SPRING

MULU CAVES 2019

An Anglo-Malaysian Expedition to the
Gunung Mulu National Park, Sarawak

Report on the findings of the

MULU 19

expedition to the
Gunung Mulu National Park
Sarawak

April 2019 - May 2019

Expedition Leaders: Andy Eavis and Ben Kent
Edited by Ben Kent

Contact: Please use the form at www.mulucaves.org/contact.php

Gunung Mulu National Park, Sarawak, Malaysia 18th April 2019 12th May 2019 The primary aim for the Mulu 19 expedition was to further exploration and connect caves in the Southern peninsula of Gunung Api. This focused on trying to join Cave of the Winds, Racer Cave, Easter Cave and Lagangs to significantly lengthen the Clearwater System. A sump from Cave of the Winds was proven to connect to Racer, so all that remains is for a diver to pass through. Lagangs and Easter were not connected but significant extensions were found.

Additional exploration was completed in the northern end of Clearwater towards the Blackrock connection. This has opened up interesting leads to be examined by future expeditions.

Scientific work examining microbiological features was also completed.

Contents

List of Figures

Bibliography

[1] Sir St. John, Spenser [Buckingham]. *Life in the forests of the Far East.*, volume v.2. London,Smith, Elder and co.,. https://www.biodiversitylibrary.org/bibliography/119455.

[2] Tom Harrison. *The Oxford University Expedition to Sarawak.* Royal Geographical Journal, London, 1933.

[3] Wilfred. *Unknown.* Malaysian Geographical Survey, 1964.

[4] Dave Brook and Tony Waltham. The underworld of mulu. *Caving International*, 1978.

[5] M. Meredith, J. Wooldridge, and B. Lyon. *Giant Caves of Borneo.* Tropical Press, 1992.

[6] Andy Eavis. *Caves of Mulu '80.* The Royal Geographical Society, London, 1981.

[7] Matt Kirby. *Mulu Caves '88 & '89 Expeditions.* Mulu Caves Project, 1989.

[8] Matt Kirby. *Mulu Caves '90 Expedition.* Mulu Caves Project, 1990.

[9] Alan Weight. *Gunung Api Connection Expedition Report.* 1990.

[10] Derek Bristol. Youtube. `https://www.youtube.com/channel/UC66bwyl1NOBVQ_gu3Zg-fnw`, 2019.

1 Introduction

1.1 Location

The Gunung Mulu National Park is situated in north-eastern Sarawak, with its northern boundary forming part of the border with Brunei, (figures 1.1 and 1.2). It was officially constituted in 1974 and opened to visitors in 1985. Lying 4°N of the equator it covers an area of 528 sq km.

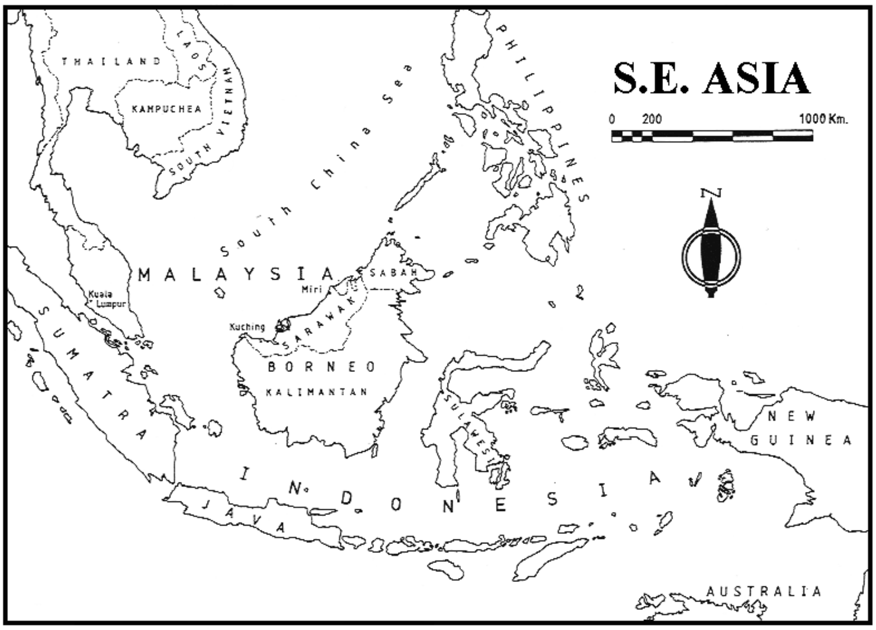

Figure 1.1: SE Asia

The Park is dominated by the sandstone mass of Gunung Mulu,which rises to 2376 m. To the west of Mulu, and on its flank, lies a band of Melinau limestone, which forms the lesser peaks of Gunung Api and Gunung Benarat. The lower slopes are covered in dense tropical rainforest, which rises to meet the montane forest of Mulus upper slopes.

Mulu is a rich mixture of plant and wildlife and in the limestones, beneath the forest canopy, lie some of the world's most impressive caves.

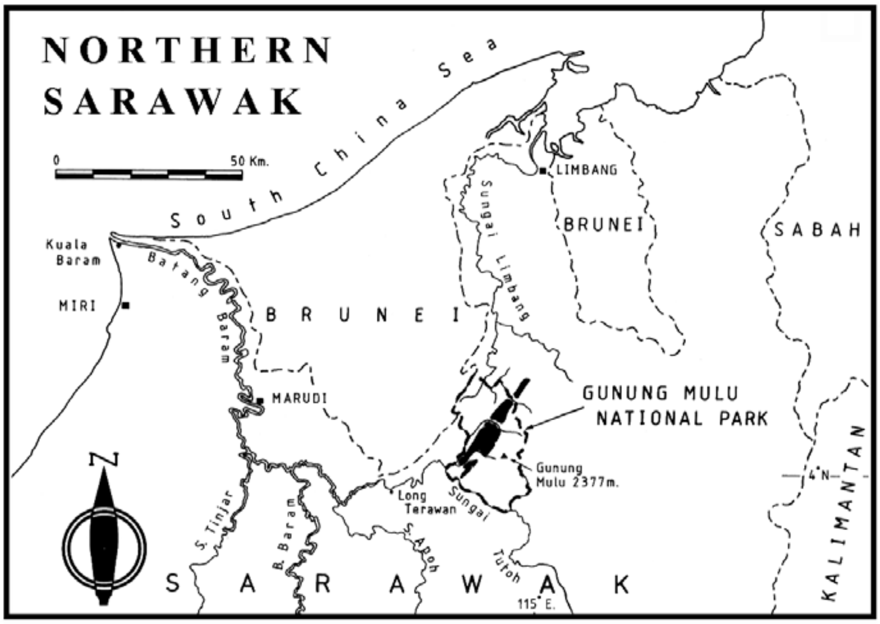

Figure 1.2: Northern Sarawak

1.2 History of exploration in Mulu

The existence of large caves in the Gunung Mulu area of Northern Sarawak has been documented for over 150 years. In 1858 reference was made to Detached masses of limestone, much water-worn, with caverns and natural tunnels around the base of Mulu by Spenser St. John in his book Life in the Forests of the Far East, [1]. St. John was Consul General in the Great Island of Borneo and made some of the earliest exploratory journeys of any European into the interior of Sarawak. His attempts to reach the summit of Mulu were thwarted by limestone cliffs, dense forest and sharp pinnacles of rock and he says, It is almost impossible to conceive the difficulty of ascending this mountain. Mulu was to keep the secrets of its summit for a further 74 years until Edward Shackleton successfully climbed the mountain during the Oxford University Expedition of 1932, [2].

In 1961 G.E. Wilford, of the Malaysian Geological Survey, visited the area to explore its caves. His work included the surveying of Deer Cave and parts of Cave of the Winds. He predicted that Mulu would yield many more caves in the future, [3]. During 1977-8 the Royal Geographical Society Mulu Expedition spent 15 months in the area studying many aspects of the rainforest. This was the largest scientific expedition ever to leave the UK. Included in the team were six speleologists who, in three months, explored and surveyed 50kms. of cave passages including parts of Clearwater Cave, Green Cave and others, [4].

During the expedition a forest camp was established in Hidden Valley from where two major caves were explored. Wonder Cave on the north side of the valley was found to have some of the largest passages in Mulu. Prediction Cave on the south side also contained enormous passages which were almost filled with river sediments, [5].

It was obvious from these findings that Mulu ranked as one of the world's foremost caving regions. As a result of the RGS expedition two large scale caving expeditions were mounted in the early 80s. The Mulu 80 expedition explored and surveyed a further 50km of cave passages, including the largest underground cavity, in the world, Sarawak Chamber, which forms the final chamber of Lubang Nasib Bagus or Good Luck Cave, [6]. The end of this chamber lies very close to the end of Prediction Cave in Hidden Valley and tantalising draughts at the end of each cave suggested a connection.

In 1984, the Sarawak 84 expedition spent one month in the field and explored 54km of caves. Clearwater Cave was extended by 14km but a great deal of work was carried out in Benarat, where Cobweb Cave was discovered, adding a further 15km of passages to the Benarat total. Sarawak Chamber was also photographed for the first time. These two expeditions carried out a great deal of scientific research associated with the caves, including dye tracing, geology, geomorphology, ecology, cave mineralogy, etc. However, although 150km of some of the largest caves in the world had been surveyed, some very significant areas of limestone remained totally unexplored, presenting enormous potential for further exploration, 1.3.

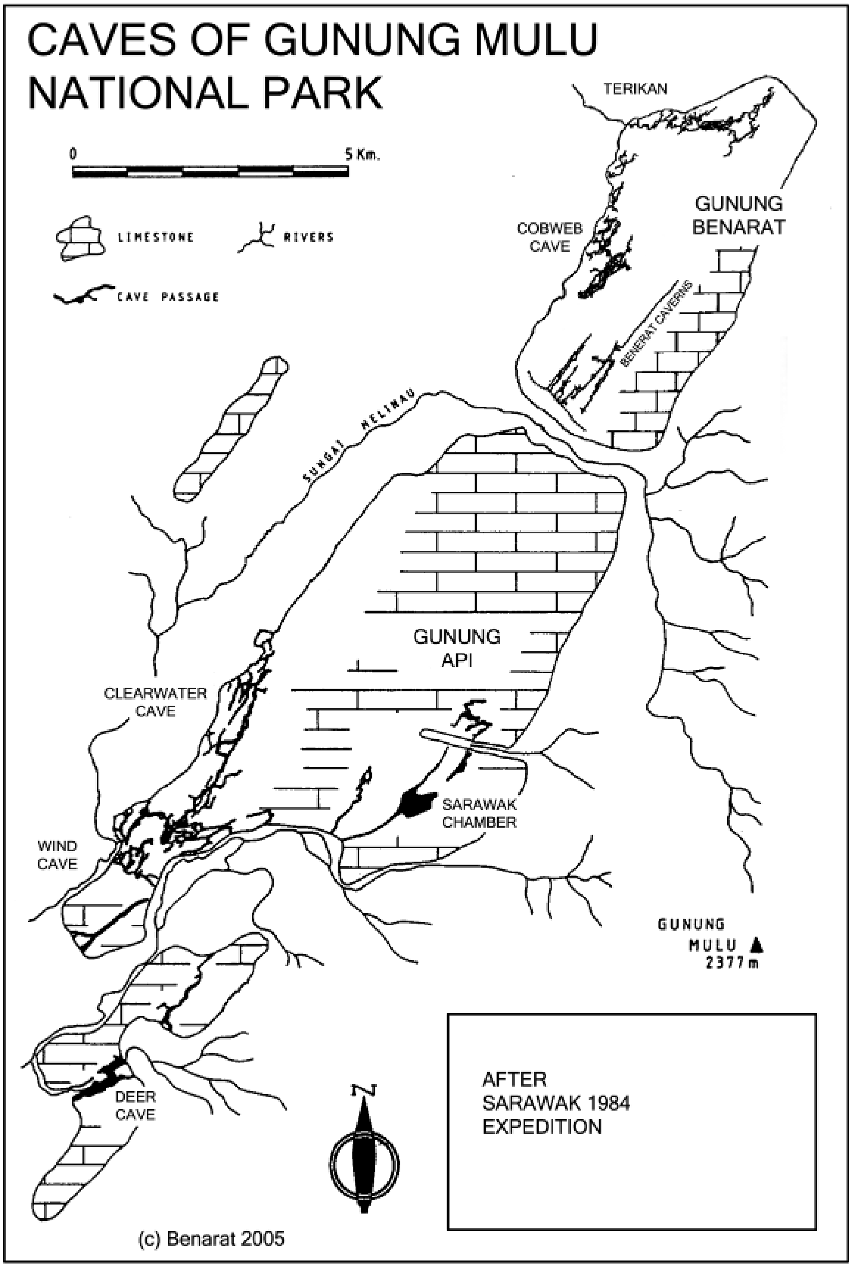

Figure 1.3: Mulu 84

During late 87 and early 88 plans were made to mount another caving expedition to the area. This would be the first expedition to visit the park since its opening to the public in 1985 and was primarily aimed at exploration, surveying and photography. Unlike the previous expeditions this was to be a lightweight venture with only six team members. The Mulu Caves

88, expedition once again proved the potential of Mulu with a further 16km of passages explored. It was also shown that exploration in Mulu using a small team was both feasible and successful.

The major discovery of this expedition was Blackrock Cave lying to the north of Clearwater and almost certainly part of the same system, [7].

As a direct result of this discovery, an eight strong group, including five of the 1988 team, returned to the Park exactly one year later as the Mulu Caves 89 expedition. Once again a lightweight venture proved to be successful, with over 24km of passages explored and surveyed in only one month. Major extensions were found in Clearwater Cave, totalling 15km, and the gap between it and Blackrock Cave was brought to within 90m. The Clearwater 5 streamway was discovered and explored for over 1km.

A new cave, provisionally named Simon's Cave, but later named Racer Cave, was discovered and explored and water tracing experiments proved a hydrological link from the Melinau Gorge through Blackrock and into Clearwater Cave, [8]. The discoveries made by these two expeditions had greatly altered the map of Gunung Apis caves.

During 1990 another British team visited the Park and continued the exploration of Racer Cave. The Clearwater 5 streamway was explored to an upstream sump. Although a sump bypass was found to lead into Clearwater 6, rain caused the bypass to sump which prevented further exploration [9]. A physical link was established between Drunken Forest Cave and Alexandra Palace in Clearwater. During February 1991 a Korean Team visited the Park. Some minor discoveries were made. Unfortunately these findings were not published.

In 1991 a group of nine explorers, five of whom were from the 88 and 89 expeditions, returned to the Park to continue exploration in the Blackrock/Clearwater area. A connecting passage was discovered which linked the two caves. This discovery made the Clearwater System the seventh longest cave in the world at over 102km. This was the Mulu Caves 91 expedition. A vast amount of work had, by this time, been carried out on the western flanks of Gunung Api and although discoveries were by no means exhausted it was becoming increasingly difficult to find major objectives which would justify another expedition to that side of the mountain. The remaining significant lead, the Clearwater 6 Streamway, was weather dependent and, therefore, could not be relied on as a sole objective.

Attention now focused on the more challenging eastern flank of Gunung Api with Hidden Valley as the first objective. This area was less accessible than the west as there were no major rivers which could be used for transport of stores and equipment. Tentative enquiries were made in 1990 to see whether it would be possible to visit the Valley during the 91 expedition. A positive response was received and this became one of the secondary aims of that expedition. Unfortunately, this was not achieved as other discoveries closer to park headquarters took priority. Instead, part of the 91 team returned approximately one year later in January 1993 as the Hidden Valley 93 reconnaissance expedition with the sole objective of carrying out a lightweight reconnaissance of Hidden Valley. The reconnaissance expedition proved a success with potential for further discoveries to be made in the two known caves within the Valley and a new cave discovered in the dolines to the west. Other entrances were noted for further investigation and surface reconnaissance suggested even greater potential further south in the deeper Third Doline, which was not entered.

With the Hidden Valley reconnaissance expedition indicating potential for further discoveries in Hidden Valley a full exploratory expedition, Mulu Caves 96, was mounted and returned to the Park in October 1996. A base camp was established within the Hidden Valley gorge between the entrances of Prediction and Wonder Caves. Although very little was found within the main gorge exciting discoveries were made in the dolines to the south west. Arch Cave was explored in the second doline. Prediction and Bridge Caves were found within the third doline and the fourth doline revealed Cloud Cave which matched Deer Cave in scale. During the last few days of the expedition a descending boulder ramp was followed which led into the far reaches of Cobra Cave. This established a through route to the Melinau Paku valley.

During 1997 an American expedition, which was exploring Gunung Buda, carried out surface searching on the northern slopes of Benarat. This led to the discovery of Deliverance Cave on the north east corner of the mountain. 3.5km of passages were explored which were heading in the general direction of Cobweb Cave.

With the success of the 96 expedition a second Hidden Valley expedition, Mulu Caves 98, was mounted which returned to the Park in February 1998. As the centre of exploration was to be in the dolines it was known that this would not be best served by a camp within the Hidden Valley gorge. Not only would a camp in Hidden Valley be remote from the caves, it would also be almost impossible to supply without helicopter backup, which would be very expensive and could not be relied upon. With this in mind, a gamble was taken on being able to reach the 4th Doline from the Melinau Paku Valley via a route, over the surface, which had never been explored. It was thought that the route through the caves would be used only as a back up, however, the severity of the climb up from Nasib Bagus, together with the surface terrain proved to be far more difficult than the underground route via Cobra Cave, which soon became the main thoroughfare.

This expedition proved a great success with further extensions in Perseverance Cave and a connection established between Cloud and Bridge Caves establishing the Cobra Cloud Bridge system at 16.1km with a vertical range of 459m, the greatest vertical range of any cave in the Park at that time.

Owing to the El Nino year, river levels were exceptionally low so a further attempt was made to explore beyond the Clearwater 5 upstream sump into Clearwater 6. This led to another sump which was bypassed into Clearwater 7 and the inevitable upstream sump which was not passable. Hidden Valley would then not be visited by an expedition for seventeen years.

Another American expedition visited Buda in 2000 and carried out further work in Deliverance Cave, bringing its total length to 4.3km. With exploration in Api now without any significant leads the attention of the British team was drawn to Gunung Benarat. It had been sixteen years since a British expedition had visited the mountain, during the Sarawak 84 expedition. The Benarat 2000 expedition continued the exploration of Cobweb Cave, where a further 10.7km of passages were explored bringing the total length of the cave to 25.9km.

As a follow up to the 2000 expedition, the Benarat 2003 expedition returned to the Park. A further 4.4km were explored in Cobweb Cave, but the significant discovery of the expedition was made in Terikan Rising Cave where 12.5km of passages were explored. Included in the team were two Api veterans who were to use the expedition, based at Camp 5, as an opportunity to prospect the northern slopes of Api between the Melinau Gorge and Blackrocks Racer entrance. This revealed a significant entrance 2.8km south west of Camp 5. The cave was named Whiterock and within the remaining three days of the expedition it had revealed 3.7km of new passages. Owing to its proximity to Blackrock, it was thought that it would soon connect and might be of little significance.

During 2005, the Benarat 2005 expedition, based at Camp 5, continued the exploration of Whiterock, which exceeded all expectations when a further 17.2km of passages were discovered, mostly lying above Blackrock. Two connections were made between the two caves, which linked Whiterock into the Clearwater System.

On the Benarat side of the gorge an attempt to climb up to an entrance high in the cliffs opposite Camp 5 was cut short when a small entrance was discovered only 60m above the ground. This cave was named Moon Cave and was explored for 6.6km in an almost straight line into the mountain. A connection was also established with Benarat Caverns making the total length of this system 16.4km Included in the expedition were two divers who investigated the sumps in the Terikan system. This proved connections between the individual elements of the system to make a total length of 32.5km.

The total length of caves surveyed in Benarat was now 90.4km and in Api was 172.6km.

During January and February of 2007 the Mulu Caves 07 expedition continued the exploration of Whiterock and Moon Caves. Significant discoveries were made in the northern section of Whiterock, where two major passages were discovered, both of which came to within 400m of Camp 5 with no apparent entrances/exits found. These two passages, the Northern Line and the 1954 Series, ran northwards in parallel with 60m of vertical separation. A great deal of in-filling was carried out, with new passages providing short cuts between previously discovered trunk routes. This reduced considerably the travel times to the northern reaches of the system. These discoveries extended the known cave to 42.9km. A major success of the expedition was the connection of Moon and Cobweb caves via an unexplored passage in Moon Cave. This connection linked Benarat Caverns, Moon Cave and Cobweb Cave to produce the Benarat Caverns System, which ranks as the second longest system in the Park at 50.7km. In the Melinau Gorge, considerable surface survey work was carried out to tie together all the known caves on the Api side of the river and link these back to the datum at Camp 5. This allowed them to be linked into the Survex master dataset. Some minor entrances were explored in this area.

During January to March of 2009 the 'Mulu Caves 2009' expedition continued to explore Whiterock Cave and discovered a further 24km of passages. Owing to the proximity of the northern passages to the cliffs in the Melinau Gorge, a considerable amount of effort was given to establishing a northern entrance. Five days were spent attempting to gain entry via a small cave to the east of Camp 5. Unfortunately, this ended in a boulder choke with a draught emitting, within 100m of Whiterock. A significant discovery in Whiterock brought its northern passages to a point underneath the Pinnacles track and even closer to Camp 5. Late in the expedition a steeply descending ramp off 1954 led into the Whiterock River, the upstream continuation of Clearwater streamway. Although not fully explored, this streamway was left at a point 60m beneath Camp 5 with potential for further discoveries.

During May 2010 a small team visited the Park. The Mulu Caves 2010 expedition was to be a small-scale venture, based at Park headquarters, with the aims of photography, science and surveying. Modern digital images were made of the caves close to Park headquarters. Further samples of speleothems, sediments and quartz were collected to enhance the scientific programme. 14.6km of surface survey was completed to tie together all the known entrances in the Southern Hills. Although not a primary aim of the expedition, a small amount of exploration was carried out, with 2.4km of previously undocumented caves explored and surveyed.

During 2011 the Mulu Caves 2011 expedition spent two months in the field. This was a two centre, two-month expedition the first month based at Park HQ and the second at Camp 5. The expedition successfully laser scanned the vast Sarawak Chamber allowing volume calculations for be made. Radio-location was used in Whiterock Cave and the Melinau Gorge to determine the precise position of the end of the cave in relation to the surface topography. A series of Geodetic GPS fixed points were established around the park to better understand the relative levels of the caves within the Survex dataset. In Whiterock Cave 13km of new discoveries were made. A series of sampling was carried out for Uranium series dating.

The Mulu Caves 2012 expedition was to be the 20th in the series of Angle Malaysian ventures and was based at Park HQ. A series of high level caves were found in the Melinau Paku valley with Train Cave extending the Cloud/Bridge/Cobra system to 20km. Attempts to connect Lagangs Cave into Racer Cave were unsuccessful but the cave was extended to 5.7km.

October 2013 saw the Mulu Caves 2013 expedition based at Camp 5. Scientific work was carried out in Whiterock cave to better understand the geology and geomorphology of this area. Further sampling was carried out for uranium series analysis. A further 7km of new passages were explored in Whiterock Cave and Deliverance Cave at the northern end of Benrat was re-visted without any major breakthroughs.

During April/May of 2013 the Mulu Caves 2014 expedition was focused on exploration at the southern end of Gunung Api. Based at Park HQ the expedition continued the attempt to connect Racer and Lagangs cave into the Clearwater system. Although the connection was not made a new cave was discovered, Easter Cave which proved to connect with the higher levels of Racer Cave.

The significant success of the expedition was to discover the 8km of passage in the Creedence series which forms the fourth horizon of development 450m above base level confirming the existence of higher levels within the cave. This discovery pushed the total length of the Clearwater System to over 200km.

The Mulu Caves 2015 expedition was an ambitious project centered on three locations, Southern Api, Hidden Valley and Camp 5. In Hidden Valley a lightweight recce was carried out to investigate a large entrance identified from helicopter video footage in the north wall of the gorge. This revealed Conviction Cave which connected into Wonder Cave, unfortunately a serious accident curtailed some of the work here. Further exploration was carried out in Racer and Lagangs caves but no connection made. From Camp 5 8065m of new passages were explored in Whiterock Cave where a new level was entered 100m above anything previously discovered. This was 380m above the lowest part of the cave confirming the existence of higher levels within the cave and potential for far more discoveries in the future.

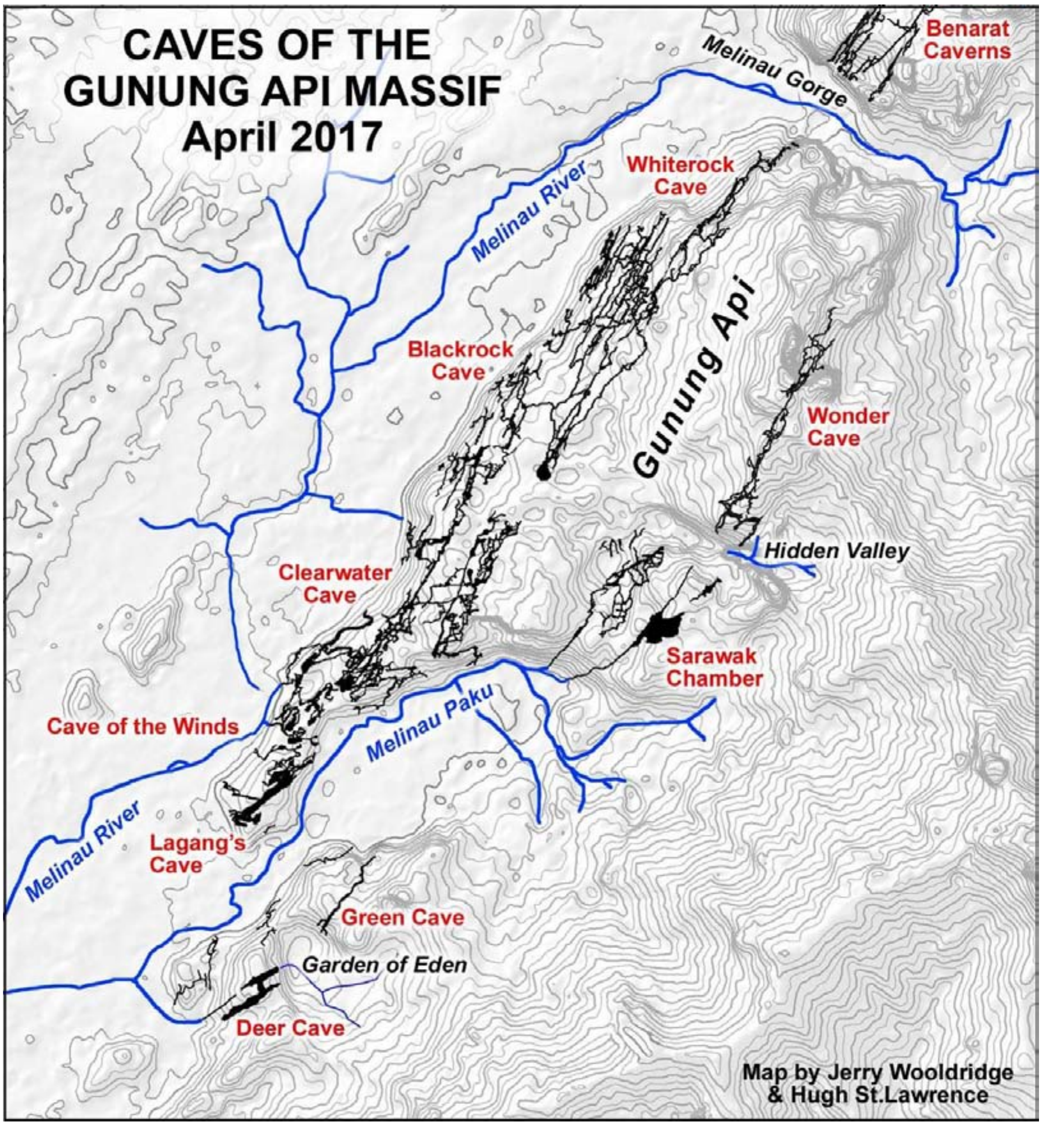

Figure 1.4: Caves of the Gunung Api Massif after the 2017 Expeditions

During April 2017 the first of two Mulu Caves 2017 expeditions visited the park and was based at Park HQ. Further work was carried out in southern Clearwater and in Cave of the

Winds where the Eureka series was discovered lying just above the river passage. This discovery has taken the Clearwater system to within metres of the Racer/Easter cave system and renewed enthusiasm in connecting the caves of the Southern peninsula. The second team at park HQ concentrated on exploration of the Creedence series. This was accessed by the 'High Noon' entrance discovered in 2014 and led to significant extensions over a number of trips.

In addition to these two teams, a third team visited the Hidden Valley and extended the length of Wonder Cave. The cave trended north towards the Melinau Gorge, with approximately 12km of new passage discovered.

The second expedition was based at Camp 5 during October where 4.2km of new passages were explored in Whiterock Cave bringing the total length of the cave to over 100km and the Clearwater System to 226.3km (Fig 4). Within just 15 years Whiterock had become a 100km cave, the longest cave in the Park.

The 'Mulu Caves 2018' expedition was a smaller affair, with a focus on trialling environmental monitoring hardware in the strong draughts felt in Mulu. A small amount of exploration was completed in Clearwater and Whiterock, and a resurvey to lay fixed survey stations through Clearwater was started.

1.3 Mulu Caves Project

It is clear from the history of exploration in Mulu that this expedition would not have been possible without the reports and data collected throughout these previous trips. The expedition is thankful for the hard work put in by all of these individuals. Special thanks is given to Matt Kirby and Tim Allen for developing and maintaining the complex Survex dataset.

2 Overview

2.1 Expedition Members

Figure 2.1: Team Photo (Chris Howes)

The team was comprised of the following cavers:

- Rambli Ahmad (from Sarawak Forestry)
- Hazel Barton (from USA / cave microbiologist)
- Derek Bristol (from USA)
- Judith Calford
- Dave Cooke
- Andy Eavis (Joint Leader)
- Chris Howes
- Ben Kent (Joint Leader)
- Tim Kent
- Elaine Oliver
- Carsten Peter (from Germany)
- Tony Radmall
- Alistair Smith
- Frank Tully
- Les Williams
- Chris Williams

The team was supported by:

- Veno Enar (local logistics)
- Jimmy (boatman / porter)
- Wilson Julie (boatman)
- Steve Lian (porter)

2.2 Aims

In 2014 the discovery of Easter Cave and its subsequent connection to Racer Cave reignited enthusiasm in connecting the caves of the Southern Peninsula to the Clearwater system. Easter Cave filled a large gap in the limestone between Racer Cave and Lagangs Cave, which if connected would give a system of approximately 20 km that could be then connected into the Clearwater Cave System. The conclusions of this expedition led to a team in 2017 continuing these objectives.

The 2017 expedition made significant discoveries in Cave of the Winds and Lagangs. In Cave of the Winds a small draughting crawl from Clay Hall was followed into a vast chamber that was named Eureka. This was pushed to a calcite choke and lower level sump, both of which have corresponding passages in Racer that align in the survey data. Radio communication was established between both sides and bolting work could be heard through the rock, but no confirmation of passable passage was seen. It was speculated that the sump was the connection.

An additional objective at the northern extremes of Clearwater Cave was also researched. To the east of the Clearwater/Blackrock connection, the north of Armistice Passage and the south of Api Chamber there is a large region with no known cave. Given that the Clearwater/Blackrock connection had not been investigated since the early 90s and that draughting leads have been left in Edwins Long Cut, both areas were written into the expedition objectives with the aim to establish if there was any undiscovered development.

These aims were formalised to give the four expedition objectives:

1. Exploration in the southern peninsula of Gunung Api, with the objective to connect the Clearwater system to the Racer/Easter Cave system and Lagangs Cave.

2. Revisiting and pushing leads in the northern end of the Clearwater Cave at the Blackrock connection.

3. Difficult aid climbing in Sarawak chamber to potentially access horizontal development.

4. Initial reconnaissance trip for cave microbiology fieldwork.

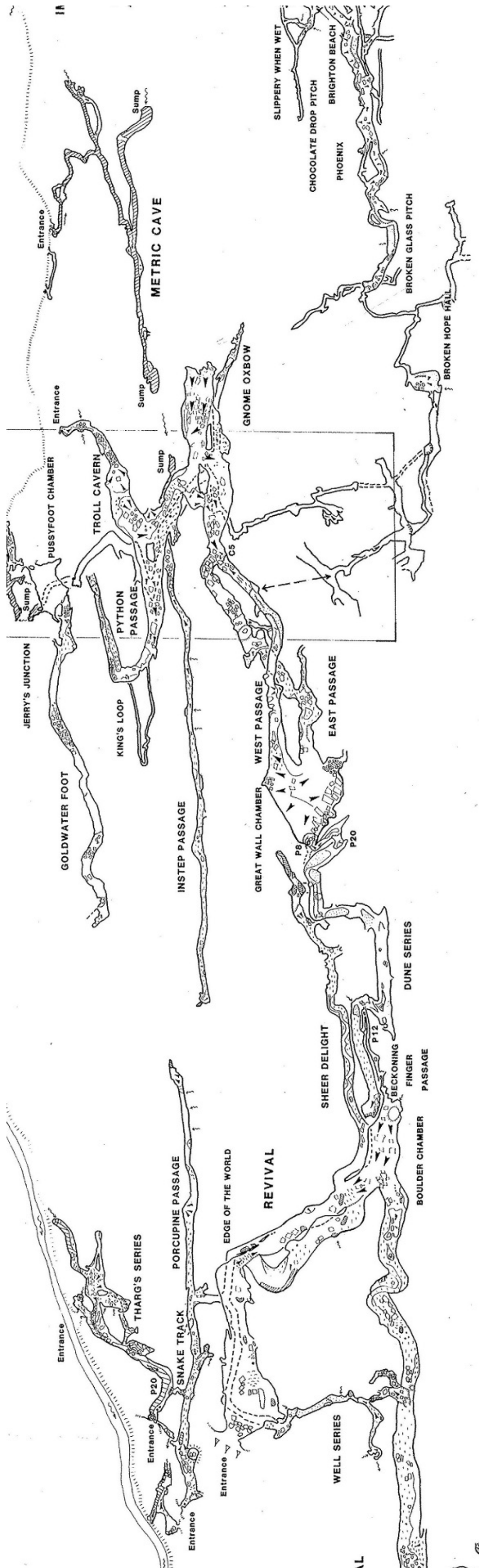

Figure 2.2: Clearwater - Blackrock Connection Area

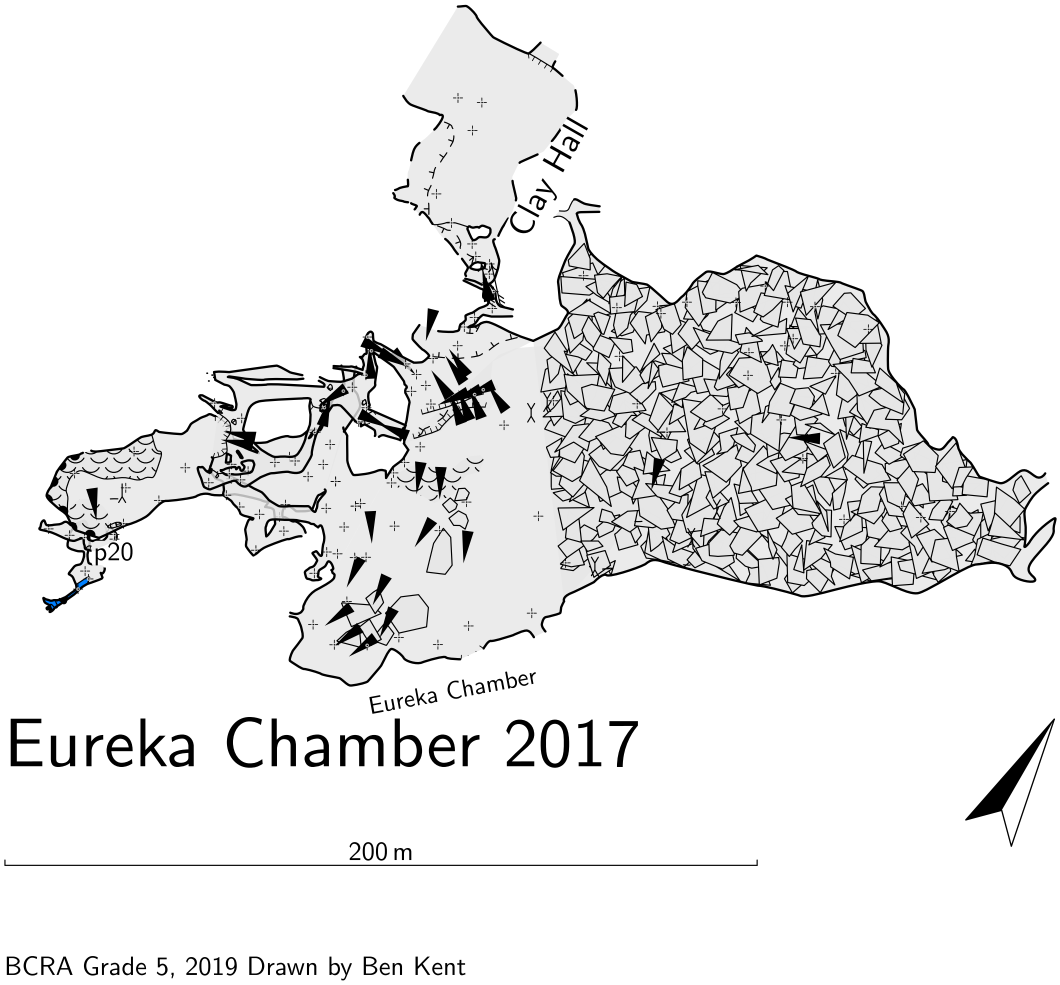

Figure 2.3: Eureka Series and Racer in 2017

2.3 Permits

National Park permits in Sarawak are issued by the Sarawak Forestry Corporation. These are required for unsupervised access to the rainforest and caves.

The Mulu Caves Project has a very good relationship with the SFC so the permit process is made relatively straight forward. Dick Willis collated expedition members CVs and submitted the application in December 2018. Regular correspondence with Rambli Ahmad, an SFC employee and expedition member, ensured the permits were successfully processed.

In addition to the caving permits, Hazel Barton required a scientific permit. This too was also relatively straightforward and gave permission for samples to be removed and analysed in her microbiology laboratory.

2.4 Fundraising and Sponsorship

The expedition benefited from the kind support from the following (listed in alphabetical order):

- Expedition Foods
- Ghar Parau Foundation, including an Alex Pitcher award issued to a young member
- Gunung Mulu National Park, especially Hein Gerstner (Park Manager)
- Lyon Equipment
- Malaysian Airline Systems
- Mount Everest Foundation
- Sarawak Forestry Corporation
- Spanset
- Starless River

In return for sponsorship the Expedition was able to offer professional quality photographs, and exposure within the caving community through events such as Hidden Earth.

Malaysian Airline Systems (MAS) provided a good rate on airfares plus 50 kg of baggage per person all the way through. This has allowed the expedition stores to be well stocked with rope and hardware for future expeditions. In return, an article for the inflight magazine 'Going Places' is being authored with some accompaning photos.

2.5 Budget and Accounts

Dave Cooke

Overall the Expedition made a small but pleasing surplus of 458 which will go forward to future expeditions.

The Expedition is grateful to the Mount Everest Foundation and Ghar Parau Foundation for their sponsorship.

Malaysia Airlines generously gave the Expedition free internal flights which reduced the transport costs. The transport costs shown are largely the international flights of expedition members.

The generous luggage allowance (50kg) provided also allowed a significant amount of replacement equipment to be purchased and taken to Mulu.

Item	Income ()	Expense ()
Expedition Fees	16200	-
Mount Everest Foundation	1650	-
Ghar Parau	150	-
Banking Fees	-	221
Accomodation	-	645
Boats	-	729
Equipment	-	1147
Food, Drink and Consumables	-	1137
Guides and Porters	-	533
Personal Insurance	-	1594
Medical	-	19
Restaurant	-	1856
Transport	-	8446
Veno Logistics	-	1215
Totals	18000	17542
Surplus	458	

Table 2.1: Mulu 2019 Accounts Summary

The bank fees for transferring money across borders remains annoyingly high but it is difficult to see how that can be avoided.

Obtaining sufficient ringgits to pay for porters, boats and logistics within Park Headquarters (a total of 2477) is a struggle since Park HQ are not used to issuing large amounts of cash. In the future should expeditions be purchasing larger quantities of ringgits in the UK for the purpose?

The breakdown is as given in table 2.1.

2.6 Travel

Malaysian Airlines Systems were contacted and offered to provide a discount group booking in return for support with their publicity. The expedition has provided an article for their inflight magazine Going Places.

The expedition flew to Mulu Airport via Kuala Lumpar and either Miri or Kota Kinabalu. The twelve from the UK flew to Kuala Lumpar from London Heathrow, with the other three making their own way from their respective home countries.

As part of the agreement with MAS, members were given 50 kg baggage allowance all the way through. This allowed the team to easily transport caving equipment to Malaysia, and to fly food shopping from Miri to Mulu. The Mulu Caves Project has an equipment store in the National Park, so excess equipment was taken out to support future expeditions that may not have such generous allowances.

2.7 Food and Accommodation

The team at base camp stayed in the National Park research centre. This comprises of bunkrooms with a central hall, kitchen and Mulu Caves Project gear store. In addition to the bunkroom accomodation, the national park has a well stocked cafe at very reasonable prices so breakfasts and dinners at HQ were eaten there. A main meal costs in the region of 2.50 - 4.

Underground food is broken into two varieties: lunches and underground camp food. Lunches consisted of cheese/crackers/dried fruit/peanuts/cereal bars/fruit cake. The expedition was fortunate to have a deal with Expedition Foods Ltd so underground camp food was all high calorie dehydrated sachets. These were favourably reviewed, and it should also be noted are available to support a wide range of dietary requirements.

2.8 Specialist Equipment

The expedition is fortunate to have a very well stocked equipment store permanently in the National Park. This meant that only a restock of consumable equipment was required.

Support of Spanset Ltd meant the expedition was able to get a very good deal on 400m of static rope, and for that we are very grateful. The expedition store now has a large quantity of rope that has been bought in the last 4 years, so it is not anticipated further expeditions will need to supplement this in the near future.

Readers are reminded that ropes that have been left in situ for long periods of time in Mulu are unsafe. Whilst traversing the Dune Series in Clearwater, a piece of SRT rope from one of the pitches was rerigged as a handline. This broke after minimal use. It is likely to be from during the early 90s. Further testing is ongoing through connections at various universities to establish the cause of the deterioration in strength.

This is not the first time a rope has failed. A piece of rope left in Wonder Cave in 1978 broke when it was being used as a handline in 1996 resulting in a 50' fall resulting in serious injuries and a helicopter rescue. An additional incident occured in 2013 in Red Tip Racer Cave also.

In addition to the ropes decaying with age, the Expedition suffered from *many* of the tacklesacks failing. This was surprising given they were generally Petzl Transporters from the previous few expeditions, but all failed along the seam holding the base to the pack. Emergency repairs were required on multiple occasions. A selection of new tacklesacks were taken out, with some kindly donated by Lyon Equipment. Future expeditions are advised though to purchase new Transporter style bags as there is a significant shortage.

Additionally, new karabiners, maillions, hangers and through bolts were taken to replenish the expedition stores. A complete inventory was taken at the end of the expedition and is available as appendix **??**.

2.9 Medical and Insurance

Standard medical forms were issued and collated before the expedition. These were collated and stored on an expedition laptop in case of emergency and shared with three emergency contacts in the UK.

The expedition medical supplies in Mulu are fairly well stocked given the quantity of recent expeditions. Given that the team were all based out of park headquarters, only one base camp kit was required with a few smaller ones for camps and day trips. A complete inventory was taken at the end of the trip and is supplied as appendix **??**.

Mulu is not well served by a hospital, with only a minor medical centre in Batu Bungan. For more serious problems the Miri City Medical Centre is advised by the local contacts, which requires flying out of Mulu to Miri. Numbers for the airport, a helicopter company known to the expedition and the medical centres were collated in case of emergency. These numbers were supplemented by a rescue plan for various scenarios deemed plausible during the expedition.

Caving insurance was generally provided for expedition members by PJ Hayman as part of ongoing negotiations between the British Caving Association. Some members of the expedition used Snowcard insurance, but this caused difficulties with pre-existing medical problems. Other insurers were not clear with their policies if they would or would not cover exploratory expeditions such as this one.

Section & Cover Limit per Event	Limit	Excess
Medical & Emergency Expenses	10,000,000	100
Emergency dental treatment (for relief of pain only)	300	-
Burial Costs / Body Repatriation	3,500	-
Hospital Inconvenience Benefit	400 (20 per day)	Nil
Search & Rescue costs	50,000 (10,000 in Home Area)	500
Personal Accident	5,000	Nil
Personal Liability	2,000,000	Nil (200 property damage)
Activity Equipment	1,000	75
Single items, pair or set limit	600	-
Delayed Activity Equipment (over 12 hours)	200	Nil
Activity Equipment Hire	300	Nil
Legal Expenses	25,000	Nil
Curtailment	2,000	100

Table 2.2: Insurance policy as provided by P J Hayman

The PJ Hayman cover is summarised in Table 2.2. In addition to this members had personal insurance for flights etc. It should be noted that the cover for Search & Rescue costs has been increased to 100,000 in the BCA expedition insurance.

3 Fieldwork

3.1 Logistics

Expedition members arrived in three groups at the beginning of the trip. The first team arrived via Miri where they had an excursion to the caves at Niah. This allowed them to visit the supermarket in Miri and air freight the shopping to Mulu. Given that all members had a 50 kg luggage allowance there were no additional charges for the freight.

The second team arrived via Kota Kinabalu on the Saturday after flying almost directly through from Heathrow. The two from the USA arrived later in the day having travelled via Japan.

Logistics in the field were handled by Veno Enar. Veno has a long history of working with the Mulu Caves expeditions and has a team of trusted boatmen and porters. The Clearwater system is reached by a boat up the river which must then be arranged for return pick up. It should be noted boats are one of the significant costs of a Mulu expedition whilst in the field.

On a couple of occasions the Melinau river flooded due to heavy rainfall, rising several metres and bringing large amounts of debris downstream. On these occasions the boatmen advised that it would be a challenge to travel upstream, so in the interest of everyone's safety other plans were made.

The most notable rain event occurred during a trip to Sarawak Chamber in Good Luck Cave. At approximately noon a large thunderstorm began and the already saturated ground quickly flooded, both above the cave and outside the cave entrance. Inside the cave the streamway became impassable and water almost instantly came in in very large quantities from all over the ceiling. An additional night was spent by the team whilst they waited for the waters to recede. This should be taken as a reminder of the environment we operate in and how quickly the flood waters can come up.

Underground camping was made very convenient by utilising almost exclusively dehydrated meals from Expedition Foods Limited. These were given unanimously favourable reviews for both taste and energy content. It would be worthwhile building on this relationship to ensure a good price again in the future.

Technical equipment was purchased in the UK and carried over in the large luggage allowance of the expedition members. Spanset Limited are again thanked for providing a very good deal on 400m of static rope, and the purchase of hardware was done through Starless River.

Figure 3.1: Judith on a flooded plankwalk (Chris Howes)

3.2 Surveying

During the Mulu 19 expedition all surveying was performed using DistoX or DistoX2 hardware. These were paired with PocketTopo on PDAs or Topodroid on Android devices. Both workflows produce digital sketches and export survex data for integration with the Mulu survey model.

Some difficulties were had using Dell Axim PDAs on the expedition. One would not charge once it reached Mulu and another had reoccurring screen alignment issues. The lack of reliability of such old hardware may be worth considering for the future, as despite their low price on the second hand market it is incredibly frustrating to troubleshoot on the go during a surveying trip.

Drawing up surveys in the UK has been done using Therion. The Mulu expedition has generally preferred to use Freehand MX, a piece of vector graphics software from 2003. Both have their advantages and disadvantages, however, the primary cartographer's preference was to draw in Therion and produce PDF surveys.

Exploration is described in detail in the following chapter.

3.3 Science

Dr Hazel Barton joined the expedition and in addition to exploration work, collected samples for analysis in her cave microbiology lab. The science was generally conducted on the go, with interesting specimens examined and sampled. Further details are found in appendix 7.

3.4 Photography and Video

The expedition was fortunate to have a number of skilled photographers and videographers to document the trip.

Photography: environmental considerations (*Chris Howes*)

As on my previous trip to Mulu, my camera system was based around Canon equipment, this year 5D Mark IV bodies and EF lenses. Different weather conditions will affect cameras in different ways and Canon produces two sorts of lens: an L series that are weatherproof and marked with a red ring, and other unsealed lenses. The main weak point in any dSLR system is the coupling between the body and the lens, which for L lenses is protected with a dust- and weather-resistant rubber seal.

In 2014 my telephoto, an unsealed lens used on the surface, failed entirely when it was taken from a shaded position into the sun (later repairs showed that the humid conditions had caused the internal motor to burn out). For 2019 only L lenses were taken to Mulu, but the weather conditions were considerably wetter than in 2014 and, again, visible internal condensation was apparent even though the lenses were sealed. Once more, this occurred when moving from shade into sunlight or from a cave to the outside any situation where a change of temperature (cold to hot) or humidity occurred. On three occasions the cameras reported communication errors with the lens and it proved impossible to take photographs during any return trip from the caves, though all the kit recovered when dried in stable temperatures at the base.

The combination of high humidity and relatively fast temperature change should not be underestimated by future Mulu photographers, and a simple, small backup camera with a fixed lens (thus, a fully sealed system) is recommended. This, of course, is exactly what most non-specialist cave photographers use anyway ... but for those using a dSLR or compact system with interchangeable lenses, you might need to budget for a full camera service on returning home.

Video

Derek Bristol has produced four videos documenting the caves and the expedition. These can be found on his YouTube channel given as reference [10].

The videos are titled:

- The Giant Caves of Mulu
- Trapped by Flood in the Largest Cave Chamber in the World
- Largest Cave Passage in the World
- The Largest Cave in the World

It should be noted that these titles are possibly misleading, with the ranking of the cave and passage sizes dependent on metrics and approximations used.

Figure 3.2: Hazel surveying in the Chinashop (Carsten Peter)

Figure 3.3: Hazel collecting water samples from the Elephants Trunk, Racer Cave (Chris Howes)

3.5 Medical Report

Tony Radmall

The expedition had no major issues to report. The following outlines the recorded medical incidents.

- In two instances there were bruised, possibly fractured, ribs but neither required external medical attention.
- As usual with Mulu, there were a fair number of cuts and bruises. These were generally treated using Iodine or Neosporin (an antibiotic cream from USA).
- There was one case of bad Mulu foot. This was treated with a variety of anti fungal creams.
- Several cases of upset tummies treated with Loperomide
- A couple of splinters, with one splinter removed and one treated with magnesium sulphate to draw out the foreign object.
- One case of foreign object in the eye, washed out with sterile saline solution.

An inventory of the first aid kits is included as appendix **??**. It is worth noting that enteric coated capsules prove to be an issue out in Mulu even when the packaging is still in good order and not compromised. The drugs dissolve in the packaging so would recommend only take out what is required and then return unused drugs to the UK.

Sourcing drugs in the field is possible but will require doctors prescriptions. Mulu medical centre has a supply of drugs so it may be worth enquiring about their availability in the future.

4 Exploration

4.1 Clearwater Cave

4.1.1 Scientific Method

Hazel Barton, *Derek Bristol, Ben Kent, Tim Kent, Elaine Oliver and Alistair Smith 565.68 m*

One of the goals of the Mulu 19 expedition was to push leads around the Great Wall Chamber and toward the Clearwater-Blackrock connection, which has not had serious consideration since the 1990s (the southeast of this area looks particularly inviting, given the blank area of the map between Clearwater and the Api Chamber). A team headed out with plans to camp near water in the large entrance by the Edge of the World, but discovered a permanent waterfall within Revival passage, with a large, sandy bench that could comfortably camp twelve. The team decided to camp here given its proximity to the Boulder Chamber. It turned out to be a fortuitous decision, as the waterfall provided a very nice shower that could be used on return to camp to remove the copious amount of mud and bird guano. Given the golden-brown colour of the flowstone around the shower, as seen in figure 4.2 , it was named Camp Golden Shower.

During the initial three day camp, the team spent a day pushing leads off of the Great Wall Chamber. The initial target had been the open lead at the end of East Passage; however, rather than a large open walking lead as indicated on the map, this lead is actually a series of inter-connecting tubes all heading down to a muddy, sumped level, which likely represents the top of the current water table.

Two teams started back-tracking from the end of East Passage, checking any small leads heading off. One team member pushed behind a large breakdown block on the southern wall, which revealed a drafting crawl heading off. Following the air, the crawl went tight before opening up in a large chamber that appeared to have formed at the edge of a large fracture zone. This large room was pushed to a small lake, with surfaces covered in 20 cm thick mud. There was a significant flood at HQ a few days later that came up the first two steps of the research centre, but the mud around this lake remained dry, indicating that the bottom of the room floods only with significant water level increases.

Crossing the lake revealed a passage heading up into blackness, and a large room (70 m across) named Hypothesis, that contained a significant joint in the ceiling with leads heading off north and south. There was also a waterfall coming into the passage at the top of a 15 17 m climb to the east. The waterfall climb was scouted by Derek as doable, but needed a rope to descend, and remains unpushed. The other leads were surveyed during the initial discovery. The southern lead ended, and while the northern lead blew significant air, the team was stopped by a 17 m pitch down a muddy slope.

Almost three hundred meters of cave was discovered and, after a comment made about scientists being poor explorers, the area was named Scientific Method.

During a second camp, a team returned to spend a day pushing the northerly lead in Scientific Method. The muddy slope was rigged and the cave continued northeast, although the team quickly reached another 8 m climb that stopped progress in that direction. In an effort to bypass the climb, the team pushed the remaining leads in this area, but they all looped back around into each other, giving the impression of this area having formed under hypogenic conditions (and very different from the rest of the cave). Without finding a bypass, the team spent quite a bit of time trying to lasso a bridge to give them access to the top of the climb, with little

Figure 4.1: Golden Shower Camp shower (Hazel Barton)

success and almost losing the hammer (which gave the rope weight for the toss). The climb remains a significant lead, with a drafting passage at least 4 m in diameter, but is in need of an aid climb to access.

The team back-tracked to a traverse into a passage heading east, but this area was relatively complex, with pits dropping down 20+ meters. Due to the late hour and the complexity of the area, it was only briefly looked at, not surveyed, and remains a low-priority lead.

4.1.2 Chinashop

*Hazel Barton, **Derek Bristol**, Ben Kent, Carsten Peter and Elaine Oliver*
176.41 m

During an earlier camp in the Revival area of Clearwater Cave, while travelling through the Dune Series, a 1.5-meter diameter passage was noted on the north side of the main passage. This hole in the wall immediately drops down 4 meters, requiring a rope, and has noticeable airflow. A rope was rigged to a natural anchor and at the bottom of the drop a steep slope continues down to a low point, beyond which is a large room that is 15 meters in diameter. The ceiling of the room is actually a steeply ascending passage with a floor that is covered in popcorn.

The steep slope is broken up with a few intermediate ledges and was free-climbed for approximately 30 meters to a large ledge where a static rope was fixed to a natural anchor. This ledge is covered in large popcorn clusters that are shaped like blooming flowers and the passage continues steeply above. There are a few steeply ascending alcoves to the west side of the ledge, but these all terminate.

The main passage was free-climbed another 25 meters with popcorn covering the right side and stalactites and soda straws covering the steeper and more delicate left side. It is difficult to get past this pitch without causing some impact, which was the inspiration for the name China Shop. Another static rope was fixed at the top of this popcorn wall in a narrower corridor where strong wind funnels through. Above this corridor the passage widens to a room that is about 10 meters in diameter with dripping water and airflow coming from above. The passage becomes nearly dead vertical for an estimated 40 meters or more. The wall above can likely

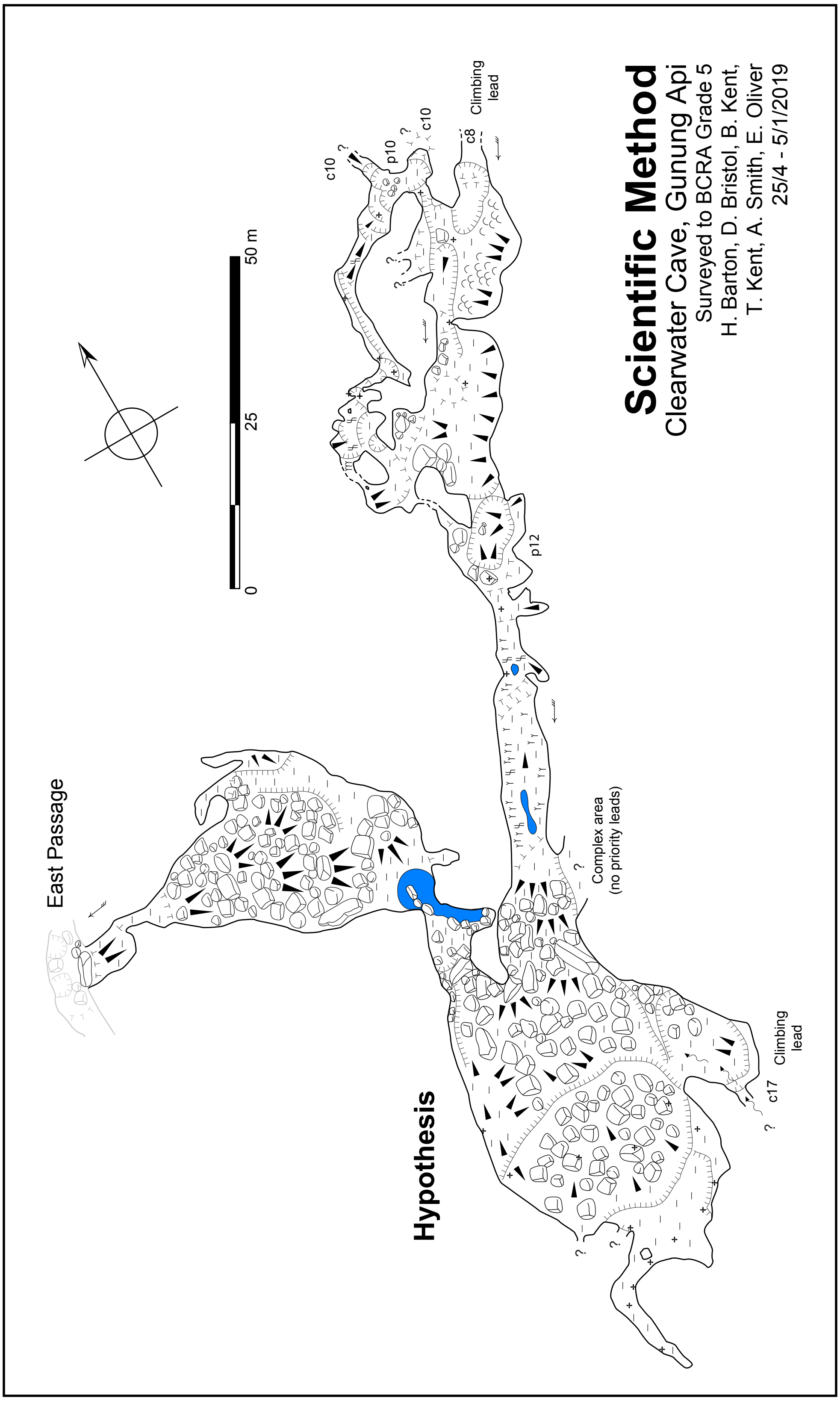

Figure 4.2: Scientific Method Survey

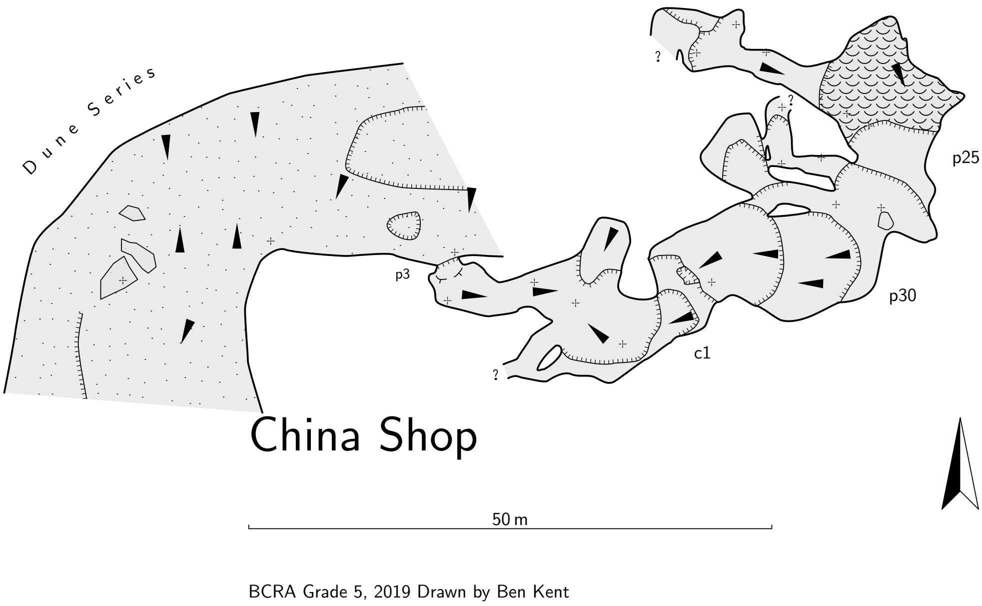

Figure 4.3: Chinashop Survey

Figure 4.4: Pitch down from Beckoning Finger into the Dune Series (Ben Kent)

be free-climbed, but not safely without anchors, a dynamic rope, and a proper belay. Without these tools the lead was left going up with strong airflow at 10 meters in diameter.

The 3 static ropes were left rigged, but recent experience suggests that these not be trusted if left for very long.

4.2 Cave of the Winds

Exploration at the south-west end of Eureka Chamber yielded new passage at multiple levels heading towards Racer Cave (the left hand side of figure 4.6). These finds are described in this section.

4.2.1 Eureka Climbs

*Derek Bristol and **Ben Kent***

176.43 m

From the central arete of Eureka Chamber, the right hand wall is followed south around the calcite until a large, isolated, prominent rock is found. The chamber here steeply dips down to the left, with the main strike passage continuation found by the climb 50m in front. An aid climb of 25m gains access to a ledge, and an exposed muddy crawl up to the left opens into a mud filled passage, approximately 10m wide.

The muddy passage can be followed for 20m, passing two closed tubes down to the left. After this the passage has a calcite floor, with a small closed pit and a handful of columns, and continues for another 20m. More columns are passed to reach a terminal flat out crawl that very quickly becomes mud choked.

To the right, half way along the passage it opens out to a small chamber with a small waterfall into gour pools on the east wall. This was bolt-climbed for 15m up a steep calcite slope to find another smaller passage also aligned along the strike. To the north the passage is calcited, but south it can be followed up a rising, calcited passage to another small chamber. Ahead closes as a calcited choke. Up to the left a narrow, steep rift can be climbed to a small calcite squeeze. After a small amount of work with a hammer this was passed, but the passage closes to too tight after 2m. A strong draught is felt out of this squeeze.

4.2.2 Eureka Crawl

*Hazel Barton, **Tim Kent**, Elaine Oliver and Alistair Smith*

56.39 m

The crawl is found to at floor level to the right at the start of the terminal passage in the Eureka Series. The initial passage had been surveyed to a connection with higher level passages, leaving this low lead.

The passage heads west from a small chamber into continuing low passage. Running water was heard at a lower level through a small slot in the floor to the right. The passage turns sharply left and opens into a small hemispherical chamber with a central column and thin mud false floor, with further mud close below.

The passage turns right sharply and forks; the right fork quickly chokes in mud and stals and ahead to a cluster of stals and calcite. To the right is too tight, and to left passing carefully through the formations reveals a ledge where the false floor has collapsed into a muddy drain approximately 3m deep with a column supported on a wafer thin floor. This was not descended and could possibly continue, but would require at least a handline.

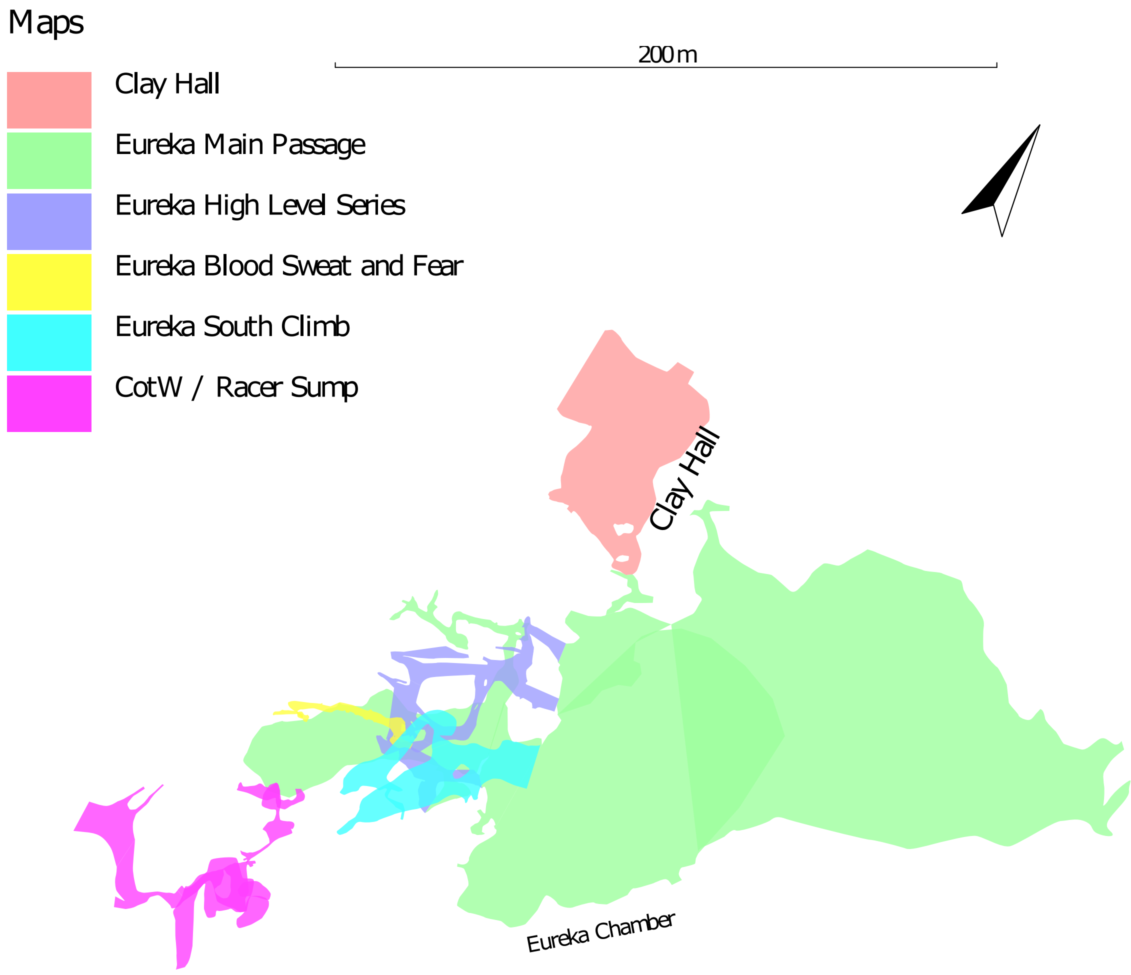

Figure 4.5: Eureka - CotW Connection

Figure 4.6: Derek stripping gear off Eureka Climb (Chris Howes)

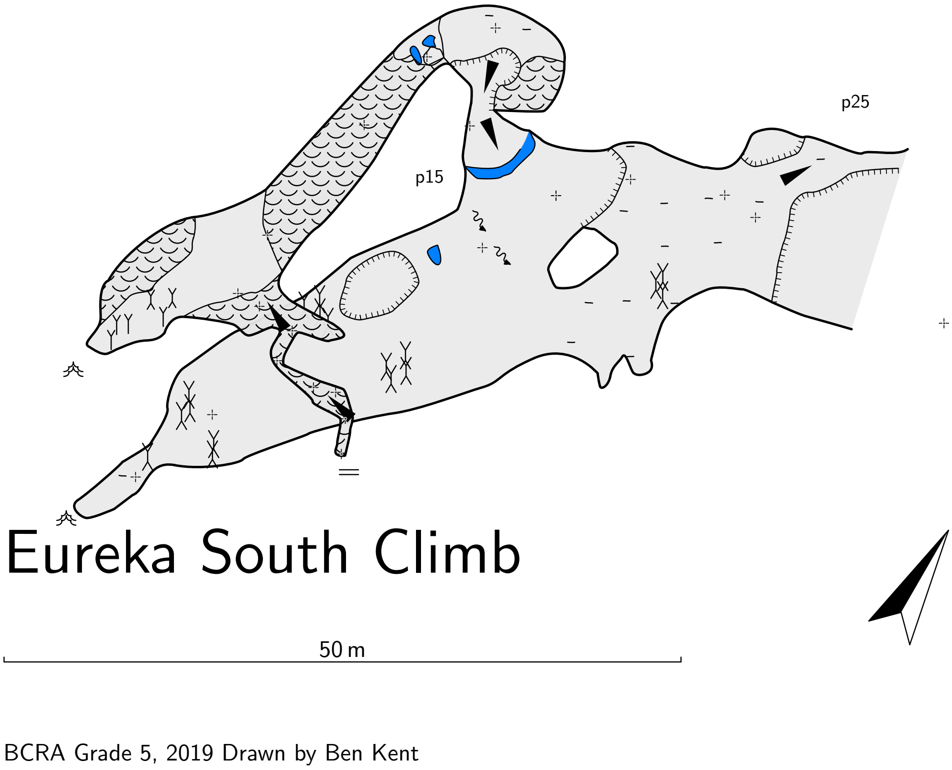

Figure 4.7: Eureka Climbs

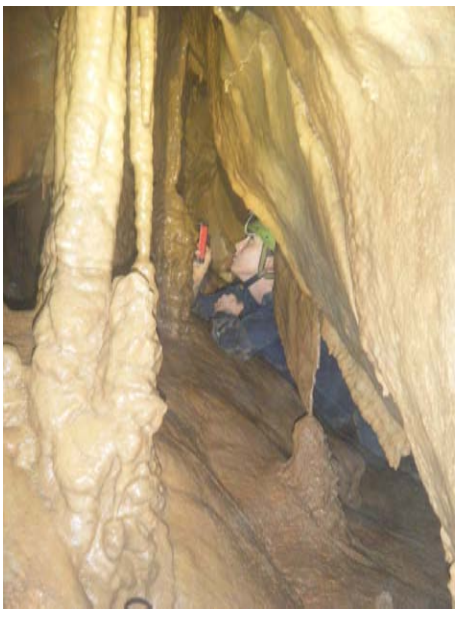

Figure 4.8: Surveying through formations in Eureka Crawl (Tim Kent)

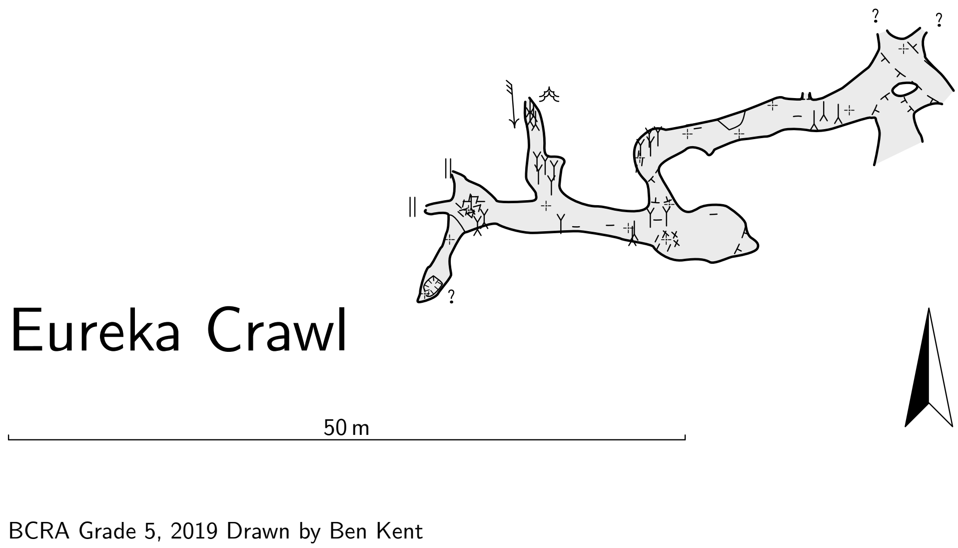

Figure 4.9: Eureka Crawl

4.2.3 Blood Sweat and Fear

Ben Kent *and Tim Kent*

50.59 m

From the high level passages at the termination of the Eureka Series, an alcove in the roof was spotted in 2017. This was accessed by bolting across a short blank wall, and using etriers for aid.

The passage continues west with a steep dip down to the left. At above head height on the right a small tube is seen. Down to the left, slots in the floor continue down into the chamber below.

Continuing up the slope reaches a small collection of stalagmites, before descending to a muddy floor. Squeezing to the left enters a small chamber mostly choked by stalagmites, but the continuation is found by doubling back on yourself underneath the mud choke.

The passage continues with a soft mud floor for approximately 5 to 10m before becoming completely mud choked.

It is of significant note that explorers on the Racer side of the choke could clearly hear the bolts being drilled for the traverse.

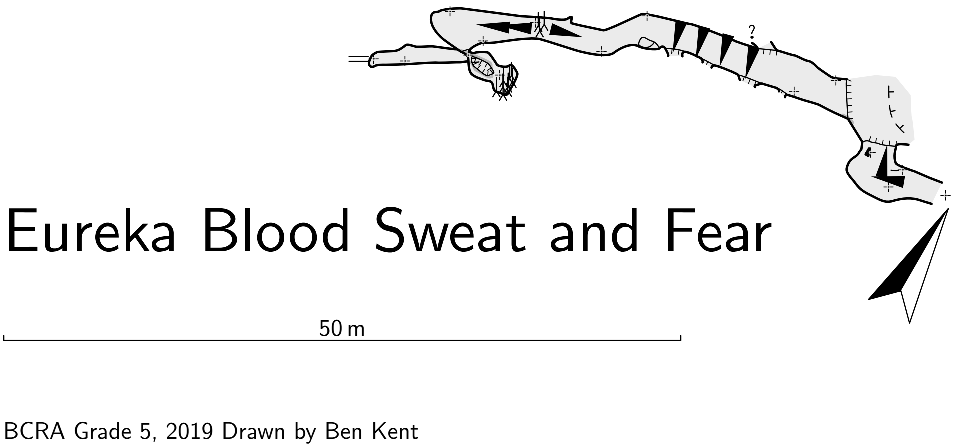

Figure 4.10: Blood Sweat and Fear Survey

4.3 Racer Cave

4.3.1 Boneyard

Dave Cooke and ***Frank Tully***
366.73 m

Just before the Elephants Trunk, a greasy climb on the North side was downclimbed with the aid of a 9m handline. It passes underneath a 25m closed aven and passes a 2m climb on the left. Straight head continues to a heavily calcited area with all ways on closing down.

The 2m climb opens into a large passage with thick rotted limestone and a dry guano floor. This descends steeply to a 3m pitch which can be rigged from a natural belay and a bolt. The chamber it opens into has a small stream from the north west corner sinking beneath the pitch. Above, the ceiling is approximately 25m and it is unclear if there is a way on above. There are two leads out of this chamber, both guano covered climbs.

From back by the Elephants trunk a second slot was explored, slightly further west into the cave. This was descended by a handline into phreatic rift with large amounts of guano. Two large snake skins were found, with lots of evidence of swifts nesting on the floor. Various short passages were explored, but nothing of significance. One easily accessible passage opened out as a window into the chamber described above, with a second window reached up a short three bolt climb. A small phreatic passage ends in a blind 8m pit.

4.3.2 Mushroom Chamber

Given that the Eureka/Racer connection seems heavily calcited at the main Racer level and sumped at the level below, two trips were made to establish if there were any leads that had been missed in Mushroom Chamber.

Ben Kent *and Frank Tully*

The Mezzanine level was accessed by following the Mushroom Level south until the easy climb up by the connection to Easter was found. This level has a different character with a much larger fossil strike passage, and huge stalagmites and columns. Quick progress north can be made, with many holes down into the Mushroom level passed. A terminal balcony is reached

Figure 4.11: New passage in the Boneyard, Racer Cave (Dave Cooke)

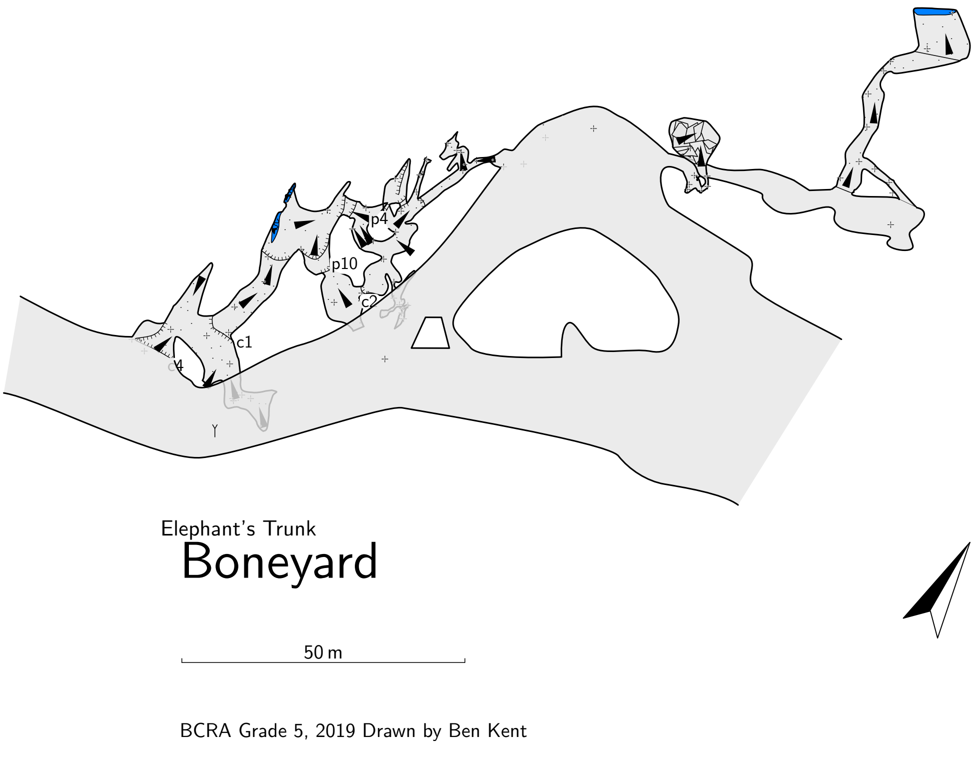

Figure 4.12: Boneyard Survey

Figure 4.13: The calcite termination of the Mezzanine level, Racer Cave (Ben Kent)

up above Mushroom chamber. The left hand wall can be carefully traversed up and across to reach the North edge of the chamber. Up to the left an exposed looking climb looks to close down, but wasn't explored as a slip on the rotten limestone would be disastrous. To the right it is possible there is a continuation over a large calcite blockage, but it is thought unlikely given the lack of draught and the quantity of formations.

An easier descent was made into Mushroom chamber by abseiling down approximately 10m. This would be a difficult climb given the rotten nature of the rock and the large amounts of guano covering it.

Rereading the Weights report [9] it appears that the passages at the top of Mushroom Chamber have been previously examined, and all found to choke quickly.

Tim Kent*, Elaine Oliver,* ***Tony Radmall****, Alistair Smith and Chris Williams*

Mushroom Chamber was thoroughly investigated by following the wall clockwise around it and ticking off any possible leads. A small lower chamber was found close to the pitch head, with views down to the bottom of the pitch. Several small passages were found at both the top and bottom of the chamber wall, however, all were almost instantly blocked by calcite chokes. To the south west of the pitch head a passage was found and pushed for approximately 100m to a calcite choke with water flowing through. This was unsurveyed.

Figure 4.14: Mezzanine Level, Racer Cave (Ben Kent)

4.4 CotW / Racer Sump

Andy Eavis *and others*

From all the searching for leads in Eureka Chamber in Cave of the Winds and the further regions of Racer Cave, the surveys made it look as though Eureka Chamber is actually a large passage going straight into Racer, but a section of this big old passage has been completely filled with stalagmite material. There must be something in the roof above this big old passage where water has come in and created a huge quantity of calcite infill. Many leads around this area aiming from Cave of the Winds to Racer, or the other way around, finish in calcite chokes and indeed the main passage is exactly the same. However, if you go down on either side of this you can get to a further level in which there is a small running stream.

From the Eureka side, the northern end, the stream comes out of a classic syphon at the bottom of a 25-metre pitch, at water level the sump is little more than body sized, but underwater it is larger with a flake at about 1.5 metre depth from which the water is coming under.

On the Racer Cave side, the southern end, you can get down to the sump where the water is actually disappearing and again at water level, it is little more than body sized, but underwater it is much larger.

Teams on either side of the sump were able to establish excellent radio communication and took drain rods with powerful torches attached. The light from the Eureka side was immediately visible from the Racer side when submerged in the sump with the water appearing crystal clear. *It is therefore now proven that the caves connect through these sumps.*

The Racer team attempted to put their drain rod into the sump, however, once Andy went in to the water the silt immediately and completely blocked any visibility and it was impossible to see the torch from the other side. Both torches were also behaving very intermittently which added to the difficulties.

Elaine Oliver spent nearly two hours in the sump on the Eureka chamber side, Andy spent

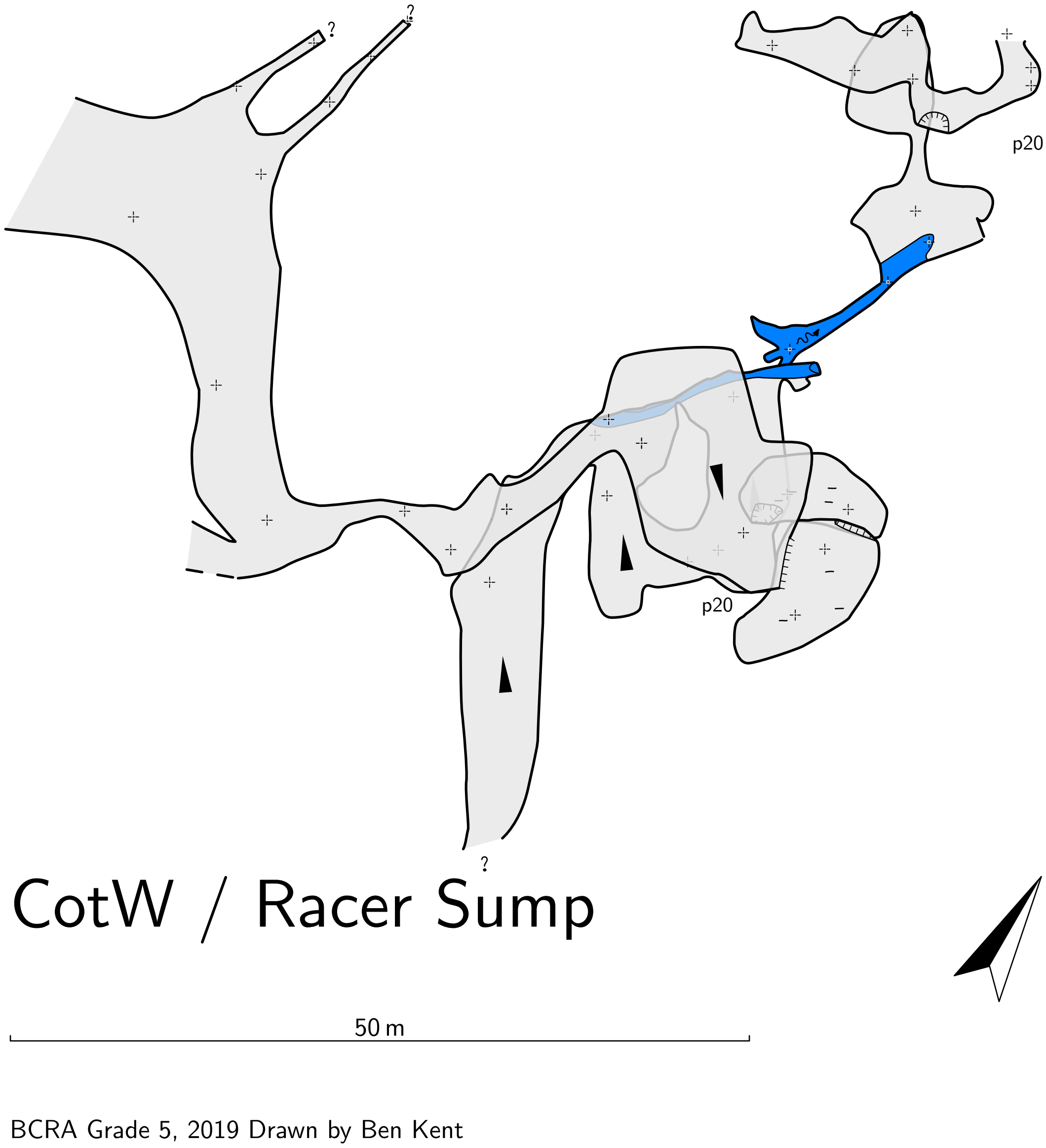

Figure 4.15: Cave of the Winds and Racer Cave sump

nearly two hours on the Racer side, and both got incredibly cold but failed to establish a connection however hard they tried. In a future expedition, a diver with a small bottle and a wet suit should be able to make a human connection.

Before reaching the pitch down on the Racer side, a large calcite choke is passed on the left hand side. This can be crawled into on both the left and right. These become too tight very quickly and even with some light breaking equipment little further progress could be made.

4.5 Easter Cave

4.5.1 Road To Nowhere

*Derek Bristol, **Ben Kent** and Frank Tully*

338.86 m

During the initial discovery of Easter Cave a large phearatic passage was found heading south along the strike. This terminated in a steep 100m ramp to a sump level: the Express Elevator. This was of significant interest as it descends to the level of Lagangs, but in an area of limestone between the Fast Lane, the Main Passage and the escarpment.

Over two trips a passage heading west from the bottom was followed. It begins by a short free climb up to the right from the final ledge before the sump pool. A sharp, narrow passage is then descended to an awkward 3m pitch over a sharp flake. This lands on a steep ramp descending down to the sump pool.

The ramp is traversed right, protected by a rope before a short 4m pitch is descended. This continues across the ramp to a large block in the entrance to the continuation passage with a strong westward draught. A 2m snakeskin was seen here.

Following the passage west, after 10m a steep guano covered 8m climb to the right is met. This was protected at the top with a rope. The passage continues as a steep, guano covered, inclined rift with a 4m descent followed by 30m of passage. After a sharp left (south), bridging is required up and over a pit (protected by a rope) to gain 2m to a small ledge. The bottom of the pit contains a low, guano-filled crawl that likely links to the next pit.

From the ledge, a similar pit is traversed around the right hand side to another ledge before descending down two steps to a guano-floored chamber. The continuation is a 10m pitch up, immediately followed by a 5m pitch down. The passage continues with a thick guano floor, passing under a small arch and down two 1m steps. A small tube is seen down to the left.

Continuing for 20m leads to a pitch down to a static sump 10m below. The continuation of the passage can be seen across this pitch. The pitch is descended, followed by immediately climbing back up to the same level 10m along the passage. No obvious leads were seen at sump level. A small guano covered slope is then climbed, followed by a short rope-protected climb totalling about 6m of ascent. Again, this is immediately followed by a pitch down a 10m guano covered ramp.

A final 6m pitch is then ascended. This may have a continuation overhead and behind, likely to rejoin the roof of the passage further back. From here the passage continues, smaller in size, passing a deep mud pit before quickly reaching an an exposed traverse. This is immediately followed by a small downclimb.

Daylight can now be seen and the cave can be exited up a short 5m scramble. This new entrance is approximately 3m wide by 1.5m high, and exits the escarpment above the Tubeways entrance.

From this entrance, traversing the escarpment to the East finds a small cave after about 50m. Despite being relatively roomy, this closes down in approximately 15m. Further exploration of the escarpment in this area would be worthwhile given the proximity of this new Easter entrance and the Lagangs main entrance.

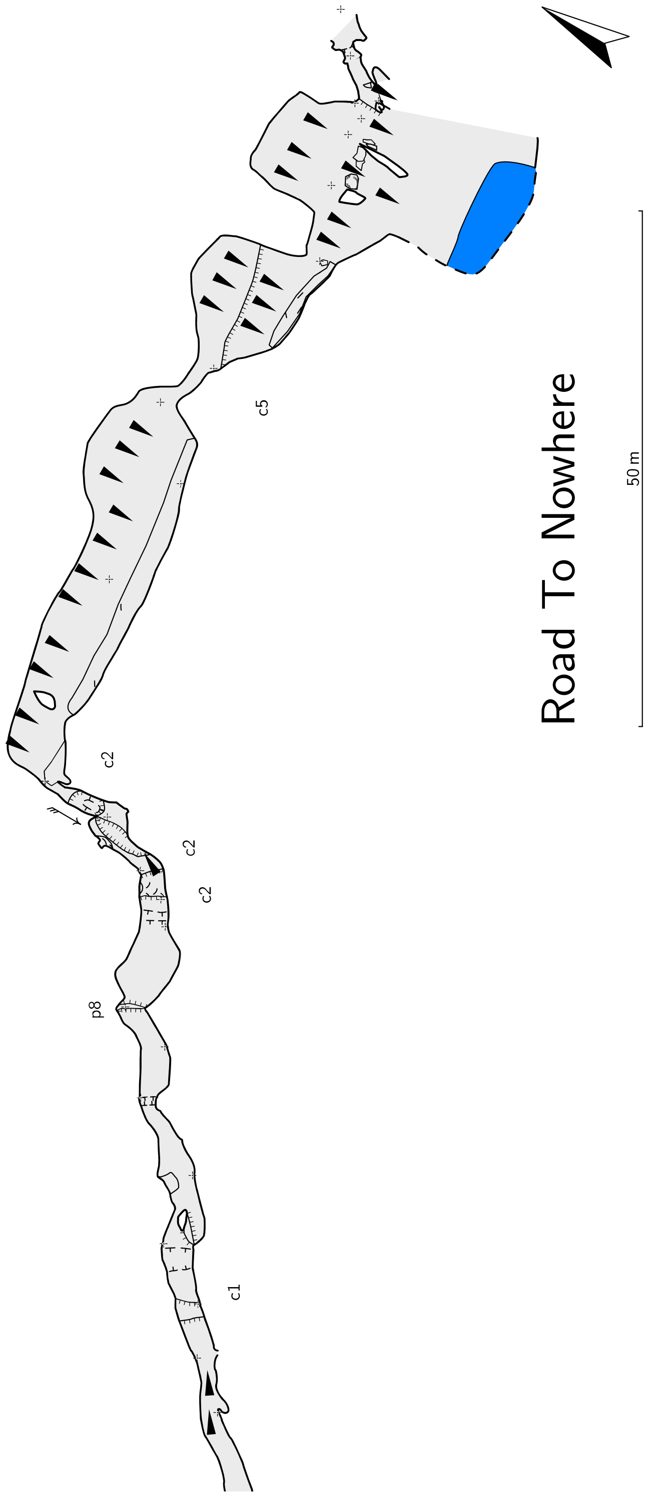

Figure 4.16: Road To Nowhere (1)

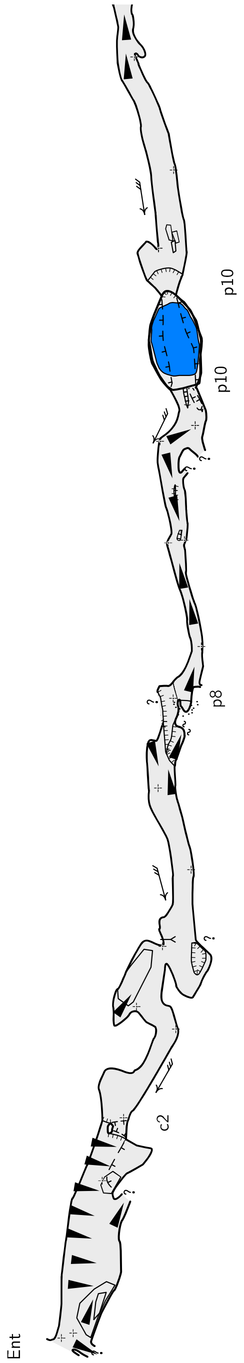

Figure 4.17: Road To Nowhere (2)

Figure 4.18: Road To Lagangs Pitch (Ben Kent)

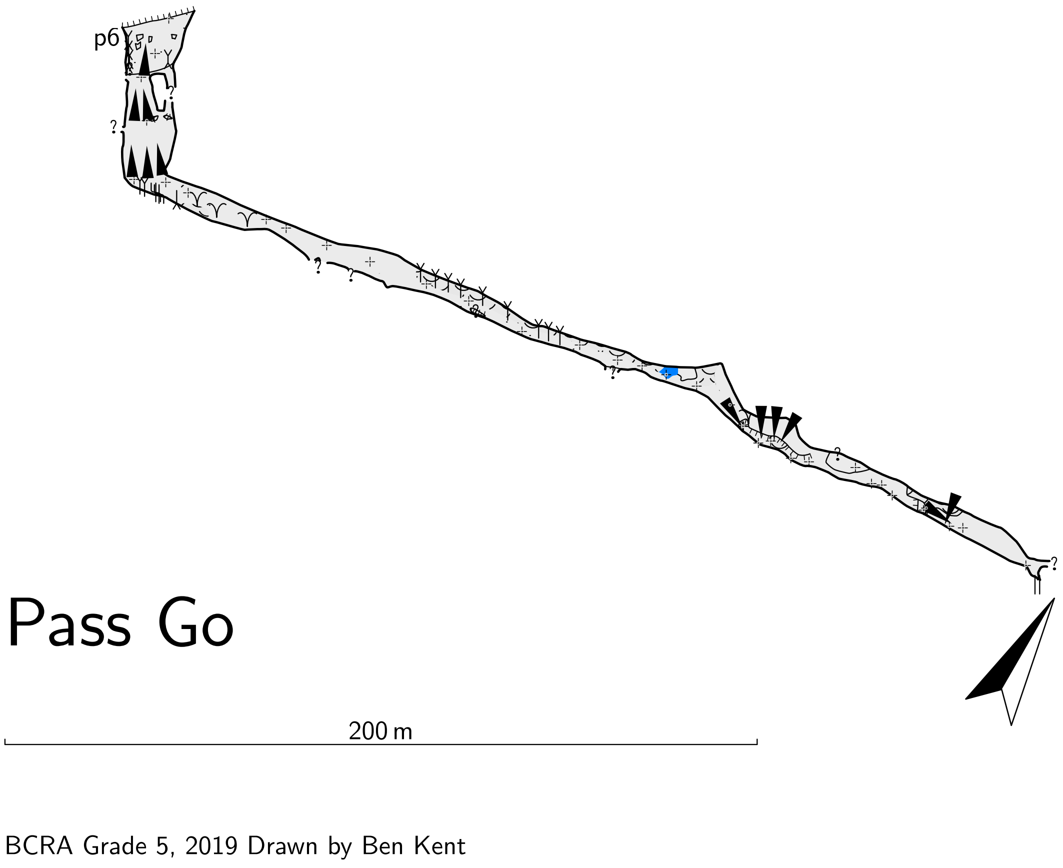

Figure 4.19: Pass Go

4.5.2 Pass Go

*Dave Cooke, Elaine Oliver and **Alistair Smith***

277.12 m

Shortly after entering the Road to Lagangs passage, a short 6m climb is seen on the left hand wall which is agonisingly close to Sago Palm cave. This was climbed with a single hanger left at the top after pulling through on the return.

At the top of the pitch is a wide slope which is loose underfoot. The passage forks left and right, with the main continuation to the right. The left fork was not explored, but possibly rejoins the right hand fork. To the right of the slope are two eye holes leading to a parallel sloped passage also opening into Road to Lagangs. This remains unexplored.

The top of the incline is choked with calcite, however, the passage continues left along a soft sandy/guano floor. It continues in this direction for some way, changing in nature to rift passage with a few unexplored man sized holes in the floor, including one larger hole which was traversed over the top of to Elaines displeasure.

The passage continues to a reasonably large boulder chamber after 150m. The main passage continues down slope to the right the balcony balcony passing around a big stal boss. Continuing back up the slope reveals a tricky climb over a large boss stall on which it may be advisable to put a hand line on for future trips. From here the route climbs down through the stal to floor level.

Following the passage down-slope for 20m leads to a fork. Down and to the right, the passage ends quickly at a calcite choke. A tricky traverse of the left hand wall climbs over the calcite choke. A bolt protects a climb down at this point, but the rift passage becomes narrower and chokes up after approximately 5m. This bolt marks the final survey station.

There is a potential continuation approximately 10m above inhabited by a large number of swifts which would be a bold free climb or ideally require some bolts for protection.

4.6 Lagangs Cave

4.6.1 Anniversary Series

379.76 m

Rambli Ahmad, Dave Cooke, ***Ben Kent*** *and* ***Frank Tully***

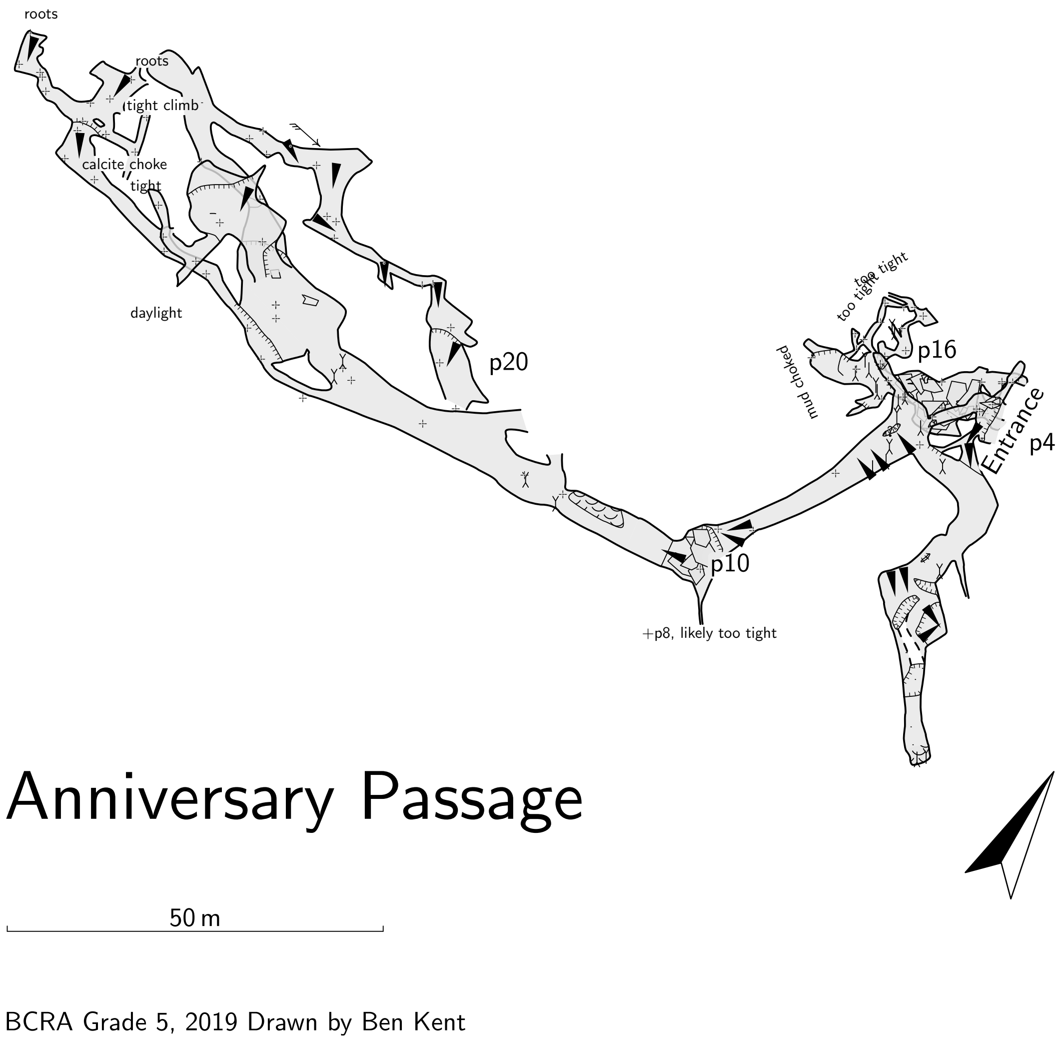

Figure 4.20: Anniversary Series

The Anniversary Series was discovered up a 15m bolt climb near the Fast Lane Entrance in 2017. It was left at a chamber with a strong draughting lead up a 13m pitch. The 2019 expedition rebolted the climbs, using approximately 40m of rope to climb the whole pitch.

Moonmilk has made the climbs and traverses very slippy so additional handlines totally 35m were used for protection.

Anniversary Chamber

The pitch was climbed to a northwards continuation full of rotten calcite and breakdown, a 20m rope was used to rig for SRT with two slings. The passage at the top is continuation of the phreatic conduit. After 25m this reaches a crossroads, with a too tight slot in the floor. Right is a continuation of the phreatic passage some holes in the floor too-tight. The passage turns north and enlarges, and an exposed traverse over a mud bridge leads to balcony. A 15m pitch down, just before the mud bridge, lands on a flat floor and continues under the balcony and up 2m climb into a continuation of the passage. After10m the passage ends in solid calcite choke with no draught and no gaps in the boulders.

Straight ahead from the crossroads, following the draught, reaches daylight in 15m. A 6m pitch is ascended to exit into a large doline. This is only approximately 100m for the Easter South entrance. Unfortunately this doline also means any connection to Easter from the Anniversary series is likely to have collapsed due to the proximity to the surface. This entrance is also the source of the strong draught through the Anniversary series.

Turning left at the crossroads and passing the large column leads to a 15m pitch down, utilising 30m of rope. A small passage is passed half way through the descent. The base of the pitch opens into an inclined chamber of about 30m by 5m. No onward continuation is seen, with the edges mostly filled with breakdown and calcite.

From the pitch base a small passage can be followed which quickly reaches a T junction. Left opens back into the chamber, whilst right climbs up 5m. A small squeeze is passed and the small rift passage can be followed to break out into the pitch, as mentioned above.

A final point of note is that in the doline, a draughting entrance was found to the east. It was not entered as it required a short climb into it.

Other Minor Side Passages

Whilst traversing the main passage a steeply descending rift to the right is encountered. This can be downclimbed to a 1m wide passage running parallel to the main passage. To the east it quickly rejoins the main passage through a low crawl. To the west it continues for 40m, rising back up 10m in height. At the end, a short 1m handline down gives three ways on. To the right, west, 10m of passage quickly shuts down. A connecting window joins the central branch which is a steep free climb ending in small tubes. There are lots of roots at this point, suggesting the surface is very nearby. The left hand, east, fork continues for 8m with a low crawl before splitting into small tubes. Up to the right appears again to be very near the surface.

Instead of descending the rift, the left hand wall whilst facing west can be climbed 9m to a chamber above Anniversary passage. Up to the right roots can be seen up a tube, whilst up the left a sharp, loose climb ascends for approximately 5m to a point where daylight can be seen through boulders.

4.6.2 Lagangs Entrance

*Elaine Oliver, **Tony Radmall**, Chris Williams and Les Williams*

662.98 m

Given that Survex shows the passages around the entrance to the Fast Lane had never been surveyed, it was thought worthwhile to collect data to see the extent of the cave near the escarpment.

Before reaching the gated Fast Lane entrance, on the right hand side is the entrance chamber. This is initially quite flat before rising to the daylight. Several holes and passages on the left hand side all go further into Lagangs joining the main cave.

After passing the entrance gate, on the left hand side of the plank walk there are two passages running parallel to each other. After 20 metres they join before turning left and meet the cliff face exiting to the left and above the Fast Lane entrance.

Back at the plank walk, a few metres further on the right, an arched passage leads to a series of three pits which finish with a window into the entrance chamber. Left at the window is a climb up into the entrance chamber, to the right is a climb up which splits either into the entrance chamber or looping back into the three pits.

From the second pit a climb to the left up a mud bank reaches a passage that ends after 5 metres in a small climb down. This was not descended.

A further 5m along the plank walk meets another passage on the right hand side. This can be followed to a boulder strewn chamber. Down through boulders there are many routes, one of which to the right takes you through to the entrance chamber very near the top of the chamber.

If instead a route left is taken in the boulder chamber, a way through to the plank walk is found. This passes the end of the Around the Houses passage that was discovered in 2017.

4.6.3 Balcony Passage

Ben Kent, *Tim Kent, Tony Radmall and Chris Williams*

Towards the northern end of Lagangs Cave a large guano-covered slope is climbed. At the top of this an exposed climb up the left hand (west) wall enters a passage at roof level hidden behind large calcite columns. These can be used to protect climbers on the ascent and descent. This passage was discovered in 2014, and the return trip hoped to find a continuation up higher towards Racer Cave.

The team had a thorough look around the passage but unfortunately no continuation was found. The U-shaped passage perviously surveyed was found to connect across to itself by squeezing up the tight, sandy bedding plane both passages sit in.

4.6.4 Minaret

Dave Cooke, ***Tim Kent****, Alistair Smith*

82.37 m

A heavily draughting entrance was found on the escarpment between the two Lagangs entrances with run-off streams to the right The entrance was found about 4m above ground level. The entrance passage has a trenched floor with onion- or minaret-domed silhouette leading to a reasonable size chamber. Ahead several passages are found through moon-milked boulders which become immediately become impassable. The way on is through a draughting eye-shaped hole to a calcited passage with a draughting rift to the right (unsurveyed - to the surface?). This opens to a larger chamber choked with large boulders to the left and ahead. A way on through the boulders continues to draught. Possibly this is the same boulder choke as in Lagangs entrance?

4.6.5 Without Wellies, Tubeways

Dave Cooke, Tony Radmall, Carsten Peter, Alistair Smith, ***Frank Tully****, Chris Williams and Les Williams*

66.62 m

Tubeways was discovered in 2017, and is found between the Lagangs Main and Fast Lane entrances. It was left with a draughting pitch to be climbed at the western end. An 8m bolt climb (16m of rope, with a deviation) reaches a squeeze that was passed by one explorer "without wellies", then is followed by a narrow rift to a sump. This was bolted across with a

Figure 4.21: Fast Lane Entrance Survey

Figure 4.22: Minaret passage outline (Tim Kent)

small closed passage in the roof. A small mud-floored passage continues north 2m above the water and quickly gains another static sump.

The draught coming down the pitch all appears to enter from small too-tight slots in the roof. There is no draught near the terminal sump.

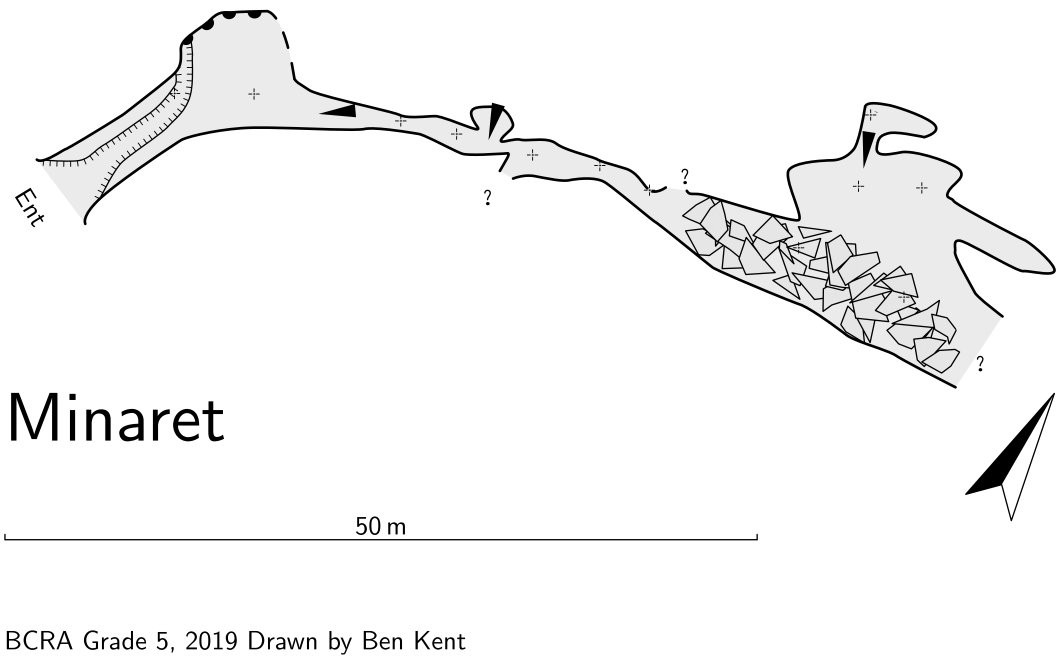

Figure 4.23: Minaret Survey

Figure 4.24: Tubeways Passage (Dave Cooke)

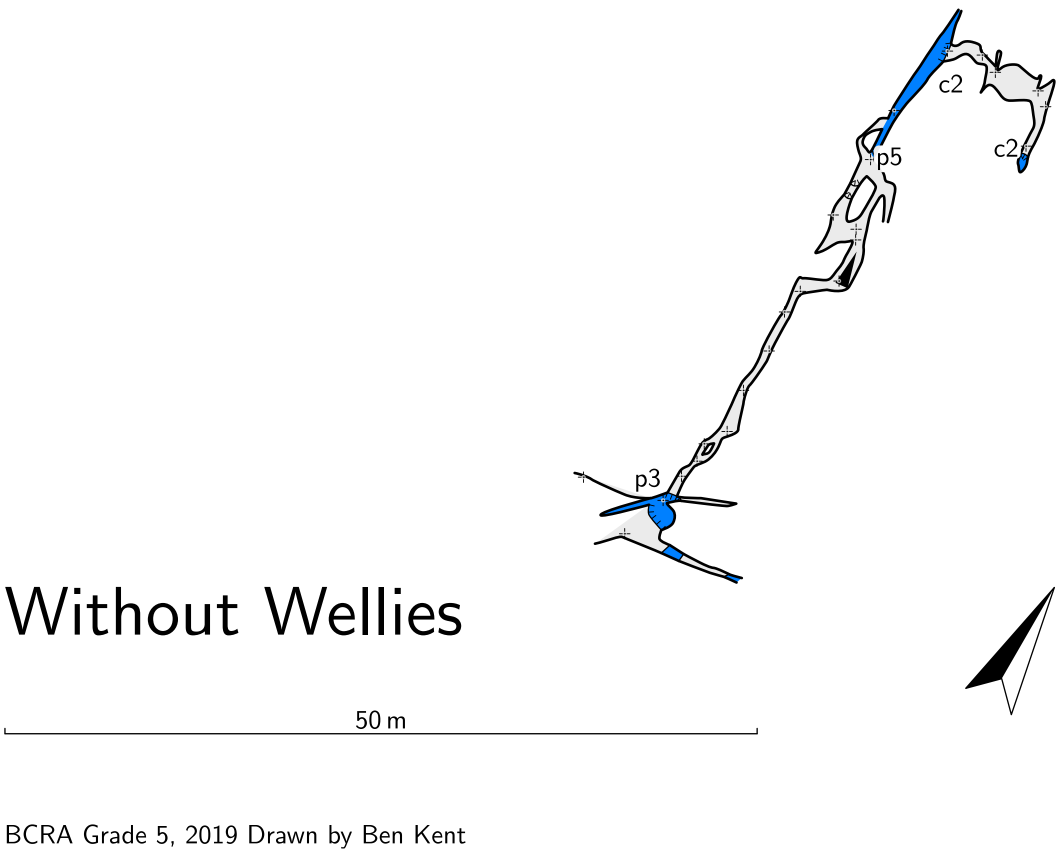

Figure 4.25: Without Wellies Survey

4.7 Other Investigations

4.7.1 Paku Crossing Cave

Tim Kent*, Alistair Smith and Les Williams*

The entrance is found slightly upstream from Paku crossing and about 2m up the cliff leads to a previously bolted climb with a small draughting slot about 6m up. The slot is too small to pass without breaking equipment and passage beyond looks very tight.

A GPS fix was taken at $4°2'59.115"N, 114°50'5.594"E$.

4.7.2 Sago Palm Cave

Andy Eavis *and Tim Kent*

To access Sago Palm Cave the most convenient route was considered to be through the western Easter entrance underground to the south Easter exit then up on the surface to the impressive Sago Palm entrance.

This entrance used to be very visible from the airport, but the trees including the sago palm itself have now grown up substantially making it quite difficult to see from afar. However, it is very close to the south Easter entrance being 100 metres above and slightly to the side of the entrance. It is very surprising that Sago Palm Cave was explored reasonably extensively in 1991, but the Easter Cave entrance immediately below it was not discovered until 20 years later.

The survey from 1991 was used and although the cave is very complicated it could be followed down to the lowest point, which from the surveys is pretty close to the Road to Lagangs in Easter Cave. A comment in the early report says, Beware Sago Palm Cave is slippery. That is an under-statement, and everybody continually slipped over, and further expeditions would be very wise to use a number of hand lines. It is one of the most slippery caves any of us had ever come across. At the lowest point in Sago Palm Cave there is simply a trickle of water disappearing onto the floor and no obvious way on. The way down to here passed an obvious hole in boulders in the side of the main passage. Later careful inspection of the surveys showed that this was a promising spot to also connect with Easter Cave, so a follow up trip was planned.

The small hole in the side of the passage noted in 1991 and ignored 3 days earlier was quickly descended. A broken 20 metre pitch led to an undercut passage with a solid roof and boulder/mud floor. It appears as though it is the side of a huge Sago Palm Cave main passage, which is infilled with boulders and mud. There were many ways, some leading to fairly substantial open spaces. Eventually a mud floor was reached, and an altimeter was suggesting a level similar to Easter Cave.

Figure 4.26: Paku Crossing Cave entrance relative to spanner (Tim Kent)

There is quite a lot of surveying to do down here and research in the boulders could easily lead to Easter. Returning to the Sago Palm entrance, it was remembered that part way down towards Easter entrance on the surface was another entrance which must be part of the Sago Palm passage. The passage inside was very similar to the hole in the floor in the main Sago Palm cave above. Horizontally, it was easy to get at least 50 metres and down produced many ongoing leads again, open space with a definite possibility of leading down into Easter and connections up into Sago Palm.

4.8 Sarwak Chamber

4.8.1 Sarawak Chamber Climb

Derek Bristol*, Andy Eavis and Veno Enar*

After camp was established at the entrance to Sarawak Chamber, the climbing team repacked gear and headed to the far side of the room to relocate a lead along the north wall that sits on an obvious fault which forms the boundary between the wall and the rest of the room. The wall is reasonably clean rock and close to vertical. A combination of 6 mm diameter screw anchors and 8 mm expansion bolts was placed using a rotary hammer. The general strategy was to place 3-4 screw anchors for speed and efficiency, followed by a thru-bolt as a fail-safe in the event of a fall. There were more than 40 anchors placed during the climb and there were no failures. A reasonably direct line was followed up the wall to reach what appeared to be a ledge or alcove.

After about 90 minute of climbing, which netted 30 meters of vertical gain, a bulge was crossed where it became apparent that there was no intermediate ledge, and the best option was to proceed up to ceiling level, where it might be possible to enter a fissure created by the fault. The wall was deceptively tall and with another 25-30 meters of climbing left, an anchor was established and the first pitch of the climb was cleaned while rappelling.

The team returned the next morning and climbed the fixed static rope to reach the high point where the ascent continued. After another 20 meters of direct aid, the ambient sound of swiftlets was very quickly replaced by the roar of water. Within roughly 1 minute the previously dry fissure, which was only 5-7 meters to the right of the climbing route, turned into a raging waterfall. Fortunately no water was coming in directly above the climbing route, though water was pouring into the room from hundreds of holes and cracks, many along the fault that formed the northern wall of the chamber. The fact that it was raining outside was obvious, and after a brief period of indecision, the climb was ended so that attention could be focused on the need to exit the cave safely.

A pair of 8 mm thru-bolts were left at the high point of the climb, which was fixed with 50 meters of 10 mm static rope. An additional 7-10 meters of climbing is required to reach the ceiling level and the fissure, which may be traversable to both the east and west, at least in dry conditions. The eastern direction certainly carries a lot of water during flood and is worth investigating as a path to either Cobra Cave or Hidden Valley.

4.8.2 Surface Exploration above CotW

Ben Kent, Derek Bristol, ***Andy Eavis*** *and Veno, plus local guide Steve*

The team went to look for a new bird nesting cave above Cave of the Winds. It would seem there was a lack of understanding between Veno and Steve and both seemed to think the other knew the way to a cave that they had both visited, at least 12 years previously.

Going up from the high point on the plank walk between Cave of the Winds and Clearwater, going straight up through the forest, it soon became clear that the guides were not sure which way to go. Ben, Derek and Andy had lunch while Veno and Steve searched. Eventually they came back, and everybody went to an entrance they had found, a pitch led down straight into

Figure 4.27: Andy belaying Derek in Sarawak Chamber (Carsten Peter)

Cave of the Winds show cave. A little bit further another hole was found which was obviously the Cave of the Winds skylight.

The large entrance that Veno and Steve talked about remained elusive. It is suggested that between expeditions Veno will return and cut a track to the proper entrance so that no similar fiascos can occur in the future.

5 Conclusions and Recommendations

5.1 Conclusions

Northern Clearwater still has a lot of potential The discovery of Scientific Method and the Chinashop demonstrate that there is still potential for significant new finds in the northern end of Clearwater. It is hoped that one of these may be pushed to find a way into the large blank space between the eastern parts of Clearwater and Blackrock/Whiterock. There should be approximately 1 km of Clearwater river passage waiting to be found!

The Chinashop was an interesting find rising up above the level of the Dune Series. The most promising lead is likely to be the climb at the top which will require aid gear and could be potentially up to 40m. Passages at the northern extreme of the Creedance series are in relatively close proximity and it is thought both sets of passages draught outwards from the leads. This is encouraging as it means they are unlikely to just close a loop!

Hypothesis Chamber was also a great discovery, breaking east from the main drag through northern Clearwater towards the big blank space in the survey. In the Scientific Method series the strong lead is an exposed climb across a steep slab, covered in a thin layer of liquid mud. This leads to a window through to a continuation of the steeply inclined passage from which the strong draught is likely to be coming. There is a possibility that this passage will continue and intersect a steep ramp from the Blackrock connection. In the previous reports a steep ramp was descended to approximately the right location about 200m away. No continuation was found at that point, so it would be interesting to see what happens.

Alternatively in Scientific Method there is another pit to descend at the north end of the chamber. This was not explored at all in 2019. Another option is to follow the water up the eastern wall. This appears to be fairly immature but could potentially offer a way on into bigger things.

The last note from the northern end of Clearwater is to update the survey through Gnome Chamber, Troll Cavern and East and West passages. The 2019 team had a brief look beyond East passage but they struggled to understand the terrain. There is likely to be plenty more passage in this rarely visited part of the cave, but without an accurate survey it will be hard work establishing where to look and what has been previously discovered.

Cave of the Winds and Racer Cave are connected By examining the sumps with lights it has been confirmed that the two sumps form a continuous passage, with the upstream side in Racer Cave. It cannot be called a human connection yet but should only be a short dive. It is thought too dangerous for a free dive as it is slightly constricted and awkward.

Southern Eureka and Northern Racer are unlikely to offer much more new passage At other levels within both Easter and Racer the cave appears to be well and truly blocked with calcite. This is seen at three different levels and given there is no notable draught in any of these it is unlikely there is a connection here. Leads in the Boneyard area of Racer were also examined with no significant headway made into the limestone separating the two caves despite quiet a lot of new passage being discovered. Surface exploration guided by Veno and Steve also proved unsuccessful, however, they are adamant that a large cave exists up high above Cave of the Winds. Possibly it is worth visiting Too Much Room in Racer?

Extensions in the Road to Lagangs has brought Easter and Lagangs closer The Road to Nowhere follows the line of the Fast Lane, offset by 20 to 40 metres all the way to the escarpment. Unfortunately there are no obvious leads within this passage so it does not offer much promise of a connection. The new entrance is not a million miles away from Tubeways which is arguably connected to Lagangs Cave, however these two are unlikely to have a passable connection.

The second discovery, a bolt climb up towards Sago Palm cave, suprised the team by continuing along the line of the Fast Lane and missing Sago Palm altogether. This has been left with an ongoing passage requiring aid climbing, and is of interest as it sits up above Lagangs Cave in an area with no other known cave.

Anniversary Series reaches the surface and is choked towards Easter The Anniversary Series was particularly promising as it climbed to the level of Easter Cave and finished with a strongly draughting aven. This turned out to quickly lead to an entrance in a large doline - possibly even the same doline as the Easter southern entrance. Continuations at this point quickly become calcited boulder chokes, likely due to their proximity to the surface. It is therefore unlikely to yield a connection across to Easter.

Sarawak Chamber climbs are unconcluded A large thunderstorm prevented the completion of climbs within Sarawak Chamber. It is therefore left for a future team to complete.

5.2 Recommendations

5.2.1 Major Leads

Scientific Method The continuation of the main strike passage is the obvious lead. There also are leads from the main chamber: one also up at the top of the north side, and one following the water flow up the steep east wall.

Chinashop A strong draught is felt at the present limit of exploration, with a bold climb continuing possibly 40m higher.

Pass Go This passage was left with an onwards continuation, likely to require a short bolt protected climb. This almost sits above the Lagangs Main passage so may shortly break into a passage along the strike. This is of significant interest as it is in part of the cave with very little known passage. Any slots into the floor may offer the potential for a connection down into Lagangs.

Road To Nowhere The initial excitement from this strongly draughting passage was unfortunately suppressed after breaking out to the surface! A further examination may yield some unexplored side passages that could bridge the short gap to either the Fast Lane or Lagangs Main Passage.

Sarawak Chamber Climb This climb was left incomplete. A short return trip may be able to top out into a continuation out of the chamber.

Lagangs Escarpment Small unexplored caves still exist between the two Lagangs entrances, and given the proximity of the new Easter entrance a connection may be forced between the two somewhere close to the surface via some of these minor caves.

5.2.2 Logistical

Equipment Tackle sacks suitable for camping trips are in short supply at Park HQ. Something over the past few years has caused the welded seams at the base of the Petzl Transporters to fail with little warning. The Easter 2019 expedition sourced some new bags from Lyon Equipment, however, despite being large these are not particularly suited to long camping trips. It is therefore recommended that the next expedition either ensures members have their own tackle sacks, or replenishes the expedition stores with some additional tackle sacks.

Medical Separate the HQ medical kit into three parts: an organised box of general first aid equipment except for drugs, a box of drugs and a box of specialised first aid equipment that is for trained medical practioners only.

Drugs in the field kits should be removed and replaced each expedition so that it is never assumed there is an adequete supply in the field. Lots of the packaging had failed when the inventory was performed during the expedition.

Accounts Paying in cash is always a problem, and the National Park centre is unlikely to be able to provide much cash. Careful budgeting to ensure enough ringgits are brought on the expedition is important.

6 Discoveries Log

Date	Team	Area	Series Name	Survex filename	Length (m)
25 Apr 19	DB, HB, AS	Scientific Series	Scientific Method	scientific_method.svx	258.56
25 Apr 19	BK, EO, TK	Scientific Series	Scientific Method	hypothesis_south.svx	137.56
30 Apr 19	HB, EO, DB, BK	Dune Series	China Shop	chinashop	176.41
01 May 19	HB, EO, DB, BK	Scientific Series	Scientific Method	scientific_method_ii.svx	169.56
21 Apr 19	BK, DB	Eureka	Eureka Climb	eureka_climb.svx	82.72
21 Apr 19	HB, EO, TK	Eureka	Eureka Crawl	eureka_crawl.svx	56.39
22 Apr 19	DB, BK	Eureka	Eureka Climb Revisited	eureka_climb_revisited.svx	93.71
23 Apr 19	BK, TK	Eureka	Blood Sweat and Fear	bloodsweatandfear.svx	50.59

Table 6.1: Clearwater System Survey Log

Date	Team	Area	Series Name	Survex filename	Length (m)
07 May 19	BK, DB,FT, TK	Road To Lagangs	Road To Nowhere	roadtonowhere	338.86
09 May 19	DC, EO, AS	Road To Lagangs	Pass Go	passgo	277.12
24 Apr 19	FT, DC	Boneyard		boneyardsump	119.10
24 Apr 19	FT, DC	Boneyard		fatsnake	164.95
29 Apr 19	FT, DC	Main Cave	Missed	missed	82.68

Table 6.2: Racer/Easter System Survey Log

Date	Team	Area	Series Name	Survex filename	Length (m)
21 Apr 19	FT, DC, RA	Anniversary Series	Anniversary Pitch	anniversary_pitch.svx	114.58
05 May 19	FT, DC	Anniversary Series		anniversary_climb_chamber	114.71
05 May 19	FT, BK	Anniversary Series		anniversary_..._side_passage	150.47
06 May 19	TR, LW, CW, EO	Fast Lane		fastlane_entrance	662.98

Table 6.3: Lagangs Survey Log

Date	Team	Cave	Series Name	Survex filename	Length (m)
27 Apr 19	FT, DC	Tubeways	Without Wellies	withoutwellies	66.62
06 May 19	DC, TK, AS	Minaret	Minaret	minaret	82.37

Table 6.4: Minor Caves Survey Log

7 Microbiology Report

Microbiology Analysis of Secondary Deposits Within Clearwater Cave

Hazel A. Barton and George J. Breley

SUMMARY

Caves host a variety of unusual deposits, whether minerals left over from initial speleogenesis or secondary deposits, which precipitate once the cave has formed (stalactites, stalagmites, etc). To date more than 600 unique minerals and deposits have been identified from caves worldwide. Exploration throughout the Mulu caves since the 1970s has revealed a host of deposits of unknown origin and mechanism of formation. During the Mulu '19 expedition, an observational and mineralogical examination of these formations was carried out to determine whether the formed from exclusively geologic processes, or whether a biogenic component is involved. The initial work had aimed to examine four types of secondary deposits: phytokarst, the curved stalactites at cave entrances, undescribed white encrustations, and unique fluted deposits. Of these features, only the phytokarst and curved stalactites had a strong biogenic component. In addition to examining these features, it appears that a very unusual moonmilk is found in these caves. But perhaps the most interesting microbial feature is the interaction of bird guano with host rock, which leads to highly aggressive dissolution. These preliminary field observations suggest that there is a significant, but undescribed microbial ecosystem within the caves, driven by the temperatures, humidity and uniquely high levels of trogloxene organic carbon input into the system.

METHODS

This preliminary description is based on field observations during the April-May 2019 Mulu Expedition, including identification of speleothems in their geologic context, scale measurements and photography. The Research was carried out at the southern end of Gunung Mulu National Park, including in the Deer Cave Massif and the southern half of Mount Api. The specific caves examined were Clearwater (both the entrance and Dune Series), the entrance to Racer Cave, and Cave of the Winds. For a more detailed mineralogical identification, with follow-on analyses, small samples (approximately 5 g) were collected under a Biological Resources permit No. (31) JHS/NCCD/600 – 7/2/107 and Park Permit No. WL15/2019 from the Forest Department of Sarawak, Malaysia, and returned to the US for analysis.

Thin sections were prepared by mounting samples on in Hillquist Thin Section Epoxy C-D resin and allowed to cure at 130 °C. The samples were then trimmed with a Buehler Isomet low speed saw and think sections were ground to a thickness of no less than 200 μm using silicon carbide powder of 600 and 1000 grit, and aluminum oxide powder of 1200 grit. The thin-sections were polished with Buehler Micropolish 0.3 μm Alpha Alumina powder on a Buehler Low Speed polishing wheel. For fluorescent microscopy, samples were stained for fungi using one drop of 1 g/mL calcofluor white M2R and 0.5 g/L of Evans blue (Sigma-Aldrich), one drop of 10% KOH solution, and one drop of Invitrogen SlowFade Gold antifade reagent (Lonza, Switzerland). Samples were viewed using an Olympus BX53 fluorescent microscope (Olympus America Inc., Center Valley, PA), using DAPI filter for calcofluor, while calcite was imaged using its autofluorescence using a GFP filter.

RESULTS: *PREVIOUSLY IDENTIFIED FEATURES*

Phytokarst (Figure 1A)

1

The recognition of unusual speleothems in the caves of Mulu began when the caves were first explored [1, 2]. The most famous of these are the phytokarst found in cave entrances (Figure 1A), which were described by Laverty in 1981 [3]. Phytokarst was first identified in coastal limestones as a specific karren, formed by the boring activity of plants that dissolved the

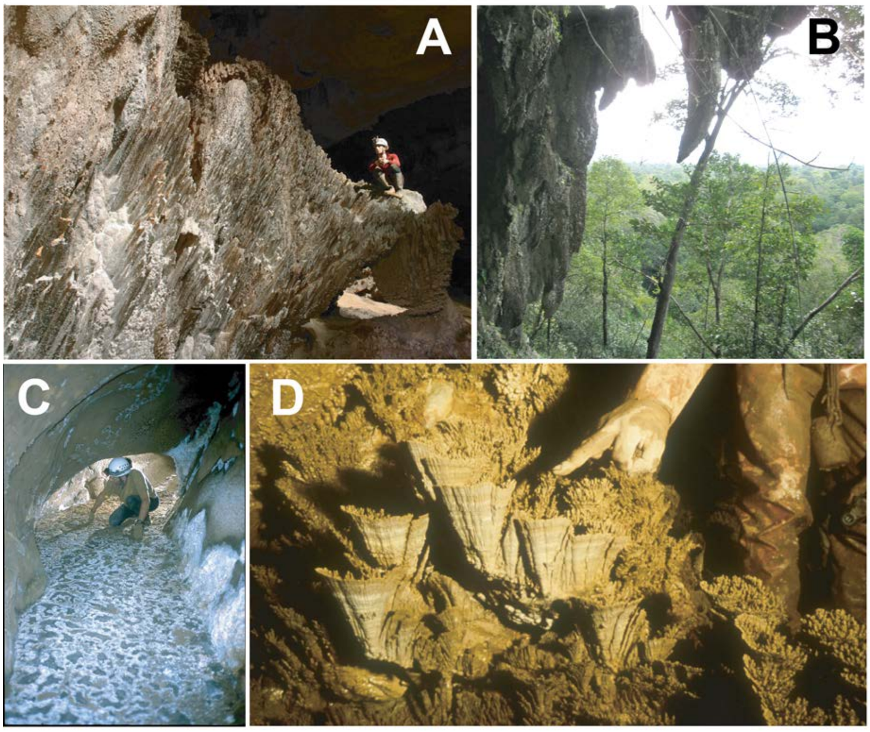

Figure 1. Potential biogenic formations within the caves of Gunung Mulu National Park. A) The long spikes of phytokarst can be found in entrances throughout the park. These pinnacles appear to be caused by photosynthetic bacteria. **B)** At the entrance of many caves are curved stalactites that appear to curve toward sunlight. **C)** White encrustations may indicate the presence of saltpeter, $Ca(NO_3)_2$, which may be biogenic in origin. **D)** There in no clear mechanism of formation of the fluted deposits seen in the cave.

surrounding rock, creating a series of cracks and fissures [4]. Nonetheless, plants are not always associated with phytokarst, and subsequent identification of black phytokarst, such as that seen in the entrance of Clearwater Cave, suggest that photosynthetic microbial species and fungi play an important role in its formation (the original definitions of phytokarst incorrectly stated that its formation was driven by algae, but cyanobacteria appear to be the dominant organisms present) [4, 5]. There are several indicators that the dissolution is driven by photosynthetic activity: 1) the pinnacles point directly toward the sunlight; 2) shaded areas do not appear to undergo dissolution; 3) the presence of a green biofilm at the presumed erosion surface; and 4) the observation of phytokarst only in the photic zones of the cave.

The current explanations for the formation of phytokarst do not align fully with our understanding of cyanobacterial metabolic activity [6, 7]. Past researchers have suggested that carbonic acid produced during the photosynthetic dark cycle, when CO_2 is being produced rather than consumed, is leading to the production of carbonic acid and dissolution [3]; however, cyanobacteria are unlikely to generate any more CO_2 during respiration than the active heterotrophic species within these caves. And while heterotrophic bacteria growing in caves do release organic acids, these are insufficient to produce the intense dissolution observed in phytokarst [8, 9]. Other researchers have suggested that pitting of the surface by microorganisms is carried out to escape the intense sunlight of the cave entrance [6]. But cyanobacteria either produce UV protective pigments or form endolithic communities to escape harmful UV radiation, both of which create a light-filtering barrier between them and intense sunlight, rather than completely eroding the surface [10, 11]. The phytokarst also seems to be more pronounced in the twilight zone, with almost none seen in the entrance areas that receive full sun. Together, these observations indicate that the formation of phytokarst is not an escape strategy.

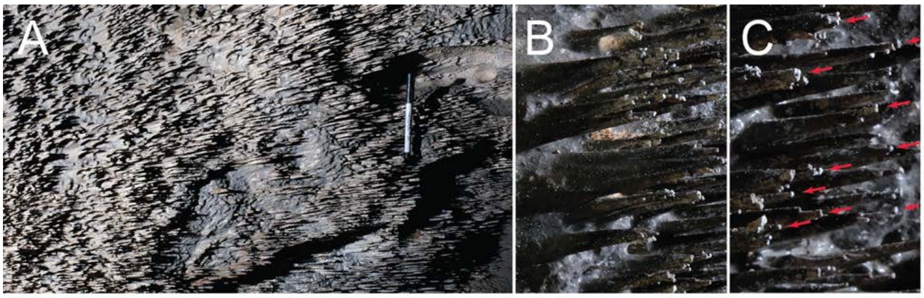

Figure 2. Phytokarst in the entrance to Clearwater Cave. A) A wall of phytokarst pinnacles pointing toward daylight (sharpie pen for scale). The area of the wall covered in this phytokarst is approximately 1.5 m high and 6 m wide. **B)** A close-up of individual pinnacles (the pinnacles have an average length of 3.5 cm, with tips 1 - 2 mm in diameter). **C)** The presence of what appears to be calcite tips on the top of each pinnacle (highlighted with red arrows) could provide a mechanism for protection on an area from photosynthetic dissolution, creating the apparent light-directed pinnacles.

Vanara and Maire [12] suggested that the sunlight-orientated pinnacles of the phytokarst (Figure 2) were created through deposition, although such an observation would not account for the consistent height of the pinnacles, which are more indicative of a shared original surface, rather than a tightly conserved depositional growth rate. On close examination of phytokarst in the Clearwater Cave entrance, the pinnacles were approximately 2 - 3 cm in length, with the tips less than 2 mm in width and appearing to be flush with a previous, contiguous surface (Figure 2A - B). The very narrow tip of the pinnacles rules out the possibility of water-mediated precipitation (Figure 2B - C), which generates secondary deposits with widths equivalent to the average width of a drop of water (~5 mm; examples include soda straws, helicities, etc. [13]). Of particular note was the presence of small calcite deposits on the tip of each pinnacle (Figure 2C). Thin-section analysis indicates that calcite deposits form on each pinnacle (Figure 3), which were consistently flat, as if they had also formed on the original surface. These calcite deposits are similar in structure to calcified *Actinobacterial* colonies commonly found in cave environments [14]. There appears to be a cyanobacterial biofilm covering the pinnacles, which is denser at the base of the phytokarst, with individual bacterial filaments burying into the bedrock, creating a more porous, millimeter-thick layer on the surface (Figure 3C). In places, additional calcite has precipitated over the phytokarst, possibly from additional bacterial growth,

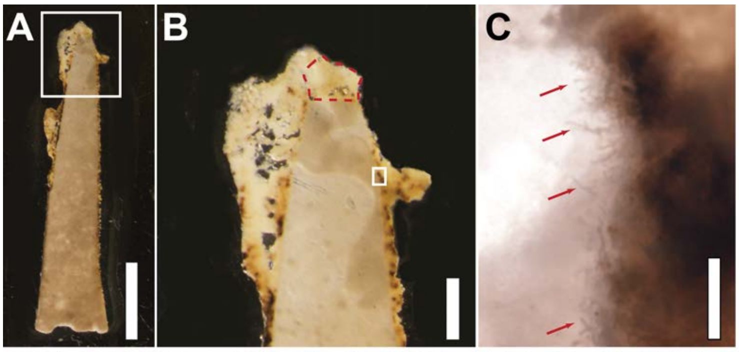

Figure 3. Thin-sections through phytokarst. A) Thin-section of a piece of phytokarst from Clearwater Cave (scale bar = 5 mm); **B)** Close-up of area indicated by white square in **A**. The limestone host rock of the phytokarst pinnacle is obvious in the thin-section, including it's flat surface. The original calcification is indicated by the dotted red line, with additional calcite build-up seen on either side, and the brown organic residue of cyanobacterial growth along both edges (scale bar = 1 mm); **C)** Close-up of cyanobacterial growth highlighted by the white box in **B**. The brown organic matter of the cyanobacterial biofilm is obvious (to the right), along with individual bacetrial filaments boring into the limestone (indicated by red arrows; scale bar = 10 μm).

creating a secondary shadowing that may limit dissolution and change phytokarst morphology (Figure 3). Based on these observations, we propose a model for the formation of phytokarst (shown in Figure 4).

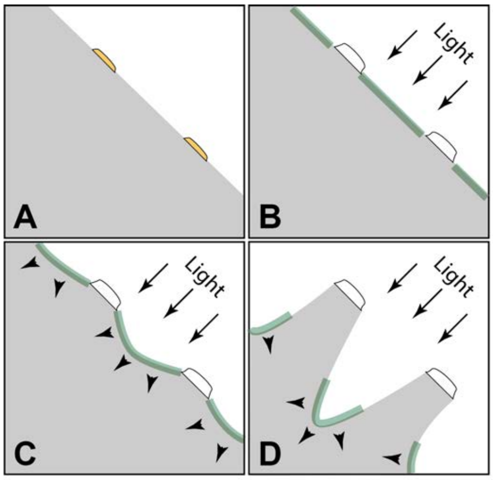

Figure 4. Model for the formation of phytokarst. Bacterial colonies are commonly found on all surfaces within the Mulu caves, and can still be seen on surfaces surrounding the phytokarst (obvious in **Figure 2B**). These colonies form independently of light exposure **(A)**. The presence of potentially toxic Ca^{2+} ions from growth on limestone rock causes these bacterial colonies to calcify, producing a small, colony-sized piece of calcite **(B)**. Calcite is opaque and prevents access of light to the surface below it, limiting growth of photosynthetic species. Cyanobacterial growth (and photosynthetic activity) can still occur on other exposed surfaces, leading to dissolution **(C)**. Over time, this dissolution becomes more pronounced, and only the region originally protected by the calcite remains intact, resulting in the formation of calcite-capped pinnacles **(D)**.

It remains unclear as to the chemistry that actually drive dissolution. It is possible that the wavelengths of light reaching this area of the cave drive photosynthetic conditions that promote aggressive dissolution, otherwise dissolution would be observed in all areas of the photic zone, including in the extensive cyanobacterial biofilms at the entrance [7]. In previous work we have demonstrated that cave entrances contain red-shifted light due to the refraction of light by limestone [15], and these conditions can drive the formation or reactive oxygen species (ROS) in cyanobacteria [7]. This can in turn drive the accumulation photorespiratory intermediates, such as 2-phosphoglycolate (2PG) [16]. In order to recycle 2PG, cyanobacteria use photorespiration to convert it back to useable 3-phosphoglycerate (3PGA) [7, 16] and two of three known pathways produce glyoxylic acid as a byproduct [7, 11]. While there is no evidence that glyoxylic acid is released during cyanobacterial growth, it is an aggressive acid (pK_a 3.32), which we have shown is released as a metabolic waste product by bacteria grown on carbonate [7, 8]. The reaction of glyoxylic acid with limestone would liberate CO_2, increasing the local concentration of HCO_3^-/CO_3^{2-} and extracellular pH, increasing HCO_3^- uptake and photosynthetic efficiency, and thus creating a feedback loop that has the potential to increase local concentrations of any acids produced [16].

Phytokarren (Figure 1B)

Some of the most extensively studied speleothems identified in Mulu are the directional stalagmites found in cave entrances (Figure 1B and Figure 5). These speleothems have been variably called phytokarren, photokarren, and biokarst [12, 17]; however, the use of the terms 'karren' and 'karst' are usually associated with dissolutional processes, while these speleothems are very clearly caused by calcite precipitation [18]. The reason phytokarren are only found in tropical areas has been partially attributed to the high humidity of the area, which slows the evaporation of pore water and allows mineralization of calcite [18]. We also noticed that many of these speleothems appeared to be associated with roots, either sounding hollow when hit or having roots emerging from the bottom (Figure 6A). When we broke open fallen phytokarren, we observed a central channel surrounded with what appeared to be decayed organic material (Figure 6B), presumably the remnants of an entombed root. There have been numerous explanations as to why these speleothems curve outward, and the consensus among researchers is that photosynthetic calcite deposition creates a microcrystalline/micrite tufa, with faster growth on the sunlight side of the speleothem [19, 20]. We have summarized this formation process in Figure 7.

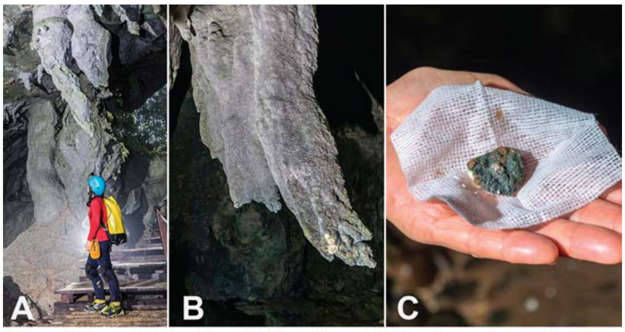

Figure 5. Curved stalactites. **A)** The entrance to Stonehorse Cave; **B)** Phytogen in Racer Cave; **C)** Fragment collected from the speleothem in **B**, with the obvious green cyanobacterial biofilm (Photos by Chris Howes).

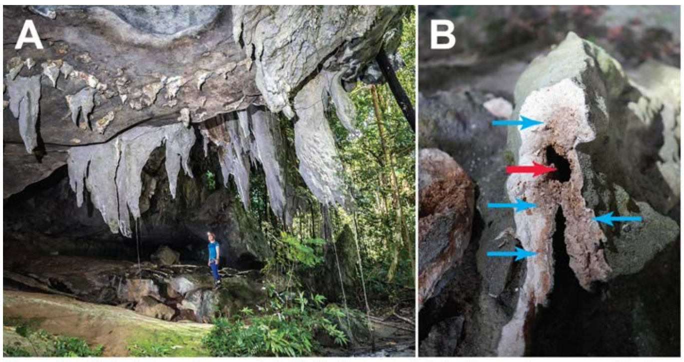

Figure 6. A) Roots are often associated with the curved stalactites, and seen emerging from the bottom. **B)** A broken stalactite reveals the presence of a central canal (red arrow), surrounded by a layer of what appears to be brown organic material (blue arrows). Photo A by Chris Howes.

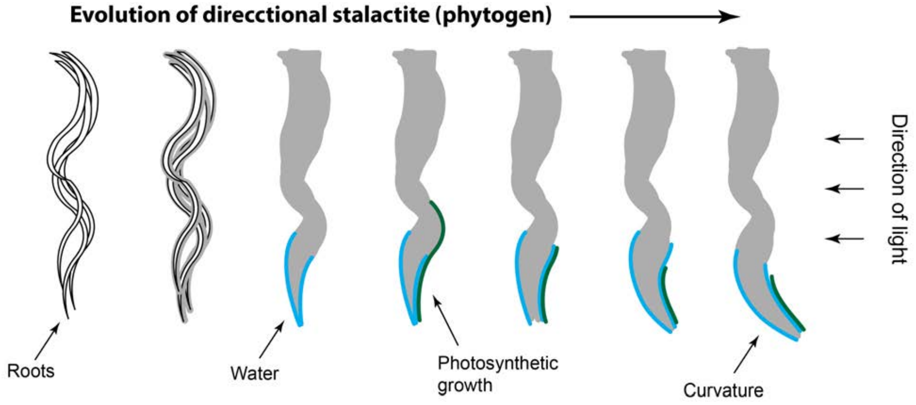

Figure 7. Formation of curved stalactites (phytogens). The initial formation of phytokarren occurs via the abiotic mechanism. CO_2 dissolved in water forms weak carbonic acid that dissolves $CaCO_3$ as it moves through the rock, creating a solution in equilibrium with respect to calcite. When this water reaches the atmosphere, CO_2 off-gases and the pH rises, increasing the saturation index for calcite, which starts to precipitate. The water dropping from the ceiling may take a preferential flow path, usually trough a crack, which may also be exploited by plant roots. As the water emerges, it tends to follow any root present due to adhesion forces. Thus, the calcite preferentially precipitates along this path and entombs the root. Due to its location in a cave entrance, one side of the speleothem faces toward sunlight, and a significant cyanobacterial biofilm forms, which is apparent as a bright green coating (Figure 4C). As the cyanobacteria carry out photosynthesis, they consume additional CO_2, further increasing pH and driving additional calcification. The cyanobacterial exopolysaccharides (EPS) in the biofilm create a charge surface, which coordinates the Ca^{2+} ions and further drives precipitation. The accelaration of calcite deposition leads to the formation of a soft, microcrostalline tufa, filled with both cyanobacterial cells and EPS. As cyanobacteria preferentially grow in wet conditions, there is greater calcification where the water is highest, which is the tip of the speleothem. This leads to an even more pronounced turn toward the sunlight (Figure 4B).

White encrustations (Figure 1C)

The white encrustations were reminiscent of cave saltpeter, which has a proposed biogenic origin. In 1901, Nicols [21] suggested that bat guano, naturally high in urea, was the origin of saltpeter; however, the low levels of organic carbon and phosphorous (which are abundant in feces [22, 23]), ruled out guano as a source of the nitrogen (and would similarly rule out bird guano as a potential source in the Mulu caves). Our past work suggests that soil-derived ammonia in groundwater is converted NO_3^- in caves through the activities of ammonia oxidizing bacteria, such as *Nitrosomonas spp*. [24] and ammonia oxidizing archaea (AOA), including members of the *Thaumarchaeota,* which dominate microbial species in cave sediments [25, 26]. Without rain to wash it away or organic carbon to power reduction, NO_3^- accumulates as saltpeter [26, 27]. One of the characteristic features of saltpeter deposits within caves is effervescence [28]. We examined these white encrustations (Figure 1C) in passages off of the Great Wall Chamber in Clearwater Cave; however, no characteristic effervescence was seen, nor did the mineral have a tart taste, ruling out saltpeter. Instead, it appears that these deposits are airflow-precipitated calcite.

Fluted deposits (Figure 1D)

We were interested in the unusual fluted deposits, because there was no clear indication as to what was causing their formation. A large number of these fluted speleothems were discovered in the China Shop area (they were essentially the floor in a number of areas). While the originally described formations (Figure 1D) were seen emerging from mud, which can sometimes be indicative of a biological phenomenon, these fluted deposits were also observed on bedrock and flowstone in the Chinashop. On close examination, there was no obvious biological component of these speleothems, and they all pointed along the direction of strong airflow. As a result, they appear to be an airflow, convection-driven deposit.

RESULTS: *NEWLY IDENTIFIED FEATURES WITH A POSSIBLE BIOGENIC ORIGIN*

Fluffy Moonmilk (Figure 10A)

Moonmilk was one of the earliest cave deposits to be associated with microbial activity [29]. Due to the lack of culturability of the microbial species involved, it was initially difficult to determine the role that microorganisms played in the formation of moonmilk. Morphological evidence suggested that moomilk forms through the microbial colonization of rock surfaces, followed by dissolution of the bedrock and the formation of a $CaCO_3$-saturated solution that precipitates into thin, microcrystalline threads (Figure 8) [30]. More recent work [31] has demonstrated that actinobacteria living in the moonmilk carry out ammonification, which increases the pH of the $CaCO_3$ saturated solution, driving calcification. The actinobacteria also serve as a nucleation site for the precipitation of calcite, which entombs the filamentous fibers of the bacteria, creating the microcrystalline threads characteristic of moonmilk (Figure 8) [30, 31]. These calcite filaments collapse, serving as a nucleation site for additional calcification, creating the characteristic, water-saturated polycrystalline chains [30]. As this process repeats, the moonmilk become thicker, forming significant, paste-like deposits that can exceed 1 m in thickness [32].

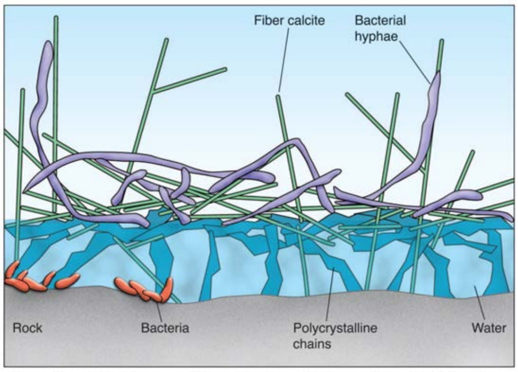

Figure 8. Model of moonmilk formation [from Barton and Jurado, 2007 (32)].

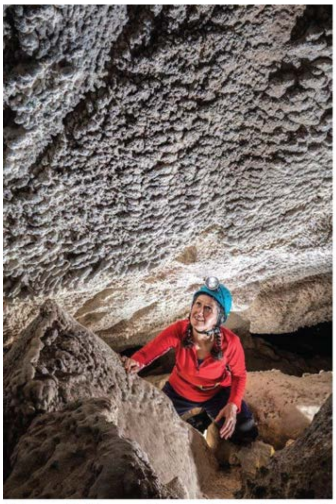
Figure 9. Moonmilk near the entrance to Cave of the Winds (Photo Chris Howes).

While the microbial physiology of moonmilk formation is relatively well understood [30-34], the environmental conditions that determine where it forms are not [13]. Moonmilk is commonly found in colder, alpine caves that have small entrances and strong airflow. While the caves of Mulu do not meet any of these criteria, there is extensive moonmilk found near many entrances, including Clearwater Cave and Cave of the Winds (Figure 9). In

Clearwater Cave, the moonmilk is particularly notable due to its fluffy texture (Figure 10A). Such fluffiness has not been previously described, and appears to be caused by material structurally similar to either actinobacterial or fungal growth, emerging from the moonmilk (Figure 10A). Microscopic examination suggests that the 'fluffs' are calcite, precipitated around either fungal or actinobacterial filaments, subsequently covered in fungi (Figure 10B - D). The presence of these fungi, with their strong chitinous cell wall, may support the final structure, allowing the development of these visible fluffs over the moonmilk surface.

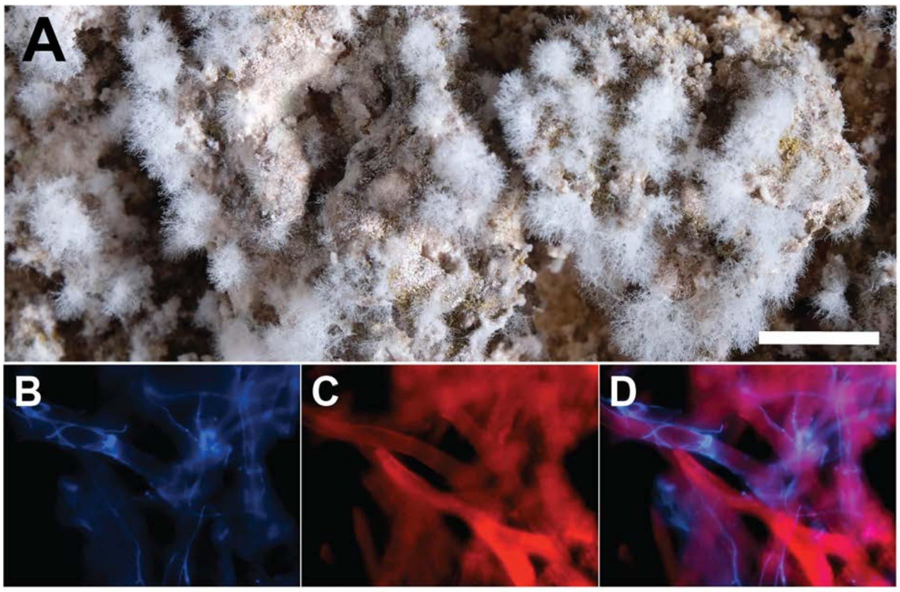

Figure 10. Gross and microscopic examination of fluffy moonmilk. A) Gross appearence of moonmilk with the fluffy tufts of material that are not normally associated with this formation (scale bar = 1 cm). **B - D)** Fluorescence microscopy of a tuft isolated from **A**. **B** is stained with the blue/white fungal-specific dye calcofluor; **C** is the autofluorescence of the same material - such autofluorescence is characteristic of calcite. **D)** Composite image of **B** and **C**, showing how the fungal material wraps around the calcite crystals.

White patina (Figures 11 and 12)

The Mulu caves are covered in a white patina that generates a gray hue to many of the surfaces (Figure 11A). This material is caused by microbial growth, which covers the rock in areas of high-moisture (Figure 11). As in other caves, this growth is driven by surface water percolating into the cave that contains high levels of dissolved organic carbon [14, 32, 35]. As microbial growth on $CaCO_3$ requires that these species deal with Ca^{2+} ion toxicity, they remove the excess ion by trapping it as insoluble calcite using atmospheric CO_2 as a source of the CO_3^{2-} ion [9]. The result is the precipitation of calcite over the microbial colonies (Figure 11B), which entombs them and gives them a white appearance [35]. As entombment causes cell death, the microorganisms are continuously attempting to outgrow this entombment, escaping from the edges of the colony, which is particularly obvious against dark surfaces in the cave (Figures 11

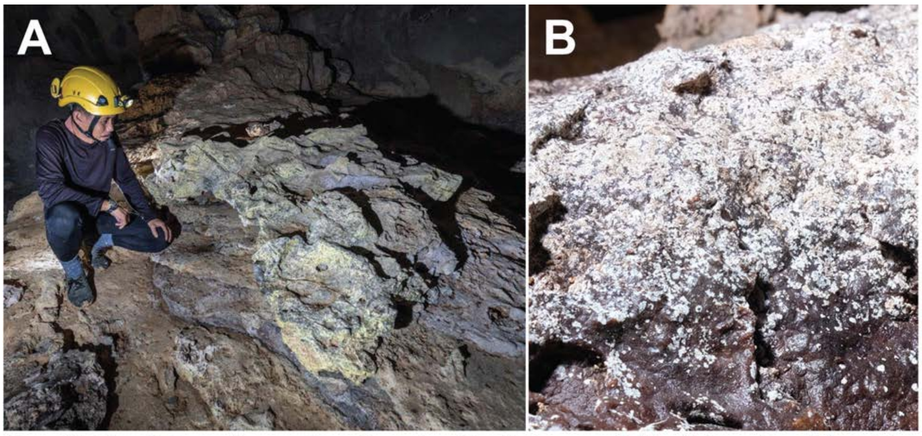

Figure 11. Microbial growth on surfaces throughout the Mulu caves. A) Microbial growth on high-moisture surfaces creates a white patina that gives many surfaces within the caves a grayish hue. **B)** A close up of microbial growth demonstrates how individual microbial colonies merge together to cover surfaces (Photo in A by Chris Howes).

and 12) [9, 35]. While molecular phylogenetic work will have to be carried out to determine the identity of these microorganisms, color, morphology and odor suggest that the colonies are dominated by members of the actinobacteria [35].

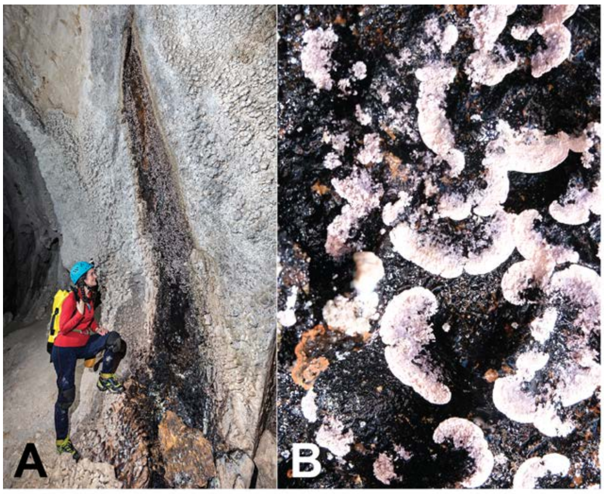

Figure 12. Actinobacterial colonies in Clearwater Cave. A) A crack in the bedrock allows organic carbon-rich water to enter the cave, which promotes microbial growth. Due to the complex chemistry of this organic carbon, microbial communities dominated by members of the Actinobacteria, which can break it down, are dominant. **B)** The dark patina of the rock makes the calcification of these colonies more obvious, with a radiating pattern following both the molecular flow of water and the growth of the microbial colony escaping entombment in calcite.

Bird guano microbiology (Figure 13)

The last microbial phenomenon we observed throughout the caves was related to the rock and rope-eating bird guano. There has been almost no work examining the impact of bird guano on stone, other than the effects of pigeon guano on masonry and concrete [36-38]; bird guano is mildly acidic from the presence of uric and phosphoric acids, with a pH that can vary from 5 - 7 (depending on the diet of the bird) and when fresh (<2 weeks) can etch stone [38-40]. The destructive activity of bird guano is extended if the guano is kept moist, which is likely in the high humidity environment of the caves (>99% relative humidity), and by sheer volume [36]. Nonetheless, the presence of high organic carbon and uric acid within the guano is likely to drive high levels of microbial activity, and much more is known about the ability of microorganism to produce acids that are able to damage stone [40-44]. In particular, the high concentration of uric acid, which is also generated as a by-product of purine catabolism in bacteria, allows the breakdown of uric acid into ammonia (via the 5-hyroxyisourate/allantoin pathway) and is a conserved pathway, both in bacterial species found in the bird cecum and cave environments [45-47]. The generated ammonia is then oxidized by ammonia-oxidizing bacteria and archaea into nitrite, which is in turn oxidized into nitric acid by members of the *Nitrobacter* [43]. These reactions have been linked to microbial activity in the past, which has been shown to damage marble and limestone monuments, and cement structures, such as bridges [43, 48]. As erosion surfaces start to form in the limestone, the guano begins to accumulate and dissolution becomes more directed, forming a pocket of material (Figure 13A). As the pocket becomes deeper, it allows the formation of anaerobic conditions in the guano, which can allow a full nitrogen cycle to develop and potentially accelerate nitric acid production [49, 50]. As these pockets continue to get deeper, the start to leave behind spires of

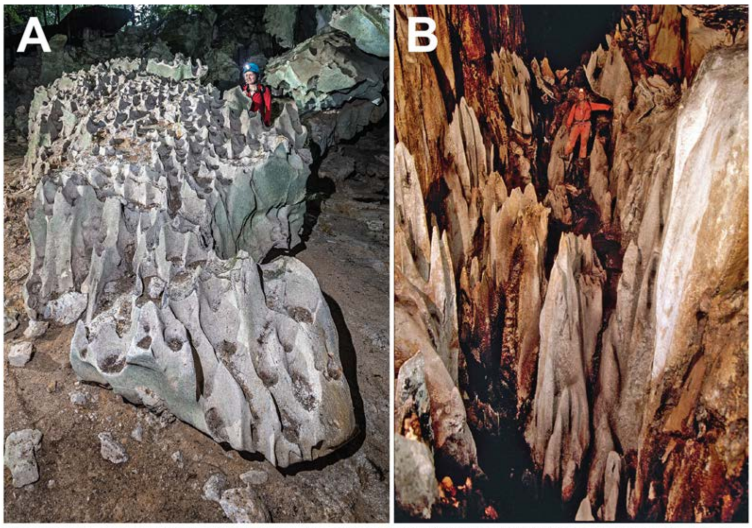

Figure 12. The impact of bird guano on rock surfaces within the Mulu caves. A) Initially, bird guano starts to accumulate on surfaces, creating pockets where the material begins to accumulate. Over time, these pockets allow much deeper deposits of guano to form, potentially speeding up nitric acid production, evenntually creating very deep pockets that leave spires of bedrock behind **(B)**.(Photo in A by Chris Howes).

unimpacted rock (Figure 13B). While there is currently no data to support this theory in the caves of Gunung Mulu, the production of the much more aggressive nitric acid could be responsible for both the aggressive rock dissolution observed, and the chemical damage to the nylon ropes exposed to these guano-covered surfaces (Figure 13).

DISCUSSION

Past expedition reports suggested a number of other unusual speleothems are found within the caves of Gunung Mulu National Park (Figure 1). We examined these deposits, along with a number of other features during the Mulu 2019 expedition, for a potential role for microorganisms in their deposition. Our results suggest that there is a strong biogenic component in a number of these formations, while the field activities allowed us to identify others that have previously been overlooked.

Phytokarst: Examination of phytokarst suggests a strong biogenic component in their formation, and our data forms the basis of a testable model. The taxonomy of the biofilm communities at the erosion surface needs to be examined, to confirm the identity of the cyanobacteria and, based on the presence of other members of the microbial consortia, provide clues as to the metabolic interactions occurring [14]. It is also important to identifying the photopigments present, which may help determine the photosynthetic strategies, and why there seems to be an enrichment for this formation in the twilight zone. Finally, infrared and Raman spectroscopy may allow us to identify specific organic acids present, and indicate the metabolic activities that are forming the erosion surface [14, 15]. While these data may help us understand why dissolution is so aggressive in the formation of phytokarst, it does not explain why phytokarst is so rare in cave entrances. It is possible that additional factors, such as the high humidity of the tropical environment, play a role in formation (for example, preventing the cyanobacterial biofilms from drying out) and these factors also need to be identified.

Phytokarren: Our observations confirm those of other investigators that there is a strong biogenic component to the formation of phytokarren, and that their formation in tropical environments is due to the need to limit evaporation for calcification, as well as the potential requirement for roots. It is therefore worth investigating what percentage of phytokarren form with guiding roots, and whether these are essential to development. Given the depositional role of photosynthesis-driven calcification in their formation, we propose that rather than the use of the term phytokarren, which is indicative of dissolutional processes, these formations are renamed phytogen to indicate the both the role of plants in their formation (*phyto*), and their depositional nature (*-gen*).

Fluffy moonmilk: Moonmilk is fairly common in caves; however, it has not been extensively documented in tropical cave environments, suggesting that there is something unusual about the Mulu cave conditions. Of particular note in the Clearwater Cave deposits is the fluffy surface of the moonmilk, which has not been previously described. Microscopic analysis suggests that these ‘fluffs’ are microcrystalline calcite, covered in fungi; we see central canals within the calcite, but are unable to stain them due to the inability of these stains to penetrate the calcite. It is therefore unclear as to whether this calcification is directly forming over existing microbial growth; cultivation will therefore be required to determine whether microorganisms are involved. Nonetheless, there is very obviously fungi on the outside of these ‘fluffs’, which may stabilize their structure. Such fungal growth in caves is fairly uncommon, and is generally powered by significant organic carbon inputs, why may indicate that high organic carbon input into these caves plays a role.

White patina - In addition to possibly driving unusual moonmilk formation, the significant amount of organic carbon input appears to be driving microbial growth on a number of surfaces - this growth is not so apparent deeper into the caves, where swift guano dominates many of the observable surfaces. Actinobacteria are important members of microbial communities, both in the soil and caves, where they break down complex soil organic carbon into more oxidized carbon, which can be utilized by other species. The actinobacteria are also important as they produce geosmins, which give caves their earthy smell, and are a major source of secondary metabolites, including a number of clinically important antibiotics (over 99% of antibiotics in medical use are natural products derived from microorganisms). The vast actinobacterial communities within the Gunung Mulu National Park caves are therefore an important source for potentially novel species and secondary metabolites.

Bat guano microbiology - At first, we didn't pay much attention to the swift guano that covers almost every surface in the caves, but in retrospect there was a clear relationship between aggressive rock dissolution and the presence of guano. It took a while to realize the significance of this phenomenon, and it was too late to collect geologic samples to examine mineralogical transformations that might be taking place at the guano-rock interface. Nonetheless, this interaction is possibly the most interesting microbiology in all the caves; if the nitric acid is responsible for the dissolution observed, this will be the first ever description for the role of nitric acid in cave passage remodeling. While the microbiology of this is interesting enough, it could also explain the susceptibility of ropes to the guano - nylon is sensitive to quite low concentrations of nitric acid. The ability of these microbial communities to carry out the pathways to convert chemically inert polymers back into their monomeric form is potentially exciting for a green recycling approach. Nonetheless, these chemistries in guano have not been tested, and it still needs to be reconciled as to how such chemistry could damage polypropylene ropes.

CONCLUSION

The results presented here where the result of a short, field excursion in the caves of Gunung Mulu National Park, where samples were only collected for mineralogical analysis. Nonetheless, the suggest that several unusual features within the cave are likely formed through the influence of really interesting microbial activity, and that more extensive microbiological studies are warranted within the Mulu caves.

ACKNOWLEDGEMENTS

The authors would like to thank Rambli Ahmad, Derek Bristol, and Andy Eavis for their field assistance. Additional photographs were provided by Hazel Barton, Derek Bristol and Dave Bunnell. We would like to thank the Gunung Mulu National Park staff, especially Veno and Jimmy, for their assistance in reaching the caves.

REFERENCES

1. Brook, D. and A.C. Waltham, *The underworld of Mulu, part 1.* Caving International, 1978. **1**: p. 3-6.
2. Brook, D. and A.C. Waltham, *The underworld of Mulu, part 2.* Caving International, 1979. **2**: p. 3-6.
3. Laverty, M., *A note on directed phytokarst in Sarawak (E. Malaysia).* International Journal of Speleology, 1981. **11**: p. 203-206.

4. Folk, R.L., H.H. Roberts, and C.H. Moore, *Black phytokarst from Hell, Cayman Islands, British West Indies.* Geological Society of America Bulletin, 1973. **84**(7): p. 2351-2360.
5. Philip, D. and M.R. Cilian, *The Fertile Rock: Productivity and erosion in limestone solution hollows of the Burren, Co. Clare.* Biology and Environment: Proceedings of the Royal Irish Academy, 2018. **118B**(1): p. 1-12.
6. Veress, M., *The KARREN and KARREN formation of bare slopes.* Earth-science reviews, 2018.
7. Montgomery, B.L., S. Lechno-Yossef, and C.A. Kerfeld, *Interrelated modules in cyanobacterial photosynthesis: the carbon-concentrating mechanism, photorespiration, and light perception.* Journal of Experimental Botany, 2016. **67**: p. 2931-2940.
8. Bullen, H.A., et al., *Use of Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy to Identify Microbial Metabolic Products on Carbonate Mineral Surfaces.* App. Environ. Microbiol., 2008. **74**: p. 4553-4559.
9. Banks, E.D., et al., *Bacterial Calcium Carbonate Precipitation in Cave Environments: A Function of Calcium Homeostasis.* Geomicrobiology Journal, 2010. **27**: p. 444-454.
10. Pathak, J., et al., *Chapter 7 - Mechanisms of Photoprotection in Cyanobacteria*, in *Cyanobacteria*, A.K. Mishra, D.N. Tiwari, and A.N. Rai, Editors. 2019, Academic Press. p. 145-171.
11. Schneider, J. and T. Le Campion-Alsumard, *Construction and destruction of carbonates by marine and freshwater cyanobacteria.* European Journal of Phycology, 1999. **34**: p. 417-426.
12. Vanara, N. and R. Maire, *Genesis of phototropic biospeleothems in Guizhou (China): occurrence of biocorrosion, microphantomization and algal precipitation.* Geologica Belgica, 2006. **9**(3-4): p. 337-347.
13. Hill, C.A. and P. Forti, *Cave Minerals of the World*. 2nd ed. 1997, Huntsville, AL: National Speleological Society.
14. Barton, H.A. and D.E. Northup, *Geomicrobiology in Cave Environments: Past, Current and Future Prospectives.* J. Cave Karst Stud, 2007. **69**: p. 163-178.
15. Behrendt, L., et al., *Life in the dark: Far-red absorbing cyanobacteria extend photic zones deep into terrestrial caves.* Environmental Microbiology, 2019. **Submitted**.
16. Eisenhut, M., et al., *The photorespiratory glycolate metabolism is essential for cyanobacterial and might have been conveyed endosymbiotically to plants.* Proceedings of the National Academy of Sciences USA, 2008. **105**: p. 17199-17204.
17. Viles, H.A., *Biokarst: review and prospect.* Progress in Physical Geography: Earth and Environment, 1984. **8**(4): p. 523-542.
18. Taboroši, D., K. Hirakawa, and T. Sawagaki, *Carbonate precipitation along a microclimatic gradient in a Thailand cave—continuum of calcareous tufa and speleothems.* Journal of Cave and Karst Studies, 2005. **67**(1): p. 69-87.
19. Dodge-Wan, D., *Elongated tufaceous stalagmites in the entrance of Batu Cave (Selangor, Malaysia).* Carbonates and Evaporites, 2015. **30**(4): p. 401-416.
20. Taboroši, D., *Biologically influenced carbonate speleothems*, in *Perspectives on Karst Geomorphology, Hydrology, and Geochemistry - A Tribute Volume to Derek C. Ford and William B. White*, R.S. Harmon and C.M. Wicks, Editors. 2006, Geological Society of America. p. 0.
21. Nichols, H.W., *Nitrates in cave earths.* The Journal of Geology, 1901. **9**: p. 236-243.
22. Des Marais, D.J., et al., *The carbon-isotope biogeochemistry of the individual hydrocarbons in bat guano and the ecology of insectivorous bats in the region of Carlsbad, New Mexico.* Geochimica et Cosmochimica Acta, 1980. **44**: p. 2075-2086.
23. Liu, Y., et al., *Global phosphorus flows and environmental impacts from a consumption perspective.* Journal of Industrial Ecology, 2008. **12**: p. 229-247.

24. Fliermans, C. and E. Schmidt, *Nitrobacter in Mammoth Cave. .* International Journal of Speleology, 1977. **9**: p. 1-19.
25. Francis, C.A., J.M. Beman, and M.M. Kuypers, *New processes and players in the nitrogen cycle: the microbial ecology of anaerobic and archaeal ammonia oxidation.* The ISME journal, 2007. **1**: p. 1-19.
26. Zhao, R., et al., *Ammonia-oxidizing archaea dominate ammonia-oxidizing communities within alkaline cave sediments. .* Geomicrobiology Journal, 2017. **34**: p. 511-523.
27. Pace, N.R., *Caves and saltpetre.* Caving in the Rockies, 1971. **13**(6): p. 7-9.
28. Hill, C.A., *Mineralogy of Cave Nitrates.* NSS Bulletin, 1981. **43**: p. 127-132.
29. Høeg, O.A., *Cyanophyceae and bacteria in calcareous sediments in the interior of limestone caves in Nord-Rana, Norway.* Nytt Magazin for Naturvidenskapene, 1946. **85**: p. 99-104.
30. Cañaveras, J.C., et al., *On the origin of fiber calcite crystals in moonmilk deposits.* Naturwissenschaften, 2006. **93**(1): p. 27-32.
31. Maciejewska, M., et al., *Assessment of the Potential Role of Streptomyces in Cave Moonmilk Formation.* Frontiers in Microbiology, 2017. **8**: p. 1181.
32. Barton, H.A. and V. Jurado, *What's Up Down There: Microbial Diversity in Starved Cave Environments.* Microbe, 2007.
33. Maciejewska, M., et al., *A phenotypic and genotypic analysis of the antimicrobial potential of cultivable Streptomyces isolated from cave moonmilk deposits.* Frontiers in microbiology, 2016. **7**: p. 1455.
34. Maciejewska, M., et al., *High-throughput sequencing analysis of the actinobacterial spatial diversity in moonmilk deposits.* Antibiotics, 2018. **7**(2): p. 27.
35. Barton, H.A., *Introduction to Cave Microbiology: A Review for the Non-Specialist.* J. Cave Karst Stud, 2006. **68**: p. 43-54.
36. Spennemann, D.H.R., M. Pike, and M.J. Watson, *Behavior of fresh pigeon excreta on masonary surfaces.* Restoration of Buildings and Monuments, 2017. **23**: p. 15-28.
37. Wei, S., et al., *Microbiologically induced biodeterioration of concrete: A review.* Brazilian Journal of Microbology, 2013. **44**: p. 1001-1007.
38. Spennemann, D.H.R. and M.J. Watson, *Dietary habits of urban pigeons (Columba livia) and implications of excreta pH - a review.* European Journal of Ecology, 2017. **3**: p. 27-41.
39. Folk, R.L., *Uric acid: The main nitrogenous excretory product of birds.* Science, 1970. **170**: p. 98-99.
40. Fernandes, P., *Applied microbiology and biotechnology in the conservation of stone cultural heritage materials.* Applied Microbiology and Biotechnology, 2006. **73**: p. 291-296.
41. Bock, E., et al., *Biologically induced corrosion of natural stones - strong contamination of monuments with nitrifying organisms.*, in *Biodeterioration*, D.R. Houghton, R.N. Smith, and H.O.W. Eggins, Editors. 1988, Elsevier Applied Science: New York, NY. p. 436-440.
42. McNamara, C.J. and R. Mitchell, *Microbial deterioration of historic stone.* Frontiers in Ecology and the Environment, 2005. **3**(8): p. 445-451.
43. Sand, W. and E. Bock, *Biodeterioration of mineral materials by microorganisms—biogenic sulfuric and nitric acid corrosion of concrete and natural stone.* Geomicrobiology Journal, 1991. **9**(2-3): p. 129-138.
44. Warscheid, T., T.W. Becker, and M.A. Resende, *Biodeterioration of stone: a comparison between (sub-)tropical and moderate climate zones.* International Biodeterioration & Biodegradation, 1996. **37**(1): p. 124.
45. Hafez, R.M., T.M. Abdel-Rahman, and R.M. Naguib, *Uric acid in plants and microorganisms: Biological applications and genetics - A review.* Journal of Advanced Research, 2017. **8**(5): p. 475-486.

46. Hu, Y., et al., *Herbivorous turtle ants obtain essential nutrients from a conserved nitrogen-recycling gut microbiome.* Nature Communications, 2018. **9**(1): p. 964.
47. Hershey, O.S. and H.A. Barton, *The Microbial Diversity of Caves*, in *Cave Ecology*. 2018, Springer. p. 69-90.
48. Warscheid, T. and J. Braams, *Biodeterioration of stone: a review.* International Biodeterioration & Biodegradation, 2000. **46**(4): p. 343-368.
49. Francis, C.A., J.M. Beman, and M.M.M. Kuypers, *New processes and players in the nitrogen cycle: the microbial ecology of anaerobic and archaeal ammonia oxidation.* The ISME Journal, 2007. **1**(1): p. 19-27.
50. Jetten, M.S.M., *The microbial nitrogen cycle.* Environmental Microbiology, 2008. **10**(11): p. 2903-2909.

the MULU Caves Project

www.mulucaves.org

Front cover: Golden Showers, Revival, Clearwater Cave - photo Carsten Peter
Rear cover: Clearwater river passage - photo Chris Howes
Cover design by Hugh St.Lawrence