate is mostly formed of rounded to subangular chert and vein-quartz pebbles having a fairly high sphericity. The composition of the pebbles reflects to some extent the subjacent rock type: in addition to chert and vein-quartz, which always predominate, volcanic pebbles are present where the conglomerate overlies volcanic units in the Kiandra Group; and quartz sandstone and lithic sandstone pebbles are present where it overlies the Tantangara Formation. The pebbles range from 1 to 5 cm diameter in the lower Nungar Creek valley, but farther south the average size increases to about 10 cm, and some pebbles are up to 20 cm diameter. The angularity of the pebbles also tends to increase towards the south (Owen & Wyborn 1979c, p.M81).

Angular clasts of cherts, in what appears to be a similar conglomerate in the Early Silurian Eurimbla Formation on the Boorowa 1:100 000 mapsheet 100 km to the north, yield Early Ordovician conodonts visible in thin sections. It would be useful to sample chert clasts from the Peppercorn Formation to see if they also contain microfossils indicative of an Ordovician age in thin sections.

Significance: Regional (Statewide) – the significance of this site is that it demonstrates a mixed provenance for the sources of the pebbles comprising the conglomerate, such as deep-water sediments (chert, potentially of the Temperance Formation or an older unit), volcanics of the Kiandra Group, and quartz sandstone pebbles of the Tantangara Formation. This mixture indicates that a variety of underlying and older rocks were uplifted and eroded during the Benambran Orogeny, possibly involving both phases 1 and 2.

Impacted by Snowy 2.0 construction zone: No – reference to large scale mapping by SMEC geologists of the area between the western shore of Tantangara Reservoir and the lower Nungar Creek valley indicates that the closest outcrop of the Peppercorn Formation lies 1500 m to the west of the Tantangara tunnel portal and associated construction camp with a steep ridge intervening between the two.

v Peppercorn Formation unconformity with Temperance Formation and Nine Mile Volcanics (category: Relationship sites)

Near Cooinbil homestead (off Long Plain Road, 8 km west of Cooleman Caves), Mufflers Creek, and Peppercorn Creek, the Peppercorn Formation lies unconformably on the Temperance Formation and Nine Mile Volcanics. This implies that the Tantangara Formation was removed before the Peppercorn Formation was deposited, during the Benambran Orogeny. At Peppercorn Creek (to the north of Cooleman Plain), where the basal conglomerate of the Peppercorn Formation is well exposed (Owen & Wyborn 1979c, fig. M12), the unconformity surface dips steeply to the north, overlying the Nine Mile Volcanics that are in the form of a tight northeast-plunging syncline with tuffaceous and cherty siltstone in the core.

Significance: Regional (Statewide)/national. This angular unconformity is an important demonstration of deformation due to the Benambran Orogeny which affected much of southeastern Australia at the end of the Ordovician Period.

Impacted by Snowy 2.0 construction zone: No [the best site, at Peppercorn Creek, is outside the Snowy 2.0 Main Works project area; other sites at Cooinbil and Mufflers Creek are within the project area but are neither directly nor indirectly affected as they are at a considerable distance from the construction zone at Tantangara tunnel portal].

B.2.5 **Cooleman Limestone** (Cooleman Plains Group)

This formation was identified in the KNP PoM (NPWS 2006) as including significant karst and cave sites at Cooleman Plain and Cooleman Caves. Those sites are monitored as part of the KGAP program (OEH 2012). The two sites documented below are additional to the karst sites which are regarded as having national and possibly international significance (Spate & Baker 2018).

i Cooleman Limestone Type Section (category: Reference site)

The type section (Owen & Wyborn 1979c, Fig. M15, Table M7) exposes the upper 250 m of the Cooleman Limestone. It starts at the base of a steep bluff on the western side of Cave Creek, about 0.6 km upstream from the southern crossing of the Blue Waterholes Trail over Cave Creek and extends east (updip) along Cave Creek for about 150 m, before following a steep gully which enters Cave Creek at a point where the creek swings sharply to the north. At the top of the gully the section continues along a bearing of 110° up to the contact between the limestone and the overlying Blue Waterhole Formation. Exposures are virtually continuous from the start of the section to the top of the gully, but are sparse over the last 150m of the section.

Significance: Regional – Cooleman Caves and associated karst are composed of Cooleman Limestone, one of only two significant areas of Late Silurian limestone in KNP.

Impacted by Snowy 2.0 construction zone: No – within the project area but not affected by construction as the Cooleman Plain and Caves are located approximately 17 km north of Tantangara Dam. The type section described here will not be affected by secondary impacts due to its remoteness from the Main Works construction areas. As documented in the Main Works Water Assessment (EMM 2019) there is no potential for impacts to water in proximity to this site.

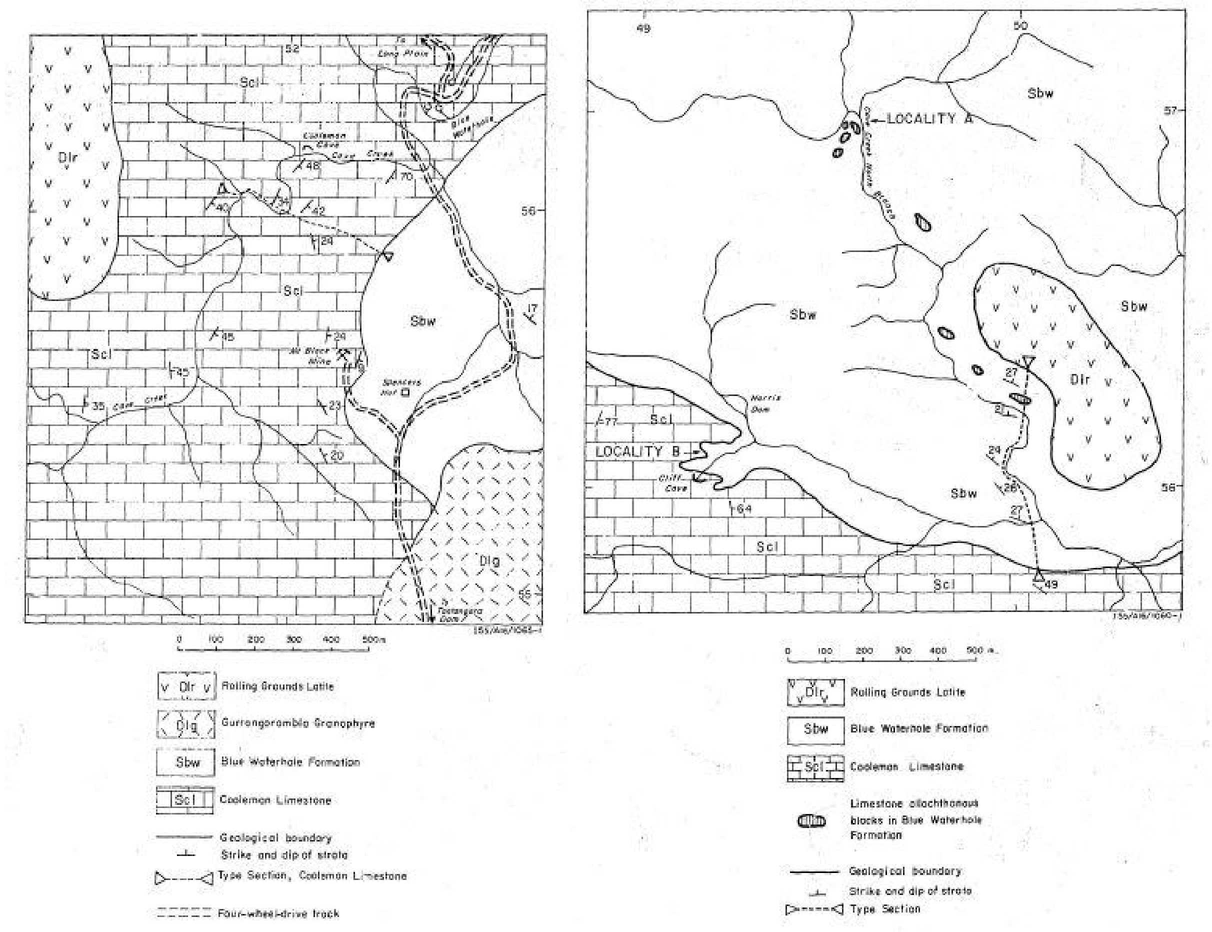

Fig.M15. Type section of Cooleman Limestone

Fig M19 Type locality of the Blue Waterhole Formation

Figure B.5 **(left) Type section of the Cooleman Limestone (from Owen & Wyborn 1979c, fig. M15), and (right) type section of the Blue Waterhole Formation (from Owen & Wyborn 1979c, fig. M19), Cooleman Caves area. Note that the area shown in M15 lies to the southeast of M19**

B.2.6 Blue Waterhole Formation (Cooleman Plains Group)

A geodiversity site identified in the KNP PoM (NPWS 2006) as 'slump bed folding, Cooleman Plain' corresponds to allochthonous (i.e. displaced and redeposited) limestone blocks occurring in a slumped horizon within the Blue Waterhole Formation. This important site, that also provides significant information on the fossil content of the Cooleman Limestone from which the allochthonous blocks were derived, is fully described in this report in Section 3.4.

i Blue Waterhole Formation Type Section (category: Reference site)

The type section for the Blue Waterhole Formation is depicted by Owen & Wyborn (1979c, Fig. M19 – reproduced as Figure A7 herein). It commences at the top of the Cooleman Limestone and follows Cave Creek northward to a point on the hillside where the formation is covered by Rolling Grounds Latite, north of where Cave Creek swings sharply west.

Significance: Local/Regional – as a reference site, the type section forms an integral part of the suite of geodiversity sites recognised in the Blue Waterhole Formation.

Impacted by Snowy 2.0 construction zone: No – within the project area but not affected by construction as the Blue Waterhole area is located approximately 18 km north of Tantangara Dam. The type section described here will not be affected by secondary impacts due to its remoteness from the Main Works construction areas. As documented in the Main Works Water Assessment (EMM 2019) there is no potential for impacts to water in proximity to this site.

ii Blue Waterhole Formation unconformity with Cooleman Limestone (category: Relationship site)

Near Cliff Cave at Cooleman Caves [Locality B on fig. M19 of Owen & Wyborn 1979c – see Figure A7 herein] and east of Harris Hut on the western side of Cooleman Plain the Blue Waterhole Formation unconformably overlies the Cooleman Limestone that has a karstified surface (indicating an interval of subaerial exposure) immediately below the boundary (Pickett 1982, p.62-63).

Significance: Regional – this is an important boundary relationship that is not easily observed and identified in limestone successions.

Impacted by Snowy 2.0 construction zone: No – within the project area but not affected by construction as the Blue Waterhole and Cooleman Caves areas are located 17-18 km north of Tantangara Dam. The type section described here will not be affected by secondary impacts due to its remoteness from the Main Works construction areas. As documented in the Main Works Water Assessment (EMM 2019) there is no potential for impacts to water in proximity to this site.

B.2.7 Yarrangobilly Limestone

The Yarrangobilly Limestone was identified in the KNP PoM (NPWS 2006) as including significant cave and karst sites at Yarrangobilly Caves and the surrounding caves reserve. These sites are also subject to regular monitoring to check their condition as part of the KGAP program (OEH 2012). The four sites documented below are additional to the karst sites which are regarded as having national and possibly international significance (Spate & Baker 2018).

i **Yarrangobilly Limestone Type Section and fossil site A** (category: Reference site and Representative fossil site)

Two sections were measured through the Yarrangobilly Limestone by Cooper (1977), the main one (Section 1) along the road passing Caves House and proceeding down the Thermal Pool track (Cooper 1977, fig. 1 inset), where an estimated thickness of 500-600 m was measured. The second measured section at Yarrangobilly Village was much thinner and only intersected part of the Caves House – Thermal Pool section. Though apparently never designated as the type section for the formation, it is recommended that Cooper's measured section 1 (Figure A8) be taken as the reference site for the type section.

Conodont microfossils described from the Yarrangobilly Limestone by Cooper (1974, 1977) provide the basis for its Ludlovian age, ranging from the *Polygnathoides siluricus* Zone of the middle Ludlovian (at a level 180 m above the base of the formation) to the *Ozarkodina crispa* Zone of uppermost Ludlovian age at the top of the limestone. The conodonts were mainly sampled from measured section 1.

Significance: Regional/Statewide – the type section and the conodont microfossils sampled from it provide significant lithological and biostratigraphic information on this formation, enabling its precise correlation with other Upper Silurian limestones throughout southeastern Australia.

Impacted by Snowy 2.0 construction zone: No – Yarrangobilly Caves and the surrounding area of limestone outcrop lies within the project area but is not affected by construction. As documented in the Main Works Water Assessment (EMM 2019) it is very unlikely that the Snowy 2.0 construction works will have any impacts to water in proximity to this site. Vibration from construction works, however distant, will have no impact on the integrity of the type section.

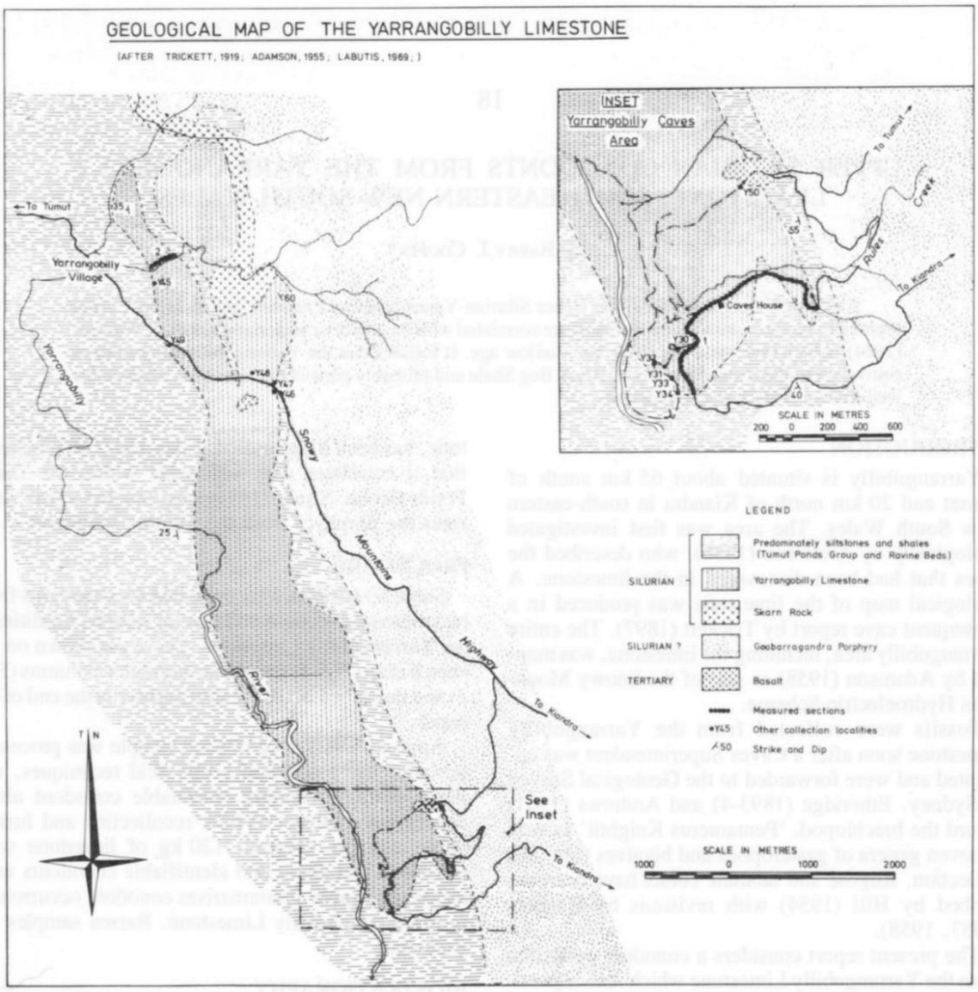

Figure B.6 **Geological map of the Yarrangobilly area, showing Type Section measured along the road at Yarrangobilly Caves and the track to the Thermal Pool (Cooper 1977)**

Significance: Regional/Statewide – the type section and the conodont microfossils sampled from it provide significant lithological and biostratigraphic information on this formation, enabling its precise correlation with other Upper Silurian limestones throughout southeastern Australia.

Impacted by Snowy 2.0 construction zone: No – Yarrangobilly Caves and the surrounding area of limestone outcrop lies within the project area but is not affected by construction. As documented in the Main Works Water Assessment (EMM 2019) it is very unlikely that the Snowy 2.0 construction works will have any impacts to water in proximity to this site. Vibration from construction works, however distant, will have no impact on the integrity of the type section.

ii Top Yarrangobilly Limestone fossil site (category: Representative fossil site)

In the uppermost part of the Yarrangobilly Limestone adjacent to the Snowy Mountains Highway is a shell bed layer composed of *in situ* trimerellide brachiopods [Figure 2.5] – the species represented in these beds is yet to be described scientifically, but is believed to be closely related to *Keteiodoros* from the Dripstone Formation of Wenlockian age in the Wellington region of central NSW (Strusz et al. 1998). This site also corresponds to conodont sampling locality Y49 of Cooper (1977, fig.1), at the western end of outcrop of the Yarrangobilly Limestone where this intersects the Snowy Mountains Highway south of Yarrangobilly Village (Figure A8).

Significance: Regional/Statewide – these fossils potentially provide a link both in palaeoecological terms and possibly in age-dating, between limestones in KNP and those in the central west of NSW.

Impacted by Snowy 2.0 construction zone: No – within project area but not affected by construction.

B.3 Devonian stratigraphic units

B.3.1 Milk Shanty Formation (Byron Range Group)

i **Milk Shanty Formation at The Walls** (category: Representative lithological site)

No type section has been formally designated for the Milk Shanty Formation, and only a summary of its lithological characteristics has been published (Moye et al. 1969, p.145) where mention is made of compact, resistant sandstones in the upper 105 m of the formation forming the distinctive cliff-line known as The Walls, above Lobs Hole. These cliffs were described by Andrews (1901) as providing the substrate down which spectacular flows of tufa were being deposited (see also Carne & Jones, p.326). The cliff-line and its tufa deposits (the latter discussed by Troedson 2019) is proposed as a geodiversity site representative of two distinctly different geological events.

Significance: Local (for the sandstone substrate forming The Walls); National (for the overlying tufa deposits).

Impacted by Snowy 2.0 construction zone: No – the site lies within the Snowy 2.0 Main Works project area but is not within the disturbance zone and is therefore not expected to be directly affected by construction. The resistant sandstones forming The Walls will not be impacted by vibration due to construction work (estimated to be 700 m away at the closest point). Refer to Alexa Troedson's report (2019) for potential sensitivities of the associated tufa deposits.

B.3.2 Round Top Formation (Byron Range Group)

i **Round Top Formation Type Locality (category: Reference site and Representative fossil site)**

No formally designated type section of the Round Top Formation has been defined. A measured section (Flood 1969) through the unit at Round Top Trig passed through 15 m of interbedded maroon sandstone and siltstone, with fossiliferous quartzite at the base of the Formation containing numerous lingulate brachiopods. These shells (that have not been formally described) are the only fossils known from this unit.

A thicker (up to 30 m) but less easily accessible exposure of the Round Top Formation forms the capping of the Byron Range to the east of Lobs Hole Ravine Road. Fossils have not been recorded from that locality. Accordingly it is not included in this geodiversity site.

Significance: Local/regional. This is the only known fossil site in the Round Top Formation. Detailed examination of the lingulide brachiopod fossils will reveal if they represent a new undescribed species.

Impacted by Snowy 2.0 construction zone: No. The widening of Lobs Hole Ravine Road, although in proximity to Round Top Trig (between 200 - 500 m away, upslope), will not intersect the outcrop at this site. The fossil bed is in quartzite, a very tough and dense indurated sandstone that is expected to be immune to vibrations associated with excavation of the road cuttings.

B.3.3 Kellys Plain Volcanics

A suite of five sites in the Kellys Plain Volcanics on the western shore of Tantangara Reservoir has the potential to be an unusual (even unique) drawcard to entice visitors to admire the engineering construction of the eastern (Tantangara) portal after it is complete and public access to the whole areas is restored. The outcrops identified in the five sites portray different lithological characteristics of the Kellys Plain Volcanics and the relation of this unit to those it overlies. After Snowy 2.0 construction concludes, each site should be easily accessible for the public to walk to, retaining as much as possible the appearance of the natural environment by keeping any tracks low-key. Two of the five sites are likely to be directly impacted by construction during the Snowy 2.0 construction works, and have been separately documented (Section 3.4). The other three sites are described below.

i **Kellys Plain Volcanics columnar jointing** (category: Representative lithological site)

Columnar jointing in the Kellys Plain Volcanics is common, especially in the lower Nungar Creek valley – e.g. on the east bank of Nungar Creek as it enters Tantangara Reservoir. The columns are up to 2.5 m long and 150 mm in cross-section and have four to seven sides (Owen & Wyborn 1979c, p.M168).

[A second site is identified by Owen & Wyborn (1979c) 600 m north of Old Currango homestead on Currango Plain west of the northern end of Tantangara Reservoir, and is not considered part of the geodiversity/geotourism site near to Tantangara tunnel portal].

Significance: Local – columnar jointing is a spectacular but fairly common feature of volcanic extrusive rocks that have slowly cooled subaerially. Other sites in KNP are restricted to Miocene basalts (one was identified as a geodiversity site in the KNP PoM (NPWS 2006). The two sites in the Kellys Plain Volcanics are the only known occurrences of the phenomena in Devonian rocks in KNP.

Impacted by Snowy 2.0 construction zone: No – the Nungar Creek site is estimated to lie 2-3 km west of the Tantangara spoil storage site, and therefore is outside the disturbance zone of Snowy 2.0 Construction Works. There is negligible likelihood of impacts to the hydrology of the site, and potential impacts on the columnar jointing due to vibration during construction can be ruled out.

Recommendation: After construction works conclude, KNP could provide signage and ensure public access by walking track with directions.

ii Kellys Plain Volcanics unconformity with Tantangara Formation (category: Relationship site)

The Kellys Plain Volcanics unconformably overlie the Temperance Formation, Nine Mile Volcanics. Tantangara Formation, and Cooleman Plains Group, indicating considerable erosion had taken place before the Lower Devonian lavas were extruded. The unconformity above the Tantangara Formation is exposed approximately 5 km SW of Tantangara Dam (Owen & Wyborn 1979c p.15). This relationship is significant in providing clear evidence of the Bowning Orogeny at the end of the Silurian Period, which uplifted and deformed Silurian rocks of the Tantangara Formation that were eroded prior to being covered by lavas and volcaniclastic deposits of the Lower Devonian Kellys Plain Volcanics.

Significance: Regional (statewide)/national significance as a very good example of an unconformity caused by the Bowning Orogeny. Useful in the context of a potential geotourism site to compare and contrast this feature with another unconformable relationship between the Kellys Plain Volcanics and another underlying formation, the Cooleman Plains Group (see next geodiversity site).

Impacted by Snowy 2.0 construction zone: No – the site is sufficiently far from Tantangara Road and Quarry Road (estimated 2-3 km away) leading to the Tantangara portal construction site that it will not be within the disturbance zone. No adverse effects on hydrology, nor any potential problems arising from vibration during construction works, are envisaged.

iii Kellys Plain Volcanics unconformity with Cooleman Plains Group (category: Relationship site)

The Kellys Plain Volcanics unconformably overlie the Temperance Formation, Nine Mile Volcanics. Tantangara Formation, and Cooleman Plains Group, indicating considerable erosion had taken place before the Lower Devonian lavas were extruded. A pronounced angular unconformity between the underlying Cooleman Plains Group and the Kellys Plain Volcanics is present approximately I km west of the western shoreline of Tantangara Reservoir, just south of where Nungar Creek enters the storage (Owen & Wyborn 1979c, p.15). This relationship is significant in providing clear evidence of the Bowning Orogeny at the end of the Silurian Period, which uplifted and deformed Silurian (in this case Upper Silurian) rocks that were eroded prior to being covered by lavas and volcaniclastic deposits of Early Devonian age. The erosional gap at the unconformity surface is less than that implied for the preceding site (on the Tantangara Formation), but the discontinuity between underlying inclined strata and overlying horizontal lavas is more obvious here.

Significance: Regional (statewide)/national – this is possibly the most spectacular example of an angular unconformity due to the Bowning Orogeny that is readily accessible within KNP. It differs from (and can be compared to) the previous site as examples of how an orogeny can affect the underlying rocks prior to deposition of younger rocks in horizontal orientation.

Impacted by Snowy 2.0 construction zone: No – this site is located approximately 2 km NW of the Tantangara portal construction site, and at its closest point is estimated to be 700 m west of the stockpile at the end of Tantangara Camp Road. Hence it lies outside the construction works disturbance zone. The site is sufficiently robust not to be subject to vibration during construction.

Recommendation: Ensure public access is provided to this and the preceding unconformity site after construction works conclude; KNP could arrange for interpretative signage to explain these features. Contact Geological Survey of NSW for assistance planning and publicising this geotrail.

Table B.1 Notes for future management on newly identified Palaeozoic geodiversity sites not impacted by Snowy 2.0 construction

Geodiversity site/category	Impacted by construction?	Potential for future work	Rationale for inclusion in Geodiversity study	Risk/ sensitivity/ opportunity
1. Temperance Formation Type Section (Reference site)	No [just outside Snowy 2.0 Main Works project area]	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM.	Type section provides the standard against which other occurrences of this geological unit are compared – this formation extends into project area	N/A
2. Temperance Formation chert outcrop A (Representative lithological site)	No – within project area but distant from, and not affected by, works	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM, with access maintained for study by geologists.	Chert lithology from this formation has been shown to contain conodont microfossils that provide a means of accurately dating the rock unit	Research opportunity to accurately age-date the rock unit
3. Temperance Formation chert outcrop B (Research potential site)	No (300 m west of Tantangara Road leading to dam)	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM, with access maintained for study by geologists.	Chert lithology from this formation has been shown to contain conodont microfossils that provide a means of accurately dating the rock unit	Research opportunity to accurately age-date the rock unit
4. Temperance Formation chert outcrop C (Rare fossil site)	No – within project area but distant from, and not affected by, works	Geologists/geotechnical engineers involved in the project construction should be made aware of the possibility of other macrofossil sites being discovered in this formation.	This is currently the only site from which macrofossils are known in this rock unit	Opportunity for further discoveries
5. Nine Mile Volcanics Type Section (Reference site)	No [just outside Snowy 2.0 Main Works project area]	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM, with access maintained for study by geologists.	Type section provides the standard against which other occurrences of this geological unit are compared – this formation extends into project area	N/A
6. Nine Mile Volcanics Type Section (Rare fossil site)	No [outside Snowy 2.0 Main Works project area]	Geologists/geotechnical engineers involved in the project construction should be made aware of the possibility of other macrofossil sites being discovered in this formation.	This is currently the only site from which fossils are known in this rock unit. Important for age-dating this formation	Opportunity for further discoveries

Table B.1 Notes for future management on newly identified Palaeozoic geodiversity sites not impacted by Snowy 2.0 construction

Geodiversity site/category	Impacted by construction?	Potential for future work	Rationale for inclusion in Geodiversity study	Risk/ sensitivity/ opportunity
7. Transition between Kiandra Group volcanics & turbidites (Relationship & Research site)	No – within project area but distant from, and not affected by, works	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM, with closely monitored access maintained for scientific study by geologists; protect site from any future impacts. Lack of publicity might be an option.	Very significant site – discovery of this transitional boundary has widespread implications for Ordovician tectonic and depositional models throughout NSW	Significant site which must be safeguarded; opportunity for further research
8. Gooandra Volcanics Type Section (Reference site)	No – within project area but distant from, and not affected by, works	No specific recommendations, as site is adequately protected at present within KNP, in vicinity of Gooandra Homestead	Type section provides the standard against which other occurrences of this geological unit are compared	N/A
9. 'Nungar beds' type/representative section	No – within project area but at closest point 300 m away from Tantangara Rd disturbance zone	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM, with access maintained for study by geologists.	Now regarded as correlative with Warbisco Shale and therefore the name Nungar beds is superseded; it is important to establish that graptolite fossils in this type/representative section are identical in age to those in the Warbisco Shale	N/A
10. Tantangara Formation Type Section (Reference site)	No – within project area but distant from, and not affected by, works	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM, with access maintained for study by geologists.	Type section provides the standard against which other occurrences of this geological unit are compared	N/A
11. Tantangara Formation fossil site (Rare fossil site)	No – within project area but distant from, and not affected by, works	Geologists/geotechnical engineers involved in project construction should be made aware of the possibility of other fossil sites being discovered in this formation, between Tantangara Reservoir and Snowy Mountains Highway.	This is currently the only site from which fossils (important for age-dating) have been identified in this formation.	Opportunity for further discoveries

Table B.1 Notes for future management on newly identified Palaeozoic geodiversity sites not impacted by Snowy 2.0 construction

Geodiversity site/category	Impacted by construction?	Potential for future work	Rationale for inclusion in Geodiversity study	Risk/ sensitivity/ opportunity
12. Tantangara Fm unconformity with Temperance Fm (Relationship site)	No – within project area but distant from, and not affected by, works	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM, and that it remains open to access by the public. Interpretative signage may be of value	Site provides field evidence for Benambran Orogeny, which uplifted and deformed Ordovician rocks throughout southeastern Australia	Potential opportunity for public education
13. Goobarragandra Volcanics Type Section (Reference site)	No – within project area but distant from, and not affected by, works	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM, with access maintained for study by geologists.	Type section provides the standard against which other occurrences of this geological unit are compared	N/A
14. Peppercorn Formation Type Section (Reference site)	No [section is located just north of the Main Works project area boundary]	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM, with access maintained for study by geologists.	Type section provides the standard against which other occurrences of this geological unit are compared – this formation extends into the project area	N/A
15. Peppercorn Formation fossil site A (Reference fossil site)	No – within project area but distant from, and not affected by, works	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM. Scientific sampling should be permitted to allow further study of conodont microfossils.	Important fossil site in limestone providing precise age date for this formation. No studies on the conodont microfossils have been carried out since 1974.	Opportunity for palaeontological research
16. Peppercorn Formation fossil site B (Representative fossil site)	No – located 1500 m W of Tantangara tunnel portal and construction camp	Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM. Scientific sampling should be permitted to allow further study of macrofossils.	Important fossil site in siltstone providing imprecise age date for this formation – fossils differ from those at previous site, and are indicative of potential for further discoveries.	Opportunity for new discoveries

Table B.1 Notes for future management on newly identified Palaeozoic geodiversity sites not impacted by Snowy 2.0 construction

Geodiversity site/category	Impacted by construction?	Potential for future work	Rationale for inclusion in Geodiversity study	Risk/ sensitivity/ opportunity
17. Peppercorn Formation basal conglomerate (Representative lithological site; Research potential site)	No – located 1500 m W of Tantangara tunnel portal and construction camp	Future opportunity for sampling of chert pebbles to determine their provenance and age.	Very distinctive lithological layer at base of this formation, providing evidence of erosion of older geological units and redeposition of material as conglomerate. Inclusion of chert pebbles is unusual – a potentially comparable layer has been recognised 100 km to the north near Boorowa, where the chert pebbles contain microfossils.	Potential opportunity for research, possibly leading to significant scientific discovery
18. Peppercorn Formation unconformity with Temperance Formation and Nine Mile Volcanics (Relationship sites	No – Cooinbil and Mufflers Creek localities within project area but are not directly affected {best site at Peppercorn Creek is outside project area)	Ensure that all three sites are brought to the attention of KNP management for possible inclusion in future PoM, and that it remains open to access by the public. Interpretative signage may be of value.	Significant sites that provide field evidence for Benambran Orogeny, which uplifted and deformed Ordovician rocks throughout southeastern Australia. The best site lies outside the Snowy 2.0 Main Works project area, but two other sites occur within the project area.	Potential opportunity for public education
19. Cooleman Limestone Type Section (Reference site)	No – within project area but distant from, and not affected by, works	Cooleman Limestone has previously been recognised as a very significant karst area and continues to be actively monitored by KNP. Ensure that this site is brought to the attention of KNP management for inclusion in future PoM and KGAP.	Type section provides the standard against which other occurrences of this geological unit are compared. This site was not previously included in Cooleman site in KNP PoM.	N/A
20. Blue Waterhole Formation Type Section (Reference site)	No – within project area but distant from, and not affected by, works	Within Cooleman Caves area, and currently monitored under KGAP. Ensure that this site is brought to the attention of KNP management for inclusion in future PoM and KGAP.	Type section provides the standard against which other occurrences of this geological unit are compared	N/A

Table B.1 Notes for future management on newly identified Palaeozoic geodiversity sites not impacted by Snowy 2.0 construction

Geodiversity site/category	Impacted by construction?	Potential for future work	Rationale for inclusion in Geodiversity study	Risk/ sensitivity/ opportunity
21. Blue Waterhole Formation unconformity with Cooleman Limestone (Relationship site)	No – within project area but distant from, and not affected by, works	Within Cooleman Caves area, and currently monitored under a Karst Management Plan. Ensure that this site is brought to the attention of KNP management for inclusion in future PoM and KGAP.	An unusual (and rarely identified) karstified unconformity surface indicates that a brief interval of exposure of the Cooleman Limestone occurred prior to deposition of the Blue Waterhole Formation	N/A
22. Yarrangobilly Limestone Type Section and fossil locality (Reference site and Representative fossil site)	No – within project area but distant from, and not affected by, construction works	Within Yarrangobilly Caves area, currently monitored under KGAP. Opportunity for future sampling in lower Yarrangobilly Limestone to determine age range of entire formation, using conodonts.	Type section provides the standard against which other occurrences of this geological unit are compared. Age of the formation is well defined in the upper part only.	Opportunity to obtain new age dating information
23. Top Yarrangobilly Limestone fossil site (Representative fossil site)	No – within project area but distant from, and not affected by, works	Site is adjacent to Snowy Mountains Highway. Monitor via KNP Pom and KGAP to ensure that fossils are not removed without scientific authority. Best to not publicise this site.	Important fossil site at top of limestone, containing unusual trimerellide brachiopods similar to those identified at a locality near Wellington in central NSW	Risk of unauthorised removal of fossils
24. Milk Shanty Formation at The Walls (Representative lithological site)	No – within project area but sandstone cliffs not affected by construction	Access is difficult. The site is best viewed from the Lobs Hole area. It is not recommended that the public be allowed access due to fragility of the tufa deposits.	Spectacular and well-known geomorphic expression of resistant sandstone in the Milk Shanty Formation. Also associated with Recent tufa deposits.	Tufa deposits sensitive to visitors due to fragility

Table B.1 Notes for future management on newly identified Palaeozoic geodiversity sites not impacted by Snowy 2.0 construction

Geodiversity site/category	Impacted by construction?	Potential for future work	Rationale for inclusion in Geodiversity study	Risk/ sensitivity/ opportunity
25. Round Top Formation Type locality and fossil site (Reference site and Representative fossil site)	No – 200-500 m upslope from, but neither directly nor indirectly affected by widening of the Lobs Hole Lobs Hole Ravine Road	Opportunity for collection of lingulide brachiopod fossils so that these can be described, adding information about a second Devonian fossiliferous site in KNP. Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM and KGAP.	Type locality at Round Top Trig is the most accessible place to view this formation. Fossil lingulide brachiopods preserved in basal beds have not been described.	Opportunity for research
26. Kellys Plain Volcanics columnar jointing (Representative lithological site)	No – the Nungar Creek site is 2 km W of Tantangara spoil storage site and is outside the disturbance zone of Snowy 2.0 Construction Works.	Ensure outcrops identified in the five sites portraying different characteristics of Kellys Plain Volcanics and relation of this unit to those it overlies are accessible for the public after construction concludes. Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM and KGAP. Potential for inclusion in a Kellys Plain Volcanics geotrail after construction concludes.	Spectacular columnar jointing is otherwise only known in KNP in Miocene age basalts, generally capping mountains. This is an accessible site of (much older) Devonian age. This site, together with the other four Kellys Plain Volcanics sites listed here (and in Table 4.1), are all reasonably close to each other on the western shore of Tantangara Reservoir. Together they would form a coherent geodiversity site that would be of interest to the public. All five sites are sufficiently robust to permit unsupervised visitation.	Minimal or no risk unless the site(s) is covered over; robust nature of rocks minimises sensitivity; great opportunity for geotourism site.
27. Kellys Plain Volcanics unconformity with Tantangara Formation (category: Relationship site)	No – site is 2 km away from Tantangara Road and Quarry Road so will not be within the disturbance zone.	Ensure outcrops identified in the five sites portraying different characteristics of Kellys Plain Volcanics and relation of this unit to those it overlies are accessible for the public after construction concludes. Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM and KGAP. Potential for inclusion in a Kellys Plain Volcanics geotrail after construction concludes.	One of two major unconformities in the Tantangara Reservoir area between the Kellys Plains Volcanics and older formations, demonstrating effect of the Bowning Orogeny. This site, together with the other four Kellys Plain Volcanics sites listed here (and in Table 4.1), are all reasonably close to each other on the western shore of Tantangara Reservoir. Together they would form a coherent geodiversity site that would be of interest to the public. All five sites are sufficiently robust to permit unsupervised visitation.	Minimal or no risk unless the site(s) is covered over; robust nature of rocks minimises sensitivity; great opportunity for geotourism site.

Table B.1 Notes for future management on newly identified Palaeozoic geodiversity sites not impacted by Snowy 2.0 construction

Geodiversity site/category	Impacted by construction?	Potential for future work	Rationale for inclusion in Geodiversity study	Risk/ sensitivity/ opportunity
28. Kellys Plain Volcanics unconformity with Cooleman Plains Group (category: Relationship site)	No – site is located approx 2 km NW of the Tantangara portal construction site and about 700 m W of stockpile at end of Tantangara Camp Road.	Ensure outcrops identified in the five sites portraying different characteristics of Kellys Plain Volcanics and relation of this unit to those it overlies are accessible for the public after construction concludes. Ensure that this site is brought to the attention of KNP management for possible inclusion in future PoM and KGAP. Potential for inclusion in a Kellys Plain Volcanics geotrail after construction concludes.	One of two major unconformities in the Tantangara Reservoir area between the Kellys Plains Volcanics and older formations, demonstrating effect of the Bowning Orogeny. This site, together with the other four Kellys Plain Volcanics sites listed here (and in Table 4.1), are all reasonably close to each other on the western shore of Tantangara Reservoir. Together they would form a coherent geodiversity site that would be of interest to the public. All five sites are sufficiently robust to permit unsupervised visitation.	Minimal or no risk unless the site(s) is covered over; robust nature of rocks minimises sensitivity; great opportunity for geotourism site.