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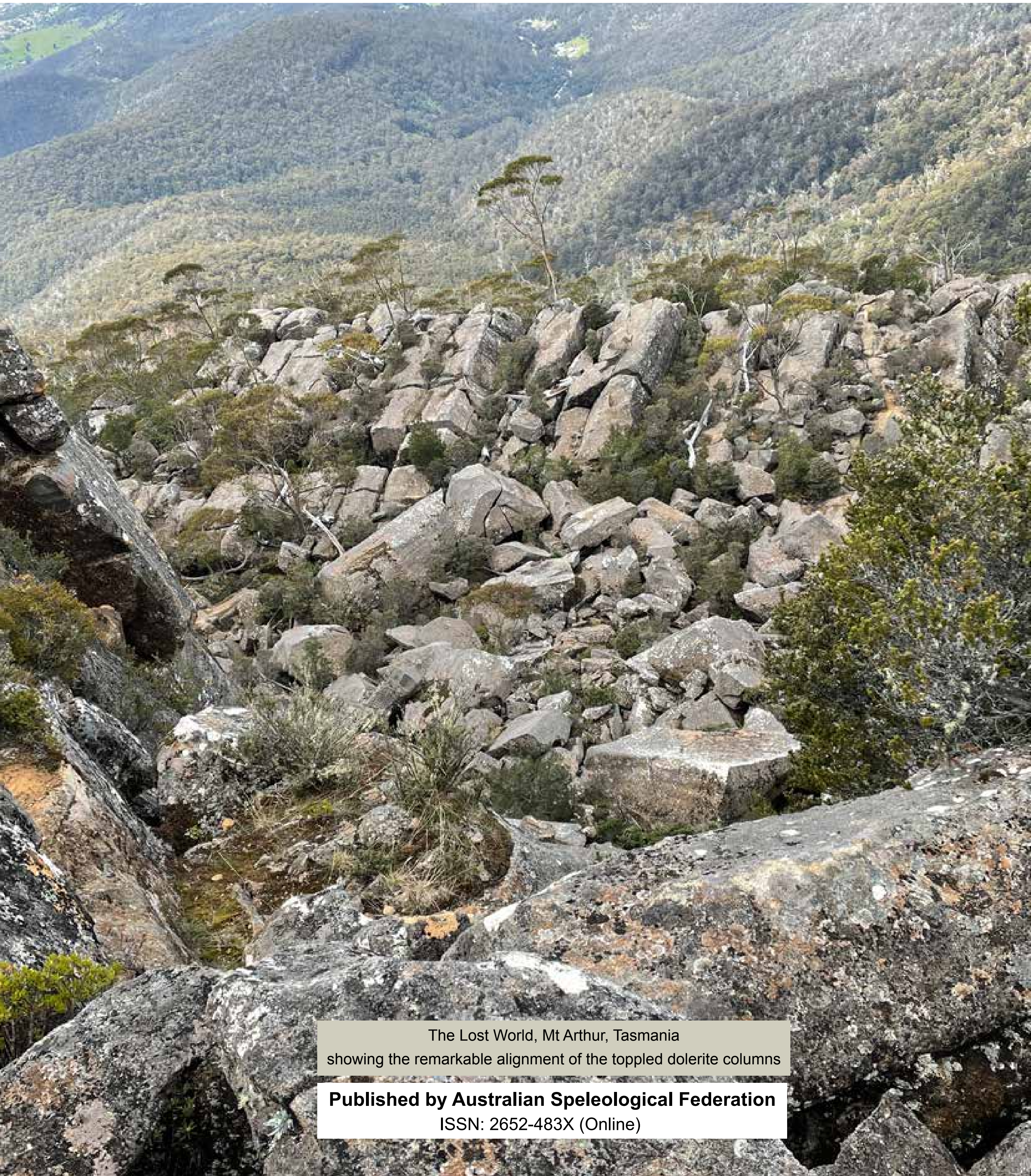

The Lost World, Mt Arthur, Tasmania
showing the remarkable alignment of the toppled dolerite columns

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Helictite was established in 1962 by its foundation editors, Edward A. Lane and Aola M. Richards. It is intended to be wide ranging in scope from the scientific study of caves and their contents, to the history of caves and cave areas and the technical aspects of cave study and exploration. The territory covered is Australasia – Australia, New Zealand, the near Pacific Islands, Papua New Guinea and surrounding areas, Indonesia and Borneo.

In 1974 the Speleological Research Council agreed to support the Journal with financial assistance and in 1976 took over full responsibility for its production. From 1974 to 1997 the Journal was edited by Julia James assisted by other members of the Speleological Research Council Ltd. In 1998 Susan White and Ken Grimes took over as editors with Glenn Baddeley as Business Manager. Stefan Eberhard joined the editorial team in 2003.

In 2000 ownership was transferred to the Australian Speleological Federation, Inc. (ASF) and the Journal is administered by the Helictite Commission of the ASF.

Greg Middleton took over as Chief Editor in 2016. The accidental death of Ken Grimes in August 2016 led to further changes in editors, with Tim Moulds and Kevin Kiernan taking on the role.

The aim of the Helictite Commission of the Australian Speleological Federation is to publish the results of scientific studies in all fields of speleology in *Helictite – Journal of Australasian Speleological Research*.

Helictite in Digital Format

From 2017 Helictite is being published in digital format only. Papers are published online, and are freely available to all. There is no subscription fee – the ongoing costs of production and archiving are borne by the Australian Speleological Federation.

Submitted papers will still be reviewed and edited as before, but the layout may be varied to suit a digital format. Each paper will be published on line as it is ready as part of what is intended to be an annual volume. Intending authors should read the latest 'Information for Contributors' on the Helictite website.

Helictite web site

The Helictite web site is part of the parent ASF site. The URL is: http://helictite.caves.org.au

The web site is maintained by Business Manager, Glenn Baddeley. It provides contact details, information for contributors, contents, abstracts and complete PDF versions of all papers ever published in *Helictite* (i.e. since 1962).

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Cover: The Lost World, Mt Arthur, Tasmania
showing the remarkable alignment of the toppled dolerite columns, beneath which lie a system of boulder caves reported on in this issue by McNab. Photo: G. Middleton

Helictite, Volume 46, 2021 consists of a single issue.

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Editorial

Greg Middleton

Welcome to *Helictite*, Volume 46 for 2021. Unfortunately, due to the widespread disturbances caused by the Covid-19 pandemic, no issue of *Helictite* was able to be published in 2020. Despite on-going disruption of many of our activities, we are pleased to resume production of the journal in 2021.

First off, Tiah Bampton of the University of Adelaide uses studies being undertaken at Naracorte Caves World Heritage Area in South Australia to describe the various palaeoenvironmental proxies being used to reconstruct the conditions experienced in that region during the Quaternary. Thanks to the detailed on-going studies of the faunal records of these well-stratified caves and the refined chronology and dating techniques being employed, Naracoorte Caves are providing invaluable insights into the changes in climate and biota of South-Eastern Australia during the Quaternary.

Kevin Kiernan has carried out extensive fieldwork, especially in South-East Asia, on the range of deleterious impacts, both direct and indirect, which war and related military activities can have on caves and the karst areas that contain them. He also notes examples from earlier times in Europe and America. International humanitarian law has been the main vehicle used to deal with problems arising from conflict but greater recognition of the need to control direct environmental impacts are called for.

The paper by University of Tasmania geomorphology student Sarah McNab sheds new light on the geoconservation significance of boulder caves located at Lost World at Mt Arthur in the Wellington Park near Hobart. These caves have been subject to few detailed investigations and their importance from a geoconservation standpoint appears to have been underappreciated. Although superficially robust, elements of these boulder caves can be as sensitive to negative impacts as other caves and more deliberative and directed management is justified.

Finally, we are saddened to record the passing of a stalwart of speleological investigations in the Macleay Valley region of northern New South Wales, Dr Philip Holberton (1935-2020). Straight after moving to the Macleay region in 1969, Philip took an interest in caves and joined the Kempsey Speleological Society. He became the group's secretary in 1983 and held the position until 2020. He was widely known as editor of the regular KSS newsletter, *Trog*, which reliably documented the group's activities. Philip will be sadly missed.

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Palaeoenvironmental proxies used to reconstruct the Quaternary of Australia: a case study from Naracoorte Caves, South Australia

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Abstract

Understanding environmental changes through time gives insight into past faunal community change and possible explanations for extinctions. Australia has a rich climate history that has been studied using multiple proxies including both marine and terrestrial records. The Naracoorte Caves World Heritage Area contains sedimentary and fossil records within well stratified sequences, which span the last 500,000 years. Stable isotope analysis of biogenic material, such as mammalian tooth material, has become a globally recognised proxy for the purpose of palaeoenvironmental reconstructions. With refined chronology and dating techniques, stable isotope analysis at the Naracoorte Caves has the potential to provide a palaeoenvironmental record through the Quaternary. Comparing this record with changes in biodiversity through time allows for improved reconstruction of the palaeoecology of local vertebrate faunas. This in turn allows for the elucidation of extinction events that have occurred and their possible links to changes in the environment.

Key words: Naracoorte Caves, Quaternary, Palaeoenvironmental proxies, stable isotopes, palaeoecology, caves

Introduction

The study of Quaternary palaeoenvironments is important for understanding long-term patterns of climate change and drivers of faunal responses to change. Importantly, palaeoenvironmental reconstructions provide a comparative context for modern climate change and its influence on fauna (Fordham and others, 2020). Australia is the driest inhabited continent in the world and its Quaternary deposits have yielded a dynamic record of past climate change (Bird and others, 2016). Shifts in environment over time have driven evolutionary changes in native fauna and flora which have led to the specialisation seen today (Tedford and others, 2006).

The Quaternary spans the last 2.6 million years and is divided into two epochs, the Pleistocene (approximately 2.6 Ma to 11.7 ka) and the Holocene (approx. 11.7 ka to present day). Reconstruction of the environments of the Pleistocene and the Holocene not only improves understanding of past climatic and evolutionary events, but also modern changes in the environment (Forbes and others, 2007). Such study requires data from fossil sites with fine-scale chrono-stratigraphic resolution, and preservation of materials that serve as proxies for palaeoenvironmental variables. Caves act as natural collectors of organic and inorganic material and preserve deep sedimentary records representing long periods of time (Reed, 2012). Cave deposits, such as those preserved at the Naracoorte Caves World Heritage Area (NCWHA) in south-eastern South Australia (Figure 1), provide 'time capsules' of information on the diversity and distribution of mammal communities over the past 500,000 years (Macken and others, 2011; Macken & Reed, 2013). When paired with climate and geochronological analysis, these faunal records have the potential to resolve the palaeoecology of these communities, including the causation and timing of both past and historical extinctions and their drivers (Reed & Bourne, 2000; Macken & Reed, 2013).

During the Pleistocene, around 46 ka, Australia and New Guinea lost approximately 60 species of mammals, birds and reptiles, mostly of body masses greater than 40 kg (Johnson, 2005). The cause of these extinctions has created great debate amongst scientists for over a century (Johnson, 2005; Wroe & Field, 2006; Saltré and others, 2016). There are three main hypotheses for the cause of these extinctions: overhunting by humans, modification of habitat due to changes in fire regime (argued by some to have been driven by humans) and changes in climate (Roberts and others, 2001; Trueman and others, 2005). More recently, another major extinction event occurred, following European settlement. Today, approximately one third of

Figure 1. Finely bedded sediment section of the Blanche Cave excavation site, Naracoorte Caves World Heritage Area. Photo Steve Bourne

the pre-European native mammalian biodiversity of Australia has become extinct or is at risk of extinction (Fusco and others, 2016).

This paper provides a broad overview of key approaches to using proxies for interpreting Quaternary palaeoenvironments. The Naracoorte Caves World Heritage Area is used as a case study to illustrate the application of some of these proxies and to highlight gaps in knowledge for this important locality.

Palaeoecology

Palaeoecological research has given insight into the taxonomy and biodiversity of both living and extinct species, as well as changes in the climate of south-eastern Australia during the Quaternary (Macken and others, 2013; Grealy and others, 2016). However, there is a lack of high resolution data on the palaeoecology of vertebrate faunas through time in relation to changes in climate and habitat (Hocknull and others, 2007; Fraser & Wells, 2010). Palaeoecology is the study of fossilised remains of organisms and the interactions they have with other organisms and/or the environment in which they live (Brenchley, 1998). This type of study relies on the involvement of a number of scientific disciplines including but not limited to; palaeontology, taxonomy, geochemistry, geology, palaeobiology and palaeoclimatology (Brenchley, 1998; Twitchett, 2006). Combining these disciplines enables a reconstruction to be made of past ecosystems and the communities within them, and the influences of climate on the environment. This is an important tool in the study of life habits of now extinct fauna. Many aspects of mass extinction events, including the extinction of Australia's megafauna, remain little understood and have been under-represented in the study of mass extinctions (Twitchett, 2006). Palaeoecology studies of the Quaternary can aid in the understanding of decline in taxa through time and provide critical information for ecosystem restoration and recovery in the present day biodiversity crisis (Birks, 1996; Huntley, 1996). This allows for better understanding of natural variability within communities in response to changes over long time periods (Macken & Reed, 2014).

Overview of palaeoenvironmental proxies used in Quaternary research

Palaeoenvironmental studies have helped determine how Australia's ecosystems have been shaped and the driving forces that have shaped them. Australia contains a wide range of environments, including the constantly wet equatorial tropics, the seasonally wet monsoonal tropics, the arid interior, the semi-arid northwest, and the temperate south (Williams and others, 2009). These have remained largely unchanged throughout the Holocene (Anderson, 2007). Reconstructions of past climatic and environmental changes have traditionally been based on physical geological evidence that is stratigraphic in nature (Anderson, 2007). In recent decades, with the advances in technology and refinement of analytical techniques, more ways have been devised in which environmental changes can be reconstructed. These methods, outlined in the following sections, are all indirect measures of environmental and climatic change and are referred to as *proxies*. The use of a single proxy at a specific location only provides a limited range of information; therefore, the use of multiple proxies is recommended to obtain a comprehensive reconstruction of broader environmental changes (Mann, 2002; Anderson, 2007). To create a reliable reconstruction, the proxy needs to be chronologically authenticated with well-established dating techniques (Bowler and others, 1976; Steinman & Abbott, 2013; De Deckker and others, 2019).

Marine cores

Marine cores provide a record of deep sea sediment that is generally less disrupted than are terrestrial sediment records. This allows for a more complete history of climatic change to be reconstructed (Anderson, 2007). These records provide information on past sea surface temperature, ocean currents, sea level change and atmospheric concentrations related to climate variability. Deep sea sediment cores contain multiple proxies which can be analysed using a variety of techniques including analytical studies of both benthic and planktonic foraminifera, stable isotope ratios, aeolian dust content, fluvial sediments, pollen and charcoal (Harle, 1997; Cordova and others, 2009; De Deckker and others, 2019). Changes in marine records can be used to determine large scale change in global climate. Although marine cores remain less disrupted than those of terrestrial sediment records, the occurrence of reworked sediments, plant and microfossil materials may not be representative of past climate and vegetation. This, paired with the large amount of sample that is needed from the core, limits the validity of the reconstruction (Groot & Groot, 1966).

Lake records

Lake sediments are commonly used for the reconstruction of past environments and are analysed for their chemical and physical characteristics, as well as the biological remains that they contain. When compared with other terrestrial proxies, lake sediments provide a continuous record of sedimentation and environments through time (Anderson, 2007). Environmental changes are reflected in the biological, chemical and physical profile of the lake sediments, with data obtained via the use of sediment cores obtained from the lakebed. Sediment cores are typically analysed for changes in bulk density, organic content, isotopic signature and moisture content, which give insight into changes in past hydroclimatic conditions (Steinman and others, 2010). Limiting factors on this proxy are those related to the environment surrounding the lake and characteristics of the lake itself, which may influence the composition and the nature of the sediments that are collected (Anderson, 2007).

Sediment analysis

The analysis of sediments can be used in a wide range of sampling environments, including but not limited to: lakes, marine environments and caves. Modern sediment analyses incorporate a variety of approaches including stratigraphy, sedimentology, geochemistry, mineralogy, isotopic analysis and micro-morphology. Sedimentary analysis is a fundamental technique for identifying changes in environments and characterising the broader climate, from which a palaeoenvironmental reconstruction can be built (De Deckker and others, 2019). Understanding the origin of sediments via geochemical analysis, for example dust transport, can help elucidate factors such as palaeocirculation patterns and associated climate (Petherick and others, 2008). Analysis of minerals within the deposit can be used as indicators of depositional conditions. An example of this is gypsum, which can be indicative of the presence of water or bat guano in cave settings (Audra and others, 2019). There are other morphological analyses that can be conducted on individual sediment grains to estimate transport distance, via grain roundness, grain size and surface alterations, such as etching (Darrénougué and others, 2009). When pairing these characteristics with geochemical analysis of the sediments and the deposit, an interpretation of the origin and the depositional environment in which these materials were deposited can be made (Forbes & Bestland, 2007; Darrénougué and others, 2009). The rate of sediment accumulation varies according to depositional setting. For example, the low rate at which sediments are accumulated in deep ocean environments or differences in accumulation rate with change in cave entrance shape and size (Groot & Groot, 1966; Reed, 2008). Reworking of sedimentary sequences has implications for stratigraphic and chronological integrity and can limit the resolution for applications of this proxy (Hunt and others, 2015).

Palynology

As pollen has an outer wall (exine) composed of sporopollenin, it is relatively resistant to decay, creating the potential for fossil pollen embedded in sediment deposited in a variety of depositional environments including caves, lakes, and marine deposits (Groot & Groot, 1966; Cordova and others, 2009; Darrénougué and others, 2009). Due to the, at times, abundance of both pollen and spores in sedimentary records, they are valuable for quantitative and statistical analysis for palaeoenvironmental reconstructions. This allows for elucidation of evolution and change in the distribution of vegetation communities throughout the Quaternary (Kershaw and others, 1991). The percentage of plant types represented in a core can be used to estimate the vegetation coverage and hydrology through time. An example of this is the ratio of tree and shrub species to herbaceous species (Kershaw and others, 2007; De Deckker and others, 2019). Some species of spores present in the deposits can be used as a proxy for herbivore biomass present at that time (Van Der Kaars and others, 2017), such as *Sporormiella*, which can be used to determine the presence of megafauna in the Pleistocene (De Deckker and others, 2019; Perrotti & Asperen, 2019). Even where it is abundant, pollen offers a relatively low taxonomic resolution, making it difficult to identify pollen to species level, limiting the accuracy of vegetation reconstructions (Cordova and others, 2009). Other useful vegetation proxies include phytoliths, leaf waxes and macro plant remains.

Charcoal

Burnt macroscopic remains of plants, namely charcoal, can be used as an indicator of past vegetation diversity and occurrences of fire events through time (Cordova and others, 2009). Charcoal can be found in terrestrial, lacustrine and marine deposits. Like pollen, microscopic analysis of this material can be used to identify dominant plant types which can be indicative not only of vegetation presence, but sometimes also distribution (Kershaw and others, 2007). The identification of fire events can be combined with other proxies, to help determine how vegetation communities have changed over time (Harle, 1997; Kershaw and others, 2007). Such information has been used to investigate the peopling of Australia (Harle, 1997; Kershaw and others, 2007), and might also yield information regarding the late Pleistocene megafaunal extinctions. Increased biomass burning due to human influence is one of the proposed hypotheses for the cause of this extinction event (Trueman and others, 2005; Roberts and others, 2019). However, the transportation of charcoal is usually over short distances, which limits its use to a local proxy of vegetation change rather than change on a larger scale (Cordova and others, 2009).

Speleothems

Speleothems provide high temporal resolution from which a reconstruction of terrestrial palaeoclimate, mainly precipitation, can be built (Bestland & Rennie, 2006). Secondary cave calcite deposits, such as speleothems (Figure 2), are the

Figure 2. Speleothem structures in Victoria Fossil Cave, Naracoorte Caves World Heritage Area. Photo Steve Bourne

result of chemical interactions between rainwater, carbon dioxide and limestone bedrock. Combined with uranium series dating, speleothems have been used to determine environmental change through Quaternary glacial cycles (Ayliffe & Veeh, 1988; Hellstrom & McCulloch, 2000; Bestland & Rennie, 2006). Other properties such as stable isotopes of oxygen and carbon, trace elements and humic substances, that cause colour differences and pronounced luminescent bands, can be used to explore aspects of environmental change (Desmarchelier and others, 2000; Bestland & Rennie, 2006; Smailer & White, 2013; Blyth and others, 2016). Speleothems provide important information on palaeoenvironments as they are not affected by post-depositional alteration, unlike some other climate proxies (Desmarchelier and others, 2000). However, speleothem growth is dependent on correlated environmental variables such as the quantity of infiltrated rainwater, presence of a carbon dioxide source and regional temperature (Ayliffe & Veeh, 1988; Ayliffe and others, 1998). Speleothem growth is favoured by wet, warm environments rather than dry, cold environments, in which there is little growth, which can cause hiatuses in the record (Ayliffe & Veeh, 1988).

Palaeontological Records

Studies into the habitats of extant fauna provide insight into the environmental niches they fill within modern communities (Moriarty and others, 2000; Hocknull and others, 2007; Fusco and others, 2016). The presence or absence of particular fauna within fossil deposits can be reflective of the environment and habitat at that particular time (Grün and others, 2001). A common outcome of the analysis of fossil material is an attempt at reconstruction of palaeoenvironments by analysing the dietary niche of preserved species, for example, the proportion of browsing fauna relative to grazing fauna (Price & Sobbe, 2005). As grazing fauna tend to inhabit open, grassy environments and browsing fauna, woodland to forest environments, the ratio of these two distinct classes of fauna can be indicative of the past landscape (Prideaux and others, 2009; Fraser & Wells, 2010; DeSantis and others, 2017). Features of mammalian dentition can also be used to indicate the diet of now-extinct species, providing an indicator of palaeo-habitat (Prideaux and others, 2009). This relies on the assumption that faunal communities fluctuate due to dietary preferences and food availability. Micro-abrasions or microwear on the enamel surface of teeth can be used to determine the likely dominant plant type eaten by a herbivore. Combining various types of analyses provides a sound basis for reconstruction of past habitats from mammal fossils. The reconstruction of the ecologies and dietary preferences of extinct fauna have traditionally been determined by taxonomic similarities to extant relatives, with the assumption of uniformitarianism of dietary preferences and ecologies, and dental morphology (Hopley and others, 2006). However, it has been established that extant species of close relation to extinct fauna do not always have similar dietary preferences or ecologies, and that dental morphologies can be a result of generalist adaptions rather than dietary behaviours (Hopley and others, 2006).

Stable isotope analysis of fossil vertebrate faunas

Stable isotope analysis of biogenic materials, such as bioapatite derived from tooth material, is a commonly used proxy for the reconstruction of environments and faunal ecologies of the past (Gehler and others, 2012; Barham and others, 2017). Stable isotopes have the potential for not only providing information on the diet and behavioural characteristics of animals, but also the environment in which these animals lived (Crawford and others, 2008). This type of analysis has been used to better understand individuals, populations and the broader ecosystems of present faunal communities (Crawford and others, 2008), and is also becoming an increasingly important tool in understanding the ecology of now-extinct species (Clementz, 2012). Different environmental and climatic settings, such as glacial and interglacial periods, provide a range of isotopic signatures. These signals are obtained and recorded in faunal materials through physiology, behaviour, dietary preferences and resource partitioning (Kohn & Cerling, 2002; Gehler and others, 2012). Stable isotope analysis of this material, such as bioapatite, is then used to infer drinking behaviour and dietary preferences, which in turn can be used to reconstruct environmental settings (Gehler and others, 2012). Stable isotopes, in contrast to other proxies, offer semi-quantitative palaeoecological and dietary preferences of extinct fauna, independent of morphological assumptions (Hopley and others, 2006; Clementz, 2012). In the past, the use of stable isotopes has predominantly focused on large mammalian material (Barham and others, 2017). A disadvantage of this is the wide range of environments that these animals migrate over, thus representing the environments they have moved through rather than the environment in which they died (Grimes and others, 2008). Large mammals are also relatively less abundant in fossil deposits, in comparison with small mammals

(Grimes and others, 2008; Gehler and others, 2012). Recent research addresses this limitation by focusing on abundant small mammal faunas which often provide a more representative record of past communities (Grimes and others, 2008; Gehler and others, 2012).

Applications of palaeoenvironmental proxies at Naracoorte Caves World Heritage Area

The vertebrate fossil deposits of the NCWHA span the last 500,000 years and provide insight into the climate and fauna of the south-eastern region of South Australia during the late Quaternary (Darrénougué and others, 2009). The study of fossil deposits, such as those found at the NCWHA, yield information about past faunal communities; including both living and extinct groups, taphonomic processes within caves and environmental changes through time (Reed, 2012; Macken & Reed, 2013; Grealy and others, 2016). This site is well known for its fossil record of megafauna. With refined chronology and investigation of palaeoenvironmental proxies, it has also contributed to research in vegetation and climate changes through time, as well as faunal community responses to these changes (Macken and others, 2011; Macken and others, 2012; Macken and others, 2013).

Sediment sequences in caves typically have a complex depositional history (Osborne, 1984; White, 2007; Hunt and others, 2015). Material such as fossils, pollen, charcoal and sediments are subject to erosional and depositional events that can cause unconformities, stratigraphic reversals, biases and changes in the lateral facies making reconstructions of past climate and faunal records difficult (Osborne, 1984; Forbes and others, 2007). The processes and accumulation mechanisms within cave environments can be further elucidated when studied across multiple sites within a locality (Osborne, 1984; Reed, 2008). The NCWHA contains multiple sites that contain finely resolved stratigraphy and chronology, whilst lying within close proximity to each other, collectively spanning 500,000 years (Reed, 2012; Reed, 2019). This provides the opportunity to study contemporaneous sites within a confined time frame and with different collection mechanisms. These factors improve understanding of inter-site variability and allow for the past climate and faunal communities to be verified and correlated through time (Macken and others, 2013; Macken & Reed, 2014; Reed, 2019). The abundance and high-level preservation of the fossils at Naracoorte, along with the presence of multiple palaeoenvironment proxies, gives the opportunity to explore the faunal community responses to change.

Climate record

Palaeoclimate studies conducted in the sites within the NCWHA, have applied a wide range of climate proxies. Records of middle to late Pleistocene glacial and interglacial climate cycles have been captured by proxies such as speleothem records (Ayliffe & Veeh, 1988; Ayliffe and others, 1998; Desmarchelier and others, 2000; Moriarty and others, 2000; Grün and others, 2001; Bestland & Rennie, 2006). There have also been investigations into the faunal assemblages in relation to climate (Brown & Wells, 2000; Prideaux and others, 2007; Fraser & Wells, 2010; Macken and others, 2012; Macken & Reed, 2014), as well as sedimentary and pollen analysis (Ayliffe and others, 1998; Desmarchelier and others, 2000; Forbes and others, 2007; Darrénougué and others, 2009; Macken and others, 2011; Macken and others, 2013).

Palaeoenvironment records from speleothems have revealed cycles of wet and dry phases over the Naracoorte record (Ayliffe and others, 1998; Desmarchelier and others, 2000; Prideaux and others, 2007). Ayliffe and others 1998 identified four major growth periods of speleothems during the last 500,000 years. The first occurred from 420 to 340 ka. Periods of active speleothem growth are commonly associated with an increase of effective precipitation, while hiatuses in growth are associated with a decrease in effective precipitation (Ayliffe and others, 1998).

The second growth period occurred between 300 and 270 ka. Vertebrate fauna records show a high diversity of large fauna, including megafauna species, during this time (Prideaux and others, 2007). Within this major growth period, at approximately 280 ka, there was a relatively high abundance of browsing fauna that supports the interpretation of a wetter climatic phase at this time (Prideaux and others, 2007). The second speleothem growth period was succeeded by a relatively dry period; evidenced by a hiatus in speleothem growth (Ayliffe and others, 1998). This relatively dry period lasted from approximately 270 ka to 220 ka, with peak interglacial conditions occurring around 240 ka. This dry period also saw a vegetation shift to grassland and open woodland environments at 230 ka (Prideaux and others, 2007), though it has been generally characterised as a heath dominated environment, based on species habitat preferences found in Cathedral Cave spanning this time-frame (Prideaux and others, 2007).

The third speleothem growth period, which lasted from 220 to 155 ka, contained the Penultimate Glaciation (195 to 128 ka) (Ayliffe & Veeh, 1988; Desmarchelier and others, 2000). This glacial period had both cold and dry conditions and local speleothem growth occurred at NCWHA. This growth was initiated in cold conditions with the dominance of herbaceous vegetation at 185 ka (Desmarchelier and others, 2000) and continued from 179 to 162 ka, where there was a period of active vegetation coverage dominated by woody taxa and temperatures similar to those of today (Desmarchelier and others, 2000; Bestland & Rennie, 2006). At approximately 157 ka there was a return to cooler conditions with herbaceous taxa dominance (Desmarchelier and others, 2000). The time preceding the Penultimate Glaciation saw a period of high temperature and low effective moisture availability, with no speleothem growth (Macken and others, 2011). At 125 ka there was a temperature peak between 1 and 3 °C warmer than today (Fraser & Wells, 2010; Macken and others, 2011). The co-existence of browsing and grazing herbivores, arboreal and heath dwelling mammals around 120 ka indicates the presence of open forest/ woodland environments leading up to the next speleothem growth phase (Brown & Wells, 2000).

Within the fourth speleothem growth phase, which occurred from 115 to 20 ka, there was some local change in climate at Naracoorte. From approximately 115 to 70 ka there was local speleothem growth (Ayliffe and others, 1998; Grün and others, 2001; Bestland & Rennie, 2006), indicating an increase in effective precipitation (Macken and others, 2011). This is supported by the increase in the relative abundance of a species (*Potorous tridactylus*) which is found in a high rainfall environment and the decrease of a species (*Perameles gunnii*) found today in grasslands around 80 to 70 ka from a fossil assemblage in Victoria Fossil Cave (VFC) (Macken and others, 2012). However also at this time, there is an increase of species that inhabit open heath vegetated environments that would indicate drying climatic conditions (Macken and others, 2012). There was a recorded hiatus in speleothem growth found in two chambers within VFC, that spans approximately 70 to 50 ka (Moriarty and others, 2000). From 50 to 20 ka there is a period of wetter conditions, with peaks in speleothem growth at 50 to 40, 31 and 23 ka (Ayliffe & Veeh, 1988; Ayliffe and others, 1998; Grün and others, 2001). This wetter event is supported by the presence of gypsum in the sedimentary sequence within Blanche Cave (Darrénougué and others, 2009). The pollen record also shows a wetter condition with the presence of woodland taxa at the expense of herbaceous and woody-herbaceous plants (Darrénougué and others, 2009; Macken and others, 2013; Macken & Reed, 2014). However, during this period there was a hiatus in the speleothem record, from 40 to 35 ka, showing a low effective moisture availability at this time (Ayliffe and others, 1998; Macken and others, 2013). The Last Glacial Maximum (LGM), 22 to 17 ka, showed a period of time where there was little to no speleothem growth, with the influx of rounded and polished quartz grains entering the caves (Ayliffe and others, 1998; Macken and others, 2013). The vegetation at the time was predominantly herbaceous (Darrénougué and others, 2009; Macken and others, 2013) with the exception of 20 ka when the percentage of woody taxa reached 90% (Darrénougué and others, 2009). After the LGM there was a return to wetter conditions with the increase of woody-herbaceous taxa, and the increase of effective moisture (Forbes and others, 2007; Darrénougué and others, 2009; Macken and others, 2013; Macken & Reed, 2014).

Palaeoecology

Due to the preservation of material within multiple, well-stratified sequences, the NCWHA deposits provide an opportunity to improve the relationship between faunal and palaeoenvironmental records. This can be used to determine the relationship between community changes and climate and understand the palaeoecology and possible cause of extinctions (Macken and others, 2011). Previous palaeocommunity studies at NCWHA have revealed fluctuations in the composition and relative abundances of species in response to changes in climate and environment in the Pleistocene (Prideaux and others, 2007; Fraser & Wells, 2010; Macken and others, 2012). However, the diversity at NCWHA was largely maintained prior to the megafaunal extinction (Prideaux and others, 2007; Macken & Reed, 2013). In the Cathedral Cave fossil assemblage there was a decline in large species during the 270 to 220 ka dry interval; however, they recovered later in the record prior to the megafaunal extinction (Prideaux and others, 2007). The Grant Hall fossil site (VFC) shows that there was no change in the total species richness with some variation in the relative abundance between species of differing ecologies, from 93 to 70 ka (Macken and others, 2012). Unlike the Cathedral Cave deposit, Grant Hall shows no decline in species richness of large mammals. However, there were species absent from Grant Hall that were present in Cathedral Cave, suggesting not all taxa are resilient at the same time or to the same extent across climatic and environmental change (Macken and others, 2012). The palaeoecology of small mammals of Wet and Blanche Caves showed that the palaeocommunity was stable through the early glaciation and LGM (Macken & Reed, 2014). However, there was variation in the species abundance during early glaciation and post-LGM deglaciation. There was also significant variation in species richness, leading to community reorganisation, during the early stages of post-LGM deglaciation due to reaching a threshold of climate change (Macken & Reed, 2014).

Palaeoecological analyses of now-extinct fauna and their responses to past climate are limited if only the inferred habitats and dietary niches of the species themselves are used as the primary palaeoenvironmental proxy (Hocknull and others, 2007). This is due in part to the taphonomic biases and the incomplete representation of communities in the fossil record (Grimes and others, 2008; DeSantis and others, 2017). There are also uncertainties regarding assumptions that extant fauna and their environmental tolerances have remained unchanged over time (Macken and others, 2012). Interpretation of dietary niche and habitat through stable isotope analysis provides a direct quantitative approach to understanding the relationship between fossil faunas and their environment.

Stable isotope analysis of fossil vertebrates at NCWHA

Studies of the stable isotopic composition of biological materials conducted in Australia include seasonal variations in present day kangaroo teeth of southern Australia (Brookman & Ambrose, 2012; Brookman & Ambrose, 2013), modern and fossil macropod tooth material from the northwest coast (Skippington and others, 2018), marsupial tooth enamel from Pliocene fauna deposits of south-eastern Queensland (Montanari and others, 2013), present day fauna and pre-contact human bone collagen studies of Roonka Flat archaeological site in South Australia (Pate, 1998), isotopic variation in Bare-nosed Wombat teeth from Tasmania (Roberts and others, 2019), fossilised fauna tooth enamel from Cuddie Springs in south-eastern Australia (DeSantis and others, 2017), isotopic and microwear analysis of macropod species tooth material in south-eastern Australia (Prideaux and others, 2009) and isotopic composition of land snails from Tight Entrance Cave in south-western Australia (Faith & O'Connell, 2011). As the NCWHA contains well stratified deposits that span a wide range of time (Figure 1), including glacial cycles, that are in association with multiple proxies and fossil material (Reed, 2019), the site has the potential of providing a near-continuous record of climate. However, the use of stable isotope analysis is yet to be fully explored in these deposits, despite it being a globally recognised proxy (Gehler and others, 2012). This field is the subject of current research by the author. Recent research using stable isotope analysis of rodent teeth from Blanche Cave revealed a shift in climate and vegetation during the LGM from drier to wetter conditions, with concurrent changes in the relative abundance of three species of *Pseudomys* (Bampton, 2018).

Utilising proxies such as isotope analysis of mammalian teeth has the potential of not only providing information on the environmental and vegetation changes through time, but to also elucidate the life habits and preferences made by the fauna present in those environments (Clementz, 2012; Gehler and others, 2012). Using traditional palaeontological techniques, such as morphological similarities to extant relatives or the association of the fossil in the sedimentary environment, to reconstruct the life habits and climates in which these animals lived can be problematic (Clementz, 2012). Fossils provide information on now-extinct animals through their palaeoecologies which can shed light on the cause of extinction (Reed & Gillieson, 2003). This information, paired with modern palaeontological, geological and ecological studies, gives opportunity to understand faunal response to climate and the life habits of now-extinct fauna. One of the species (*Pseudomys auritus*) in the current research by the author, became extinct soon after European arrival; consequently, little is known of its ecology (Prideaux and others, 2007). The use of stable isotopes indicated the dietary and habitat preference of this species during the last glacial cycle (Bampton, 2018). Understanding extinction events and their links to climate change and evolution is critical for the conservation of present day species that are currently under threat from human-driven extinction and changes in climate (Hocknull and others, 2007).

Conclusion

Palaeoenvironmental studies are important for understanding the climatic history of Australia and the corresponding biodiversity response. The NCWHA has an extensive faunal record that lies within well-stratified deposits that contain many palaeoenvironmental proxies. With refined chronology and dating techniques, this site holds the potential for improving understanding of changes in climate and fauna in south-eastern Australia during the Quaternary. Understanding fine scale changes in vegetation and water availability through glacial cycles can aid our understanding of changes in faunal communities, including megafauna, through time. Stable isotope analysis of biological materials, such as bioapatite derived from mammalian tooth material, has become a globally recognised proxy for reconstruction of palaeoenvironments and palaeoecology. This technique provides an opportunity to expand our knowledge of environmental change in south-eastern Australia during the Quaternary, and how fauna has been directly affected by these changes. Pairing this analysis with other established proxies, such as microwear, has the potential to provide insights into now-extinct species and their behaviour, dietary preferences and the habitats in which they lived. The stable isotopic composition of extinct megafaunal remains has the potential to improve understanding of the cause of these extinctions, by elucidating the palaeoecology of these animals. This information also provides a critical baseline for understanding recent extinctions and the impacts of present and future climate changes on faunal communities in their environments and how these communities may be conserved for the future.

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Some impacts of war on karst environments and caves

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Abstract

Humanitarian concerns generally predominate when the harmful effects of armed conflict are considered. However, armed conflict also typically implies considerable damage also being inflicted upon the environment. When the biology and physical landscapes around theatres of war are damaged, not only does that degrade natural environmental values, but it can often also compound the social and cultural impacts, due to the resulting disrupted supply of ecosystem services such as productive soils and healthy water supplies. Attempts to better protect the environment using the international laws of war generally continue to be founded upon international humanitarian law alone, but greater recognition of natural environmental values is warranted.

Karst environments have figured prominently in many past conflicts. Some consideration of the harms karstic battlefields have suffered, or to which they are likely vulnerable, might allow insights that could allow the possibility of better integrating karst into emerging legal protocols. Activities within caves during wartime represent only a relatively minor part of the damage that can be caused to caves and karst because wider interventions in natural process systems are caused by disturbance of the surface environment. Impacts generated during active combat are often also dwarfed by those that result from pre-conflict military preparations and from post-war circumstances that are initiated by wartime activities. The latter includes on-going degrading processes, such as continuing soil erosion originally triggered by combat-phase impacts. In the absence of specific research, potential harm caused to cave biota can only be estimated by analogy with the effects of war upon human health. Legal instruments available to better safeguard the environment during armed conflicts remain poorly developed, and they are also negated when potential military targets such as guerrilla bases are established within karst areas.

Key words: karst, geoheritage, sustainable development, weapons, war industries, bomb craters, refugees, unexploded remnants of war.

Introduction

Predictably, humanitarian concerns generally predominate when the harmful effects of armed conflict are considered, and when attempts are made to formulate improved international laws of war. In contrast, the considerable environmental harm caused by war receives very little consideration. Karst areas have consistently figured very prominently in armed conflicts worldwide, obvious examples including karsts in Cuba, Indochina, the Balkans and Timor Leste (Day & Kueny 2004). In part this has stemmed simply from the fact that limestone is a common rock type and hence it inevitably underlies many contentious areas. But more significantly, the physical characteristics of some karst landscapes, such as the presence of rugged inaccessible terrain and hidden caves, can make karst areas particularly useful as bases for guerrilla-style operations. The environmental damage this can cause is compounded when the presence of a base draws fire from opposing forces. Those same physical characteristics of rugged inaccessible terrain and natural shelter also make karst areas attractive as sanctuaries for non-combatants who are displaced by armed conflict, and environmental degradation may also be generated by refugee pressures. Adverse environmental outcomes are not confined to caves but can include serious soil degradation, damage to surface landforms and aquifer contamination that implies harm to both people and the natural environment. Because the sensitivity of many karst environments places them at particular risk, more consideration of the natural and cultural processes to which they are vulnerable in wartime is warranted, in order to formulate appropriate protective measures that might be incorporated into emerging environmental protocols, including the international laws of war.

Armed conflict inevitably causes environmental harm because the practitioners of war routinely employ, as their standard tools of trade, not merely the machetes, chainsaws and graders that typically attract the attention of environmentalists, but instead the most destructive explosive tools ever produced by humanity. They may also employ a wide range of other types of weapons that can include chemical and biological agents. It has recently been estimated that pollution from US military sources alone is greater than that from as many as 140 entire countries (Crawford 2019; Neimark and others 2019). Most conventional businesses in developed countries are required to pay some regard to the environmental consequences of their operations, or are subject to environmental impact assessment processes. In contrast, the mega-business of active armed conflict is invariably conducted free of any effective environmental constraints beyond whatever social or political pressures can be brought to bear to stem the worst excesses, such as nuclear strikes. For example, the US government insisted upon an exemption for military emissions before signing the 1997 Kyoto Protocol, even though it is the world's largest single institutional consumer of hydrocarbons (Neimark and others 2019). A recent wide-ranging review by Broomandi and others (2020) has shown the extent to which many potentially toxic elements, energetic compounds and chemical warfare agents have the capacity to contaminate virtually any area subject to military activity.

Notwithstanding the inevitability that the hugely powerful and environmentally unregulated enterprise of active conflict imposes a massive environmental footprint, it has received remarkably little attention by environmental researchers, including karst researchers. In part this is readily understandable given the immediacy of the social costs of war, the practical safety issues involved in conducting research fieldwork during actual combat, and also the risks that may be posed in the aftermath of conflict by UXO (UneXploded Ordnance), that is, ordnance that failed to detonate as intended, and ERW (Explosive Remnants of War), unexploded munitions left behind following the cessation of active conflict. Notwithstanding such difficulties, the magnitude of the harm caused by war to karst and other natural environments warrants much greater attention at both scientific and environmental policy levels (Machalis and others 2009).

Karst sensitivity

The gross physical architecture of caves can sometimes prove remarkably robust but the same cannot be said about many of the values that caves host and which contribute in a fundamental way to the importance of caves (IUCN 1997). Because karst landscapes are complex and integrated natural open systems composed of air, water, rock, soil, life and energy (Yuan 1988), attempting to achieve protective management of caves in isolation from the surrounding environment that sustains their values is a little like trying to manage the holes in Swiss cheese without also managing the cheese. Anthropogenic deforestation and soil erosion inevitably interferes with natural cave hydrogeochemistry including the processes of speleothem deposition. Speleothems can be damaged by changes to atmospheric conditions underground such as dehydration associated with enlargement of a cave entrance, and the potential exists for cave adapted-biota to be eliminated or genetic drift to occur if atmospheric contaminants on the surface are drawn underground by natural cave breathing. Pollution of surface or underground waters that flow through what are essentially natural pipes can result in contaminants being spread rapidly and in unexpected directions. The need to consider more than just the immediate locality is especially important when considering the impacts of war on karst, because fluvial or atmospheric carriage can spread some contaminants widely.

Determinants of the environmental damage caused by war include the nature of the activities undertaken, the intensity with which energy is applied, the materials utilised, particular military strategies, the environmental and other expertise employed and social factors including the environmental consciences of the practitioners of war. In the Dolomites of Italy some entire mountain summits were blown apart during World War I, many major rock-falls and collapses were triggered, and the mountains remain strewn with war-time debris (Figure 1) but other damage is more subtle.

Figure 1. Environmental damage remaining from World War I on a summit in the Dolomites, Italy.

Given the very limited study of the impacts of war on the values of caves and karst, and the absence of pre-conflict baseline data that could facilitate post-conflict measurement of the damage done, it can be difficult to demonstrate the full extent of war's impacts. In some instances it is presently possible to address likely impacts on karst only by analogy with impacts recorded from other types of environments, coupled with assessment of their likely consequences given the particular characteristics of karst environments. For example, the recorded consequences of military contaminants for the human organism might potentially allow some insight into likely consequences for cave biota that is often highly adapted to the environmental stability provided within caves and karst aquifers.

The impacts of military activity on karst environments entail more than just the direct physical damage caused in theatres of battle, and the long-term effects of war are generally far more serious than just the damage incurred during the actual conflict phase (Kassim & Barcelo 2009). Even before a battle takes place there are military environmental impacts associated with weapons development, war industries often generating severe impacts. Military training activities can also cause serious environmental damage. War-related investment entails major opportunity costs whereby resources are directed towards the military at the expense of other programs such as health, education or the environment. This diversion of the resources necessary for environmental and civilian purposes is merely exacerbated when active conflict and use of destructive weapons take a more direct toll on the environment. During wartime the priorities of government become realigned such that the perceived "national interest" may lead to environmental outcomes that would never be countenanced in peace-time. There is often a selective collapse of effective governance, including environmental governance, which may allow corruption to flourish and illegal poaching or theft of natural resources. Then during the so-called "post-conflict" phase after battlefield activity has concluded there are a variety of additional impacts. Some are associated with the process and completeness of demilitarization. Others involve changes to natural processes caused by ground surface damage such as devegetation and soil surface exposure to erosion, trench and tunnel construction, bomb crater formation, the degradation of abandoned materials, and impacts associated with ERW, such as land mines. A post-war governance vacuum, and populations driven to desperation in a quest to rebuild their lives, often adds to the environmental pressures. Moreover, this so-called "post-conflict" phase is in many respects a misnomer because in the wake of the main battles there are almost invariably ongoing subsidiary conflicts as factions contest supremacy or vested interests seek to establish or cement their economic or political position in the new order, again often with implications for karst.

Some values at stake

Karst as the basis of sustainable social and economic development

There is a reasonably abundant literature on the effects of geomorphology on the effective conduct of war, such as the avoidance of terrain likely to entrap equipment, but there is little literature on the effects of war on geomorphology. Humankind is fundamentally reliant on the uppermost few centimetres of landforms – the soil in which we grow food. Soils in karst areas may be formed from material liberated by *in situ* dissolution of limestone, or they may be formed on allogenic materials deposited by streams, glaciers, slope instability, the wind or other agents. Soils derived from *in-situ* breakdown of limestone take a particularly long time to form, largely because limestone contains a high proportion of calcium carbonate which runs off-site in solution leaving only a small volume of insoluble residue, often less than 5% of the original rock mass, as the mineral skeleton for soil formation. A deep and mature soil profile is able to form only where the epikarst is weakly developed or its crevices are blocked by regolith or sediment, and where the ground surface has remained stable for a particularly long period. Where these conditions do not exist soils may remain very thin or skeletal, sometimes amounting to little more than an organic mat that lies draped across well-developed epikarst. Under these circumstances soils are highly vulnerable if vegetation cover is disturbed because soil may be eroded not only downslope but also vertically downwards into epikarstic crevices. If the regolith or surficial sediments are thick the same mechanism can cause anthropogenic cover-collapse sinkholes. Once the epikarstic pathways have been opened up and soil loss commenced, increasingly energetic runoff from progressively-exposed rock surfaces further destabilises the remaining soil such that erosion may continue to occur long after the original stimulus has been removed.

Understanding of the potential for war to damage soils is impeded not only by under-recognition of the particular vulnerability of some karst soils, but also by a common failure to realise that soil is not just "dirt". For loose lithic material at the Earth's surface to become a soil requires that it be converted into a potential medium for plant growth by pedogenesis. Pedogensis involves various progressive processes; including the weathering of minerals, leaching, the shrinking and swelling of clay minerals, the addition of aerosol inputs, enrichment by organic matter, internal redistributions of matter, the development of soil structure and differentiation into soil horizons. Soil formation takes a long time and, even where climatic conditions are warm and moist, rock weathering rates may allow no more than 1 m of soil to form in 50,000 years on most rock types (Boyer 2004) and considerably longer on limestone (Yuan and others 1991). The uppermost horizons are generally the most productive part of a soil profile and both Nature and Humanity lose that life-sustaining and fragile film across the landscape if anthropogenic activities cause accelerated erosion, churning and profile mixing or inversion by traffic, structural damage by compaction, nutrient depletion or soil pollution. All these impacts occur readily during wartime due to the passage of vehicles, the detonation of explosive ordnance and various other activities. A single event can cause instantaneous soil loss (in seconds) due to initial mass displacement, and subsequent progressive soil loss (minutes to millennia) due to derailment of natural processes. Both instantaneous and progressive damage reduce the productivity of a soil, and damage to soil resources implies ongoing environmental, economic and social harm.

Karst as natural and cultural heritage

Under-recognition of the impact of warfare on the environment exists only partly because the social costs commonly overshadow other evidence, but also because "Nature" is commonly equated only with the biotic environment and hence impacts on the abiotic environment are overlooked. Yet Nature comprises far more than merely biodiversity. The wider environment in which we live also comprises various other critical components that also form integral parts of "Nature", including the rocks of which the Earth is composed, the landforms present at the Earth's surface, the soils that carpet the terrestrial landscape and the ongoing geological and geomorphological processes that produce and sustain much of the abiotic environment. Karst is a distinctive component of this geodiversity and one that has proved particularly vulnerable to damage when armed conflict occurs (Kiernan 2010a, 2010b).

Physical phenomena such as the caves, hills and sinkholes present in karst areas are important in their own right for their existence and intrinsic values, much as whales or ancient forest giants are important for such reasons. This existence value alone demands respectful stewardship of geo-environmental phenomena, including landforms, simply because they are just as legitimate a part of the cosmos as is the Earth's biota, and even the human species itself (ACIUCN 1996). But karst geodiversity is also fundamental to the functioning of natural process systems, including ecosystems, for there can be no biodiversity without the geodiversity that forms the stage upon which the dramas of life are enacted. Karst geodiversity is also of instrumental value to humans as a source of various goods, ranging across spiritual, inspirational, scientific and other uses, including the maintenance of ecosystem services upon which humankind and human communities are dependent, such as soil (in which to grow food) and natural water supplies. Karst embraces a wide range of such values.

The significance and geoheritage importance of a karst feature may derive from several possible perspectives. One is the genetic system context in which it occurs; that is, the basic geologic climatic and other environmental factors that have controlled its evolution. This is because some combinations of these factors are common, while others are infrequent. The specific types of landforms and landform assemblages present represent a second important consideration. As with biodiversity, there are many different "species" of particular karst landforms, such as different types and morphologies of caves and karren. As with biological communities, there are also different landform "communities", that is, assemblages of different landforms that are strongly inter-related, such as stream-sink to cave to resurgence networks. In addition, many of these assemblages involve interactions with non-karstic processes, such as varying levels of fluvial, glacial or coastal process intervention with the solution processes that characterise karst. As with biological species and communities, some types of landforms and landform assemblages are common and some are rare, some are robust and some are fragile. A third potential pathway to significance in nature conservation terms is the contents of some karst landforms. Even a common and outwardly uninteresting sinkhole or cave may be rendered valuable if it contains certain biological species that are reliant upon it as habitat, or from the presence within it of archaeological relicts or other special phenomena. Finally, the nature conservation significance of a karst phenomenon may derive from the benefits it offers for humans, such as its being of spiritual, cultural, recreational, scientific or economic value. Herein also lies an important linkage with environmental sustainability for human benefit.

But what constitutes damage to an important karst landform, and what merely represents change? At one level this question is straightforward to resolve by entirely objective means. Because landforms are defined by their natural contours, any anthropogenic change to those contours, at whatever scale, necessarily represents damage, by definition. However, ascertaining the significance of that damage is more challenging than merely recognising that is has occurred, because human value judgements are entailed, and what one person may perceive as unacceptable may be perceived by another as inconsequential (Kirkpatrick & Kiernan 2006). Questions that invariably require resolution include the proportion of the feature that has been damaged, the significance of the part damaged to broader functioning of the natural system, the extent to which a perceived value of the feature has been compromised by the damage sustained and competing perspectives in relation to instrumental or economic gain versus the protection of nature. Potential instrumental gain can include the use of karst topography for military purposes. It is not only the immediate and direct physical damage that war causes to karst landforms, soils and hydrology that needs to be taken into account, but also the broader consequences of various environmental contaminants and their effects upon waterways and aquifers, the biota dependent upon karst and the ecosystem services from which the human residents of karst areas benefit. Hence, the damage caused to caves by war extends far more widely than merely conspicuous impacts caused by human activities underground. Rather, some of the most profound impacts of military activity on caves and karst are the consequence of its impacts on karst environmental process systems.

Pre-conflict and extra-conflict activities and impacts

Resourcing war investment

The emergence of Great Britain as a global super-power stemmed in large measure from its naval capacities, and this required timber for ship-building. Once domestic supplies were exhausted overseas sources were pursued, with timber samples from North America sent for testing by the Royal Navy as early as 1606. Pines among the forests cloaking the coastal karst areas of British Columbia, Canada, were among those that subsequently succumbed. Convoys of specially built “mast ships” carried their cargo homewards under armed naval escort (Vaillant 2005), the economics of such enterprises sometimes being enhanced by the back-loading of Irish nationals who were displaced by the English colonisation and economic strangulation of their homeland, effectively a form of human trafficking (McMahon 1996). Major deforestation that affected karst was also associated with the American civil war (Royster 1991, Winik 2001). Deforestation was a prominent consequence of that nation’s response to World War I, following passage of its 1909 *Enlarged Homesteads Act*, when the “Food will win the War” program saw deforestation for housing add to the timber lost for constructing ships and other direct defence purposes. Resulting major extension of agriculture into marginal lands, including karstlands, continued following World War I when European markets became available for US farm products. This overly-rapid expansion into marginal lands occurred under temporarily favourable climatic conditions and it led directly to the 1930s dustbowl disaster when drier conditions returned (Worster 1979). The forest cover in North America was further depleted during World War II for such purposes as procuring light timbers for aircraft construction, including spruce from the Pacific northwest of the USA, the karstic southern Appalachian Mountains and the karst-rich forests of British Columbia, Canada (Williams 1999, Silver 2003).

The expansion of infrastructure for military purposes often also impacts on karst environments, both in terms of construction impacts and also the consequences of economic activity that new infrastructure facilitates. In the USA major new railway systems were developed to aid the movement of goods as part of war efforts when their strategic value became apparent, commencing during the US Civil War. In 1919, immediately upon conclusion of World War I, army Lt. Dwight D. Eisenhower was involved in the first road crossing of the USA by a military convoy. His commitment to road construction as defence infrastructure was subsequently compounded by his exposure to the highway system in Germany while he was serving as Supreme Commander of the Allied forces in Europe during World War II. After this war he championed development of a defensive highway network in the USA, and as US president during the Cold War he signed the *Federal Aid Highway Act* of 1956, then popularly known as the National Interstate and Defense Highways Act. This legislation consolidated these defence-oriented roads to enable rapid deployment of military assets and to facilitate evacuation of populations in the event of a nuclear attack. The provision of this highway network also contributed to the love affair with private motor vehicles that emerged in the USA and which stimulated another cascade of different environmental pressures, including oil-related military activities in which various karst areas also became enmeshed. Accelerated development of the western USA was in part encouraged for defensive purposes as the Cold War intensified, together with duplication of US defence infrastructure there, a trend which the Korean War further exacerbated (McNeill & Unger 2010). While economically beneficial to the USA in many ways, impacts on karst triggered by this road construction, and the development that this facilitated, are also worthy of record.

During the Cold War considerable environmental harm was also caused in the USSR through its efforts to develop and maintain military readiness (Josephson 2010). Meanwhile the US attempted to achieve certain of its specific geopolitical goals, aimed at holding back communism, by seeking to convince newly independent states of its good intentions through selective foreign aid and technology transfer. This gave rise to a world-wide proliferation of hundreds of large hydro-electric dams, most in very different geographical contexts from those in which the concept of such dams as keystones for economic development were developed (Sneddon 2013, Tucker 2010). Karst environments were among the many important natural places that were inundated as a result of this cold war militarist strategy. In the case of the Aswan Dam development in Egypt, a less than compliant attitude by Egyptian leader Nasser led to US Secretary of State John Foster Dulles, brother of then CIA Director Allen Dulles (Kinzer 2013), withdrawing funding for the Aswan Dam, but the void was rapidly filled by its cold war rival, the USSR. This provided the opportunity for the USSR to involve itself more directly in the Middle East, triggering the 1956 Suez Crisis and other ongoing tensions. But paradoxically, it was damage caused to historic monuments by eventual construction of the Aswan Dam that first stimulated formulation of the World Heritage Convention under which numerous cave and karst environments are today protected.

Weaponry experimentation

One of the more bizarre military enterprises to have caused environmental harm in karst caves outside any direct battlefield was the attempt by the US military to develop “bat bombs” during World War II. This project, conceived by dentist Dr Lytle S. Adams, following the bombing of Pearl Harbour and his visit to Carlsbad Caverns in New Mexico, entailed the proposed release of incendiary devices attached to bats. The proposal was sent to the White House in January 1942, endorsed by the Army Chemical Warfare Service (CWS) & Army Air Forces, and was approved by President Roosevelt. Those charged with developing the project visited ~1,000 caves and ~ 3,000 mines to choose the best bat species for the purpose, ultimately selecting the Free-Tailed Bat, an animal that could carry three times its own body weight, would fly into secluded places like buildings to roost, and had the capacity to travel ~65 km from their release point (Couffer 1993). Dr Louis Fieser, the inventor of military napalm, developed bombs with a delay mechanism for deployment by ten B24 bombers that would release up to 1,040,000 bat bombs (Figure 2) over industrial sites around Japan’s Osaka Bay. The army used >3,000 bats in tests but experienced

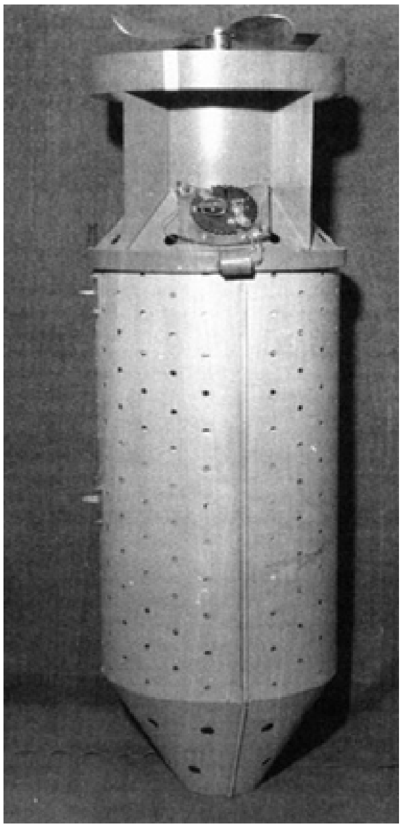


Figure 2. Cannister developed by the US military as part of the bat bombs project, an operation that involved intrusions into hundreds of caves and the killing of thousands of bats. Image source: US military archives. Source: Couffer (1992).

various problems, including one incident in which the Auxillary Army Air Force Base in Carlsbad was set on fire, bats roosted under a fuel tank and a general's car was destroyed. The project was then handed over to the US Navy which leased four caves in which to conduct further work, the exercise then re-named Project X-Ray. In turn, the US Marines then took over the project, conducting successful tests on a mock-up Japanese city in Utah. Full-scale tests were proposed for 1944 but the project was abruptly abandoned by the Chief of Naval Operations due to time needed to develop it. By this time some 6,000 bats had been killed, various cave environments impacted and in excess of US$2 million expended. Although the exercise was later derided as *"Die Fledermaus Farce"*, Dr Adams always maintained that the thousands of fires ignited simultaneously for ~65 km around each release point would have caused great devastation but with less loss of human life than was caused by the atomic bomb (Glines 1990).

Development of conventional weapons

Energetic materials, that is, substances used for propulsion or explosion, raise many environmental issues relevant to karst. Weapons development and testing releases heavy metals and the explosives TNT (Trinitrotoluene) and RDX (chemically cyclotrimethylenetrinitramine, the abbreviation RDX being derived from the term Research Department Explosive employed by the British when they secretly sought to better weaponise it in the 1930s). Some of these materials persist and migrate into groundwater, notably TNT and RDX (Sunahara and others 2009). Organic energetic materials such as TNT and RDX may contaminate soil, water or air. Both are possible carcinogens and genotoxins and prolonged exposure to TNT is known to be associated with liver conditions and anaemia in humans while acute exposure to RDX can cause seizures. By analogy, this suggests that other organisms, including those in cave ecosystems, are also likely to suffer harm. Propellants such as hydrazine, used in the aerospace industry, damage the human nervous system, mucous membranes, kidneys and lungs in the event of inhalation, ingestion or skin contact. Organochlorines such as PCDD (Polychlorinated dibenzodioxins) and TCDD (Tetrachlorodibenzo-p-dioxin) are able to contaminate soil, water and food and they are known carcinogens and teratogens that may cause human birth defects (Ghalaieny 2013). Given the adverse effects of these materials on humans it can reasonably be assumed that should development or testing occur in any karst area their release is likely to harm karst biota and ecosystems.

Development of nuclear weapons

At present there are around 20,000 nuclear warheads shared among at least eight nations, significantly less than at the height of the Cold War in 1960 when stockpiled nuclear weapons worldwide were equivalent to about 1.4 million Hiroshima bombs. The USA produced 70,000 between 1945 and 1990, with a peak holding of 32,000 in 1967 (Sidel and others 2009). The atomic bomb dropped on Hiroshima followed less than two months after the first testing of that weapon, so further refinement and testing of atomic bombs was still desired, and these tests generated major impacts on some caves and karst environments (Merlin & Gonzalez 2010). At Bikini Atoll, drilling to a depth of 780 m revealed the subsurface to consist almost entirely of limestone including cavernous zones (O'Emerey and others 1954), and physical damage to the karst caused by testing there is most dramatically illustrated by the complete obliteration of three islands to form the Bravo Crater (Figure 3), which is over 2 km wide and 80 m deep (ROMI 2010). Other karstic sites used for nuclear testing have included Maralinga, in the Nullarbor karst of Australia (Cooper and others 1994, Johansen and others 2014, Parkinson 2004, Tynan 2016) and Muroroa Atoll in the South Pacific. Artificial cavities used for underground nuclear testing by the former USSR included some excavated into potentially karstic limestone (Murphy and others 1997).

Figure 3. Bravo Crater, a crater over 2 km wide produced by nuclear weapons testing in the karstic Marshall Islands.

In addition to the direct explosive impacts caused by detonation of these devices, the spread of nuclear contaminants by water or air implied additional impacts on karst. Twelve of the underground tests at Mururoa saw formation of a chimney into the carbonates through collapse of the underground nuclear explosion cavities, potentially releasing tritium, strontium and caesium into the karst groundwater. An additional four tests released tritium into the karst despite expectations that volcanic cover rocks would contain contaminants (Leith 2001). Health consequences for humans following nuclear testing (Kenyon 2002, Steinmaus and others 2004; Levy & Sidel 2008) might serve as a proxy measure by which to gauge the potential for impacts on cave and karst biota and ecosystems. For example, atmospheric fallout over a film crew operating in Nevada occurred during nuclear weapons testing in Nevada in 1953, sand from the site was also transferred back to the film studio for set enhancement and more than 90 members of the film crew of 220 people contracted cancer over the next 30 years. Half of these people died from the disease, including the star of the film, John Wayne (Opie 2006), this archetypal US war movie hero perhaps thus effectively falling victim to his own nation's "friendly fire". Researchers from the US National Cancer Institute have suggested that 49,000 excess cases of thyroid cancer in humans were due to release of iodine 131, which raises the probability that other species, including karst biota, also suffered detriment (US National Cancer Institute 1998, Simon and others 2006). A study within the US Department of Health and Human Services released in 2002 concluded that up to 22,000 melanomas, breast and other cancers, about half of which proved fatal, might be directly attributable to atomic weapons testing in the Nevada and western deserts of the USA (Kemiya 1997). Although the infamous USSR Semipalatinsk (now re-named Semey) nuclear test site in Kazakhstan consists predominantly of granitic terrane, its geographical proximity to the karsts of central northern Kazakhstan implies the virtual inevitability that they too have suffered contamination from the more than 456 nuclear tests known to have been conducted there, 116 of these being atmospheric tests which caused high levels of radioactive contamination over 300,000 km^2. Potential adverse consequences for karst ecosystems are again emphasised by the fact that nearly half a million people have now been recognised by the Kazakh government as having cancers, genetic defects and other health problems due to the nuclear testing. Hazards associated with mining radioactive materials, storing tailings and contamination around processing plants (Miller 1999) add to the risks for the biota in some affected karst environments.

Obscurants, incendiaries, chemical weapons and biological weapons

Obscurants are substances that have been widely used to provide visual cover for military operations, often with insufficient understanding or regard for their environmental consequences. Direct skin contact with some obscurants such as white phosphorous can result in severe burns in humans, while inhalation can cause severe internal burning and organ damage. In addition to the damage that results from the use of napalm to remove vegetation, it has also been dropped into the entrances of granite boulder caves in Vietnam in an attempt to extinguish the oxygen in the cave atmosphere available to guerrilla fighters sheltering underground, a threat to which cave biota may also be susceptible.

A wide variety of chemical and biological weapon systems have been developed by some nations, and given that these are intended to cause biological harm to humans it is reasonable to assume that cave and karst biota is also likely to be harmed. In the karst areas of Sardinia (De Waele 2009) increased lymphoma and leukemia in humans and birth defects among livestock ultimately led to the state prosecutor ordering exhumation of bodies for tissue analysis and a subsequent call for 20 officials, academics and technicians to be tried for negligence (Ghalaieny 2013). However, prosecutions after the fact cannot undo the environmental damage also likely to have also been caused to karst ecosystems.

Abandonment of weapons facilities

There have been numerous controversies associated with cancer clusters and other public health problems proximal to military sites in the US, and changes in national boundaries have left a similarly unwelcome inheritance in some emerging nations (Ghalaieny 2013). For example, massive volumes of military material were left behind following withdrawal of Soviet control from parts of the former USSR. Following abandonment of these bases, training areas and testing grounds, many thousands of square kilometres were left degraded and polluted, some with significant karst. In the case of Estonia the estimated costs of clean-up were nearly quadruple the national budget. The USSR remained too powerful an adversary from which to seek redress, and its refusal to contribute was backed up by a legal disclaimer it had succeeded in having written into the withdrawal agreements.

Military training activities

The exclusion of economic activity from areas used for military training or weapons testing may be beneficial for the conservation of some natural values. But training activities may themselves cause damage through stresses imposed on vegetation and resulting erosion and sediment transport, and also by direct modification of ground contours and impacts on soils caused by vehicles, construction activity or use of weapons. Because caves and karst have figured very prominently in past conflicts, it is unsurprising that some caves have been directly impacted by training activities. For example, during World War II Australian commandos who were engaged in operations on Pacific Islands, and potentially in defence of their homeland had the Japanese landed, undertook training courses in the Mt Etna karst of Queensland, which overlooks a rail link southwards towards the most populous parts of Australia. This training covered tasks such as finding caves and gaining entry to them without leaving tracks, surveying cave systems with minimal equipment, developing the ability to explore and climb using ropes, techniques for achieving permanent safety from possible enemy attack by flame-throwers, gas, explosives or water poisoning, destruction of enemies should they enter caves, obtaining a permanent water supply from cave drips, providing light and heating, communications, learning to traverse selected caves in total darkness and techniques for the elimination of boredom should troops be confined within a cave for long periods (Carey 1991). Although training in not leaving tell-tale traces in caves is potentially consistent with present day minimum impact caving techniques, many of the other training measures diametrically contradict present-day conservation strategies. Material left behind in one of the Mt Etna caves, now known as Commando Cavern, has latterly been regarded as being of historical interest, but in purely objective terms it is simply litter discarded underground, with all that potentially implies for cave conservation. (Two years after the war ended the instigator and leader of this endeavour, Sam Carey, founded Australia's first caving group, the Tasmanian Caverneering Club, and he went on to achieve international renown as a geologist). Additional concerns arise from the use of harmful substances during training in some karst areas, such as the RDX, TNT and heavy metals released from weapons.

Explosive weaponry often also triggers secondary fires that are potentially injurious to karst through damaging the vegetation cover. On the outskirts of Marseille, France, where karst is prominent (Jaques 2004), military practice shelling in July 2009 triggered a major wildfire that incinerated several square kilometres, destroying homes and causing the evacuation of hundreds of residents (Allen & Sparks 2009). Similarly, in October 2013 military practice shelling in NSW, Australia, triggered a wildfire that burnt out 50,000 hectares, together with a number of homes (Wroe & Whyte 2013). Where such ignitions occur in karst, erosion and sediment transmission has the potential to cause significant harm. In addition, some legacies of past military training may also prove problematic for ongoing land management. In January 2013 fire-fighters in New South Wales, Australia, were faced with an impossible situation when a wildfire approached the Tianjara plateau, now part of Morton National Park but used as a practice range for 30 years until 1970. Unexploded ordnance littering the range precluded safe entry of fire-fighters on foot, and inhibited the use of water bombers due to the risk of dumped water impacts triggering detonations (Anon. 2013a). While carbonate rocks are absent from this particular area the situation nevertheless warrants registering as another example of the sort of situation that has the potential to occur in karst areas.

The environmental hazards associated with training also include accidents. On Tuesday 16 July 2013 four unarmed bombs totalling 1.8 tonnes (Anon. 2013b) were dropped in the World Heritage-listed Great Barrier Reef Marine Park, a coral reef complex that stretches for 3000 km along the north-eastern coast of Australia and which contains a variety of antecedent karst features related to former low sea levels (Hopley and others 2007). According to a US 7th Fleet spokesman the bombs were jettisoned after a planned target on Townshend Island bombing range could not be used, and because the planes were short on fuel and could not land with their bomb load.

Environmental standards at overseas military establishments

Historically, the niceties of present-day western urban life have not been considered necessary on many military bases. This situation has changed in some jurisdictions as environmental protection has come to be demanded more widely, but such changes are not universal – especially when overseas bases, distant from domestic scrutiny or laws, are involved. Legacies of past inadequacies often remain after closure of overseas bases, a non-karst example being the US Subic Bay base in the Philippines. This was never provided with any sewage treatment facility, waste simply being continuously discharged into the sea, and so much other waste was also left behind after base closure, including asbestos, as to cause health problems when locals fled to the apparent safety of the site during the eruption of Mt Pinotubo in 1991. In this case the US successfully claimed that it was absolved from any responsibility for clean-up by the original 1947 military bases agreement (Kemiya 1997). Were similar negligence to occur at any overseas military base in a karst environment the implications for aquifer contamination could be profound.

Conflict phase impacts

Deliberate removal of vegetation

Deliberate devegetation is sometimes employed during armed conflict in a bid to deny the cover that vegetation may offer to opposition forces, or to destroy food crops that opponents might utilise. Where such actions occur the soil may be left exposed to agents of erosion, of particular concern in karst areas where soil formation is typically very slow, and where soil may be flushed downwards into the epikarst by the water previously removed by transpiring vegetation. Lush forests fell prey both to plunder by English colonisers and in a quest to strip potential refuge for Irish resistance fighters following the Elizabethan Wars (McMahon 1996). Devegetation tactics employed by US forces in Vietnam included widespread use of chemical defoliants and incendiary napalm, and large scale ground-based bulldozing, that destroyed 44% of the forest cover across this highly karstic nation. More than 75 million litres of dioxin-bearing Agent Orange (AO) defoliant was also sprayed onto Vietnamese territory by the US between 1962 and 1971, including large areas of karst (Marchak 1995, Marcoux 2000, Allukian & Attwood 2008).

Wartime devegetation can be exacerbated if logging becomes a source of revenue to support a war effort, a situation more typical of civil wars than international conflicts. After enduring murderous incursions by the forces of Cambodia's genocidal Khmer Rouge regime, Vietnam invaded Cambodia in 1978 and deposed the Khmer Rouge, which was driven into remoter areas, including karsts in southern and western Cambodia. Following collapse of the USSR, overseas assistance to the warring factions in Cambodia declined because Cambodia was no longer needed as a pawn in wider geopolitical power plays. Thereafter, both the Khmer Rouge and the Royal Cambodian Armed Forces became heavily involved in logging in order to fund their military operations against one another, the Khmer Rouge often exchanging timber for weapons and munitions from army generals in neighbouring Thailand who were themselves heavily involved in their own country's logging industry (Global Witness 1996, Le Billon 2000). Meanwhile personal fortunes were amassed by Cambodian military and political leaders on both sides, timber exploitation itself becoming a cause of conflict, albeit with some co-operation sometimes also occurring between the theoretically warring parties as political and military leaders became increasingly addicted to the money generated by illegal logging, both for funding their forces and for personal gain. Under such circumstances the logging is unlikely to be even remotely compliant with the sorts of standards now expected when logging occurs in karst (eg. BCMF 2003), and while only a relatively small proportion of the area involved in the Cambodian case was karst that may not always be the case. Legacies of this corruption in Cambodian logging still persist decades after active combat ceased (Global Witness 2007). There are striking parallels between this situation and the funding of war by African "blood diamonds".

Deliberate landform remodelling

There is a long history of deliberate landform modification for military purposes, including reshaping of defendable high points and construction of defensive walls. Despite already offering many natural defences, karst areas have also figured prominently among environments subjected to such activities. Formed access routes, trenches and tunnels are frequently constructed during wartime in order to provide cover for ground forces and communications between different parts of the theatre. These activities are injurious to soils, some landforms, and potentially to karstic aquifers and the caves associated with them. Many former World War I battlefields in Europe remain scarred by wartime trenches over a century after conflict concluded (Figure 4). North Vietnamese guerrilla forces made particularly effective use of tunnels during their conflict with American forces, secretly gaining entry even into sites that their opponents believed they had rendered entirely secure. Where

Figure 4. World War I trench that still remains prominent in Slovenia, typical of the situation across extensive parts of Europe.

such activities occur in karst significant harm may result, excavation having the potential to degrade soils and derange natural water infiltration.

The construction of buildings to serve as bases or for other functions also typically implies ground and soil disturbance. Larger-scale military engineering that can include the establishment of fortifications, roads, railways (Figure 5) and airstrips. Some of these can similarly imply landform damage and soil profile loss that can assume particular significance in karst areas. A major network of nearly 200 US airfields that was established in Laos during the American War in Indochina included many in karst terrane. Construction of some entailed smoothing alluvial plains overlying limestone while others entailed major redistribution of earth materials over linear distances >1.5 km. There was additional disturbance to provide aprons and associated bases (Kiernan 2013a).

Extraction of military resources from caves

There have been many cases worldwide of guano having been mined from caves to obtain nitrate for manufacture of gunpowder, this soluble mineral being preserved underground from the leaching that degrades surface guano accumulations. Guano in caves in the USA had captured military

Figure 5. A considerable portion of the Thai-Burma railway (sometimes termed the Death Railway) that was built by the Japanese during World War II using forced labour, was constructed through karst terrane.

interest by no later than 1701 when the French were aware of a saltpetre cave in Minnesota. Later American political leaders were likely also well aware of caves with guano resources. For example, George Washington's active interest in caves is evident from his 1748 signature in a cave in Virginia which he carved at the age of 16, while Thomas Jefferson's 1784 *Notes on the State of Virginia* contains the earliest known map of any cave in the USA. In 1796 Jefferson recorded and published on the bones of a large quadruped that were discovered in a cave in Virginia by saltpetre miners, the first ground sloth ever found - *Megalonyx jeffersoni* (Halliday1976). Saltpetre was mined from numerous caves in the eastern USA during the American Civil War from 1861 to 1865.

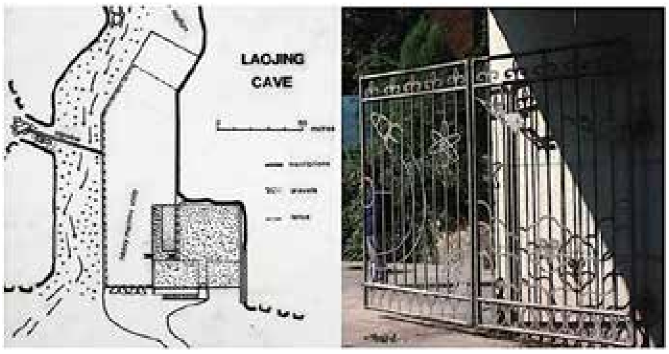


Figure 7. A large and very heavily-constructed factory building inside a cave in southern China, with hidden connections to services such as electricity (memory sketch on LHS of image), was explained to the writer by his escort in the 1980s as being merely a bicycle factory. Ornamentation later photographed on the gate to the compound surrounding the cave is illustrated on the RHS of the image.

Figure 6. Disturbance of the cave environment in Mammoth Cave, Kentucky USA, due to mining for saltpetre for use in gunpowder production.

Production from Mammoth Cave (Figure 6) peaked around the time of the War of 1812, some of the enslaved African-American labourers later being re-deployed as cave guides.

Many other caves worldwide have also been quarried for gunpowder manufacture, including some on multiple occasions, such as Tham Pha Ban, Lao PDR, which was exploited for Japanese manufacture of gunpowder during World War II and again during the American War in Indochina. In the absence of pre-mining data it is not possible to precisely define all environmental impacts of military guano mining, but they were probably significant. Removal of guano from caves involves destruction of a key energy source for some cave ecosystems and it may also eliminate rare cave minerals that are associated with cave guano deposits.

Shelter and secrecy in caves

Caves have often been used for shelter, protection from enemies, and secrecy (Figure 7). The presence of people underground, the activities they undertake there, and an emphasis on wartime priorities rather than conservation, all augur badly for cave environments. Predjama in Slovenia comprises 12 km of cave passages that contain evidence of human occupation since 12 ka BP. Establishment of early fortifications in this cave, which has secret entry/exit routes that could be used during sieges, was followed by initial castle construction in the main entrance as early as 1202. The present castle was constructed during the 16th century (Figure 8). Elsewhere, Irish resistance fighters sought refuge in caves of The Burren from which they launched occasional attacks against the colonising English (McMahon 1996). During the American Civil war troops were garrisoned in Melrose Cave, Virginia, together with their stores. In addition to damage

Figure 8. Predjama castle (16th century), constructed in the mouth of a karst cave in Slovenia.

caused by their direct trampling of the cave floors, speleothems were also used for target practice. Scarring of the cave by bullet holes still remains evident today, as do holes that were drilled into the cave walls to hang candles, and widespread graffiti (Halliday 1976).

Graffiti is common in many caves that have been used for military purposes (Figure 9). During the anti-colonialist wars of the 20th century many Indochinese caves were utilised by guerrilla fighters, and refuse, smoke-stained walls and ERW remain in some of them. Some Laotian caves were heavily modified at this time, ranging from the excavation of cave sediments to provide flat surfaces for sleeping to the construction of concrete anti-blast walls and other structures to protect cave occupants.

Figure 9. Nazi graffiti defacing the wall of a karst cave in Slovenia

At Vieng Xai in Huophan province (Figure 10) physical modifications include artificial connecting tunnels, underground buildings and extensive areas of cave floor paved with concrete (Kiernan 2012).

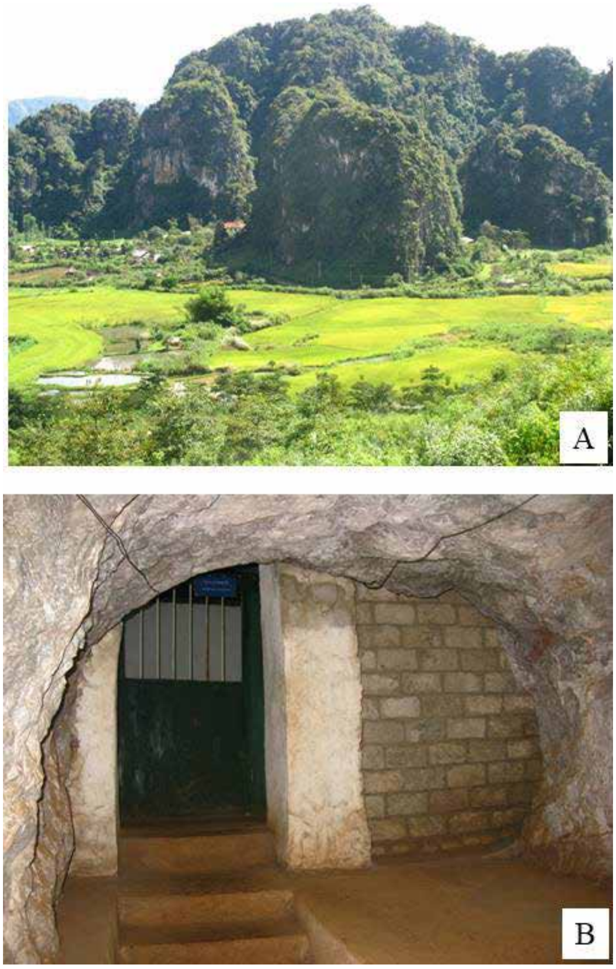
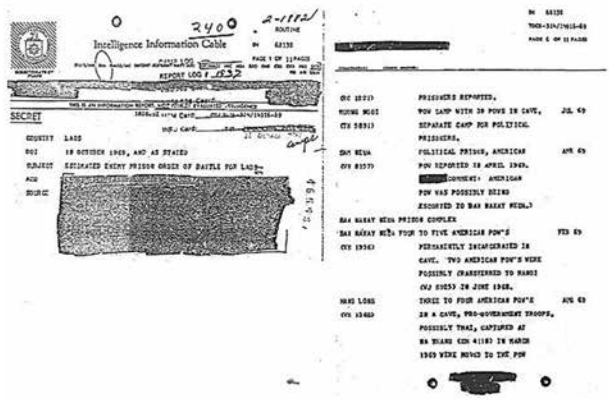


Figure 10. (A) Karst towers around Vieng Xai, Lao PDR; (B) Major physical cave passage re-modelling and construction undertaken in caves by the Pathet Lao during the American War in Indochina.

During the American War in Indochina a number of caves were also used as prisons by communist forces, including various caves in Khammouan Province, Lao PDR (CIA 1969) (Figure 11). It is likely that sanitary and other *ad hoc* facilities were deleterious to cave ecosystems. Caves have often also been used as secure strongholds in which to secrete medical facilities. Examples include the Laotian caves Tham Pha and Tham Xang in Xieng Khouang province which were used for this purpose by communist forces during the American War in Indochina in the 1960s and 1970s. One of the largest such facilities was a major hospital cave complex near Viang Xai. Environmental impacts resulting from the establishment of underground medical facilities here included physical modification of cave architecture and the introduction of injurious foreign materials underground, including various chemicals and medical drugs (Figure 12).



Intelligence Information Cable

ROUTINE

REPORT LOG # 1532

[redacted]

SECRET

COUNTRY LAOS

DOI 18 OCTOBER 1969, AND AS STATED

SUBJECT ESTIMATED ENEMY PRISON ORDER OF BATTLE FOR LAOS

ACQ

SOURCE [redacted]

[redacted]

PRISONERS REPORTED.

POW CAMP WITH 30 POWS IN CAVE, JUL 69

SEPARATE CAMP FOR POLITICAL PRISONERS.

POLITICAL PRISON, AMERICAN POW REPORTED IN APRIL 1969. APR 69

[redacted] COMMENT: AMERICAN POW WAS POSSIBLY BEING ESCORTED TO BAN NAKAY NEUA.)

BAN NAKAY NEUA PRISON COMPLEX

BAN NAKAY NEUA FOUR TO FIVE AMERICAN POW'S PERMANENTLY INCARCERATED IN CAVE. TWO AMERICAN POW'S WERE POSSIBLY TRANSFERRED TO HANOI IN JUNE 1968. FEB 69

THREE TO FOUR AMERICAN POW'S IN A CAVE, PRO-GOVERNMENT TROOPS, POSSIBLY THAI, CAPTURED AT ... IN MARCH 1969 WERE MOVED TO THE POW AUG 69

[redacted]

Figure 11. Wartime CIA Intelligence Information Cable detailing knowledge of cave prisons in one sector of Laos.

Tham Pha Tok near Nang Khiaw, in Luang Prabang province, was a multifunctional facility

Figure 12. Medicine bottles remain in Tham Xang, Lao PDR, and other caves previously used as secure underground wartime hospitals, and they attest to the introduction of unnatural chemicals and substances with potential adverse impacts on sensitive cave and karst ecosystems.

that housed the Pathet Lao provincial government during the American War. To facilitate this there was significant remodeling of the floor contours to construct suitable topography for office and work areas, and barriers to insulate against attack. One chamber with a separate entrance served as a small hospital. Another small cave nearby was modified for use as a bank. The most extensive use of caves for shelter and safety during the American War in Indochina occurred in Huophan Province, Lao PDR, where an underground city of 20,000 people and the services they required was established in a network of over 200 caves. Massive modification of the underground environment included excavation of new connecting passageways and large scale underground construction using concrete, wood and metal (Kiernan 2012).

The environmental damage caused by military bases in caves is commonly compounded by additional damage incurred when discovery of those bases results in their coming under attack. During World War II occupying German forces established a fuel dump in Postojna, Slovenia, sealing and guarding the entrance. On 23 April 1944 partisans used their local knowledge of other entrances to gain access to the fuel dump and set it on fire. The resulting conflagration burnt for 7 days and caused much smoke and heat damage to the cave (Figure 13). In Laos, Tham Pha Kuang, overlooking the Nam Ou near Nang Khiaw, suffered considerable damage as a result of a rocket attack that appears to have also detonated munitions stockpiled in the cave. The military function of parts of the underground complex around Vieng Xai also attracted many bombing attacks by the US and its allies. The hazards of

Figure 13. Smoke damage to cave walls in Postojna Cave, Slovenia, following detonation of an underground German supply dump by local saboteurs.

Figure 14. Entrance to Tham Piu, Lao PDR, massively damaged by rocket attack in the American War.

combining civilian and military facilities in a single cave are perhaps illustrated by the case of Tham Piu in Xieng Khouang province (Figure 14). This cave is said by locals to have sheltered civilians and

Figure 15. Rock debris and a small shrine in Tham Piu, Lao PDR, where hundreds were killed by rocket attack during the American War in Indochina.

an underground hospital. Correctly or otherwise, it was perceived by others as a military facility and a rocket fired into its entrance in 1968 may have killed as many as 400 people, caused substantial rock-fall (Figure 15), and blackened the walls and ceiling deep into the cave (Kiernan 2012).

The use of cave passages as secret routes that allow infiltration of forces has a long history in south-east Asia. Examples include Nguom Ngao Cave in Cao Bang province, Vietnam, which lies very close to the Chinese border, and which was probably most recently used militarily during the Chinese invasion of Vietnam in 1978. In addition to the actual environmental consequences of such use, even the mere suspicion of the potential for military use may be sufficient to trigger actions that lead to caves being damaged in a bid to thwart perceived threats. Caves figured prominently in the Spanish Civil War (Jackson 2005, Fernandez & Moshenska 2015). The original (Lepineaux) shaft into Gouffre de Pierre St Martin is located in the Basque country on the French side of the Pyrenees. During the civil war that followed toppling of Spain's republican government in 1936, most Basques fought on the Republican side. After Franco's right-wing Nationalists emerged victorious, Basque culture was ruthlessly suppressed by his secret police, together with denial of many rights taken for granted in the west, curtailment of fair elections and the banning of political opposition. The Lepineaux shaft was discovered in 1950, three years after the new dictator had become head of state for life. In these Cold War years Franco's regime was supported as being safely anti-communist by major western powers, the virulently anti-communist USA Secretary of State John

Foster Dulles even visiting him in 1955, around the same time as the latter's withdrawal of funding for the Aswan Dam was facilitating soviet expansion into the middle east and triggering the Suez Crisis. Within a year of its discovery the Lepineaux shaft had attracted considerable attention from having been recognised as being the longest natural shaft (334 m) known in the world at that time. Continued exploration led in 1953 to the discovery of the largest cave chamber then known in the world (4.5 million m^3 - 255 m long, 245 m wide, 180 m high). The Pierrre St Martin complex also became the deepest cave system known in the world at the time (Tazieff 1966). More concerningly in political and military terms, a system of underground passages that crossed beneath the border between France and Spain had also progressively been revealed.

When the 1952 exploratory expedition arrived, they were met by Spanish rifleman contesting their access. The cavers themselves were a politically diverse group. They were led by Max Cosyns, a physicist who was later alleged in a 1961 report by the US Congress' House Committee on Un-American Activities to have been a subversive communist (Committee on Un-American Activities 1951, Douat 1998). Exploring alongside him were Haroun Tazieff who was later to become a stridently right-wing French politician and outspoken advocate for nuclear testing at Muroroa Atoll, Jacques Labeyrie, a member of the French Young Communists Movement, Norbert Casteret and others. A curious equipment failure caused the death of Marcel Loubens in 1952 when he chose to exit the shaft prior to the planned descent of others. Deficiencies in a new electric winch are commonly blamed for the accident (Casteret 1955) but, notwithstanding a somewhat acerbic opinion piece by de Joly (1952) no comprehensive and definitive account seems ever to have appeared concerning the exact reason for its failure, and all those who were present are now deceased. There are now known to be at least seven entrances to the Pierre St Martin system within France and another four in Spain. The perceived risk that this ramifying cave system might be used for military infiltration led at one stage to the Lepineaux shaft being deliberately vandalised by being blocked. Since Franco's death in 1975, debris from road construction and deliberate entrance enclosure have all but erased the surface identity of this once celebrated vertical shaft.

Deployment of weaponry

Various injurious obscurants, including white phosphorous, were used over karst areas in Indochina during the American War. Apparent increases in human birth defects that occurred in the Gaza strip following use of white phosphorous by Israel in 2009 (Naim and others 2012) raise the possibility that biota in karst areas there, and in other karst sites where it has been deployed, are also likely to have been harmed.

Many caves have been disfigured by small arms fire, and contaminated by lead bullets and other projectile materials. The pattern of this physical damage typically depends on local conditions. Around the Moso Caves in the Mekong River delta of southern Vietnam, scarring by projectiles has damaged nearly 25% of the total exposed rock surfaces near swamp-water notches and cave entrances at the base of a limestone tower that provided refuge and cover for guerrilla fighters. However, in the nearby Da Dong area where vegetation masked part of the hill base and accessible caves occur higher on the hillside, scarring affects only ~10% of the exposed rock surfaces in the basal zone, increases to ~15% on higher and more exposed parts of the cliffs, and reaches 23% around the high level caves (Kiernan 2010b).

Various heavy metals are also released during conflict. They include tungsten compounds used to harden penetrator ordnance, lead used in bullets and mercury used in old fuses and missile systems. Contamination of soils can therefore result (Hupy 2006). Some tungsten compounds are proven carcinogens in animals and are considered risk factors for lung fibrosis in humans. Lead is a human neurotoxin that impairs brain development, and some forms of mercury are associated with brain, lung and liver damage. Inhalation, ingestion and contaminated food are all potential pathways into organisms.

Depleted uranium (DU), a by-product of nuclear enrichment processes, is used to harden penetrating ordnance. Although less radioactive than natural uranium, it is highly toxic. A known carcinogen, teratogen and genotoxin in humans, DU also affects kidney function. Inhalation, penetration of shrapnel and contamination of soil are all potential pathways into organisms. Potential problems with DU include the fact that 70% of what burns becomes bacteria/virus size, 1000 times smaller than human blood cells (gas masks cannot filter out such small particles and no protective clothing is 100% effective). The particles may readily be distributed in dust storms and contaminate food or water, and theoretically they can gain access into blood, lymph, bones and organs. The use of DU remains controversial, its advocates arguing that the detonation products are not dangerous and that they stay close to the struck target, while the opponents of DU emphasise the health risks and question the morality of discarding domestic nuclear waste by exporting it in the form of DU weapons. Evidence suggestive of its persistence and harmful effects includes its presence in Iraq 10 years after the 1991 Gulf War, coincident with birth defects, its persistence in street dust in Kosovo following the hostilities of 1999, increases in childhood leukemia in Iraq and perhaps the "Gulf War Syndrome" that has affected tens of thousands of US Gulf War veterans who are now on permanent medical disability pensions (Hagopian and others 2010a, 2010b; Greiser & Hoffmann 2010; Alaami and others 2010). No investigations have been conducted into the possible impacts of DU on cave and karst ecosystems but a number of karst environments have now been exposed to this product and, given the known effects in other environments, its implications for karst settings warrants concern.

Bombing that is undertaken to eliminate enemy forces operating in karst environments, destroy their assets or drain their morale, also implies immediate damage to karst landforms and soils. In the Lao PDR, US bombing from 1964 to 1973 entailed 580,994 sorties (1.5 times the number flown in Vietnam) that delivered the equivalent of one plane-load of bombs every eight minutes, 24 hours a day, for nine years (Figure 16). This amounted to about half a tonne of bombs for every man, woman and child in the country at that time, with some particularly targeted areas receiving 12 tonnes/km^2. The pay-loads included at least 460,000 cluster bombs containing >260 million sub-munitions. However, even this record is insufficient to reveal the real extent of likely damage to karst in Laos. The US bombing records are incomplete, considerable additional ordnance was deployed by other protagonists, and no records are available for ordnance deployed by ground forces, nor for the thousands of land mines that were also installed. Environmental legacies include shattered caves and bomb craters that commonly exceed densities of 200/km^2 and in some areas 800/km^2 (Kiernan 2012; 2013a).

During the 1999 conflict in the former Yugoslavia at least 13 national parks and nature reserves were bombed (CERPLA 2001), many of them karstic. There were deliberate attempts to destroy travertine dams that impound the World Heritage-listed karstic Plitvice Lakes in Croatia in a bid to wreak

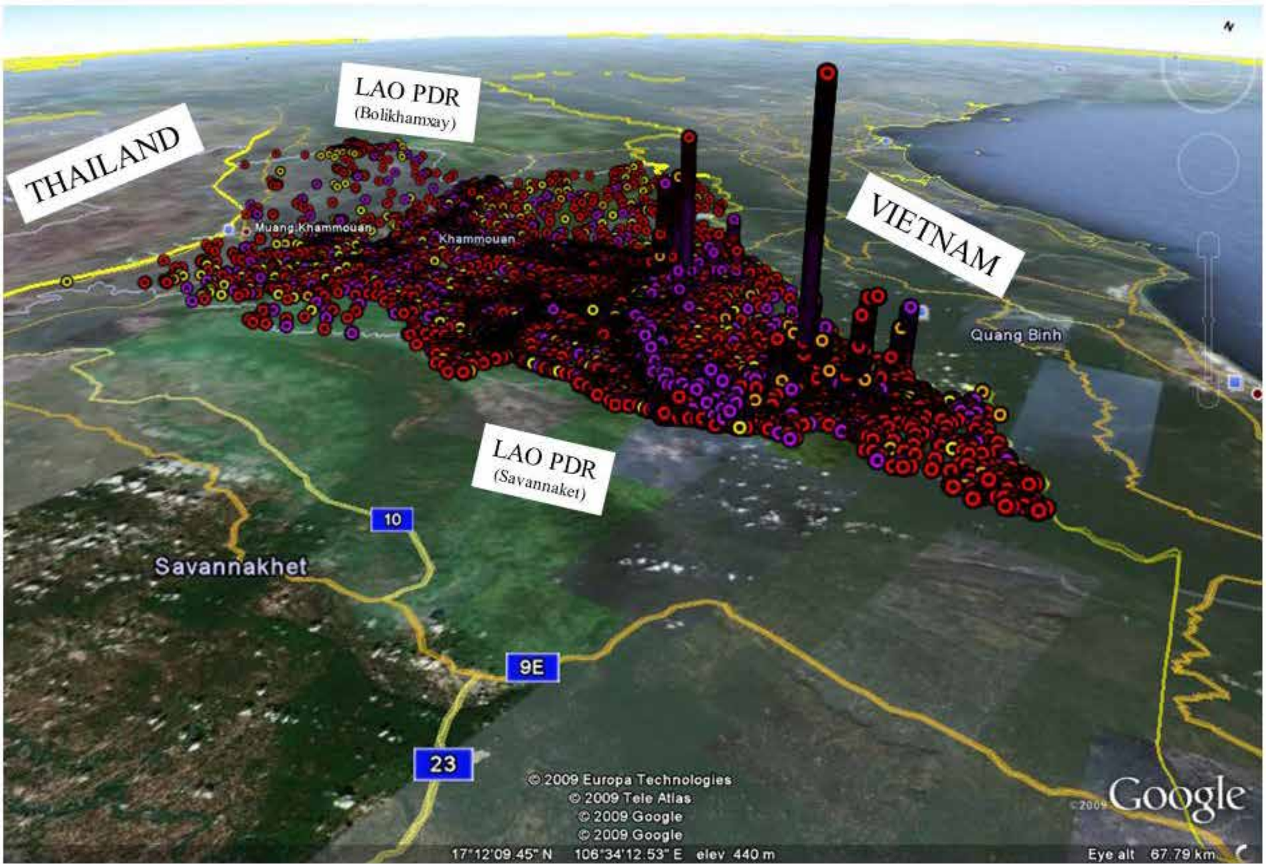


Figure 16. Data from incomplete US bombing database for Khammouan province, Lao PDR, presented on an oblique Google Earth view of southern Laos that extends across the province from Vietnam in the east to Thailand in the west. Different coloured discs represent different sized bombs and each disk represents multiple bombs. Source: MAG Lao.

havoc downstream. Effectively an act of war-time environmental terrorism (Schwartz 1998), this tactic recalls the World War II "Dambuster" attacks by British aircraft on the artificial Mohna and Eder dams in Germany, which caused release of massive volumes of water causing widespread damage, loss of life and deflection of German resources away from warfare and into repair works. Such tactics also imply harm to any karst areas in the path of the floodwaters.

While the environment is likely to be harmed when any targeted karst site is hit, damage is by no means restricted to targeted sites and collateral damage to the environment is typically very high. At Alexandria in 1881 the British fired 3000 shells at Egyptian forts but recorded only 10 hits, while a 1967 CIA study of aerial bombardment of one zone containing karst terrane during the American War in Vietnam revealed that of 11,744 bombs dropped only 249 (slightly over 2%) hit their intended target (Fuller and others 1996). Media reports during the 1991 Gulf War emphasized the precision bombing technology that had by then become available, but the wider picture was that 93% of the total bombs dropped were basic gravity bombs, 70% of which missed their intended target. In part the degree of damage inflicted is related to weapons technology, the potential for environmental harm having progressively been increased over the years by massive advances in firepower.

Bombing may also trigger wider damage by virtue of its political impact. For example, US carpet bombing of suspected Vietnamese facilities in Cambodia, including karst areas around the Mekong delta, entailed widespread trauma and loss for Cambodian civilians. Disaffection caused by the bombing, and by the compliant attitude by the US puppet Lon Nol government in Phnom Penh, promoted the growth of the notorious Khmer Rouge which, according to its leader Pol Pot, had previously numbered "fewer than five thousand poorly armed guerillas … scattered across the Cambodian landscape, uncertain about their strategy, tactics, loyalty and leaders" (Kiernan & Owen 2010). This bombing thus played a critical role in the subsequent usurpation of power by the Khmer Rouge, the Cambodian genocide that it went on to inflict, the massive damage it inflicted upon the natural environment including karst sites, and then years of ongoing armed conflict and resulting environmental damage during efforts to remove it from power and suppress its return.

Pollution and contamination

Even in peacetime, military bases and general field facilities see release of PCBs, PAH (polyaromatic hydrocarbons), particulates, TCE and fuels (Broomandi and others 2020), but release of such materials is greatly amplified during times of active armed combat, when heavy metals, RDX, TNT and obscurants such as white phosphorous are added to the toxic load imposed upon the environment in which operations are conducted (Hupy 2006). Infrastructure destroyed or damaged by bombing in turn releases such materials as dioxins, PCBs, PAH and heavy metals. When forward bases and other installations are abandoned, stockpiled or discarded, munitions add TNT, RDX, hydrazine and nitric acid to the load. PCBs (polychlorinated biphenyls), some of which are known teratogens and probably also carcinogens, were widely used in electrical transformers and hydraulic fluids in some older equipment and hence may be spilt during the destruction of infrastructure, contaminating soil, water and food. Aviation involves the release of various contaminants including fuel additives, and this increases during active conflict. During the American War in Indochina the remote Long Tieng airfield in Laos became one of the busiest airports in the world, being the source of many thousands of over-flights and bombing missions directed against surrounding karstlands. Large areas of karst were included among the areas contaminated by Agent Orange in Vietnam. There are about one dozen particular AO hotspots around former US bases, soil sampling from the Bien Hoa in 2003 revealing TCCD levels up to 180 million times higher than the safe level set by the US Environment Protection Agency (USEPA) (Hatfield Consultants 2007). Remnant contamination has been shown to be particularly severe around the former US base at urbanised Danang where leakage of stored AO had occurred into soil and groundwater, but the status of karst areas in more rural settings where AO was deployed, probably including the nearby Marble Mountains, appears not to have been scrutinised.

NATO flew 34,000 missions over the former Yugoslavia between 24 March and 5 June 1999, involving 150,000 flying hours and 2,300 strikes. Some 22-79,000 tonnes of ordnance were deployed against 78 industrial sites, 42 energy installations and various other targets. In a bid to avert the risk of explosion should the Pancevo industrial complex be bombed, its operators discharged various toxins from the plant into the Danube River. This included 14,000 tonnes of ethyl dichloride, 800 tonnes of 33% hydrochloric acid, 3,000 tonnes of lye and 1,000 tonnes of sodium hydroxide, together with mercury and various other substances. This contamination was swept downstream into Romania, the Ukraine and Bulgaria, including through such karsts as those in the Cazanele Dunarii area in the Carpathian Mountains and in the Danube Plain in Bulgaria. No resulting trans-boundary impacts on karst groundwater appear to have been recorded, but such effects are possible. Considerable air pollution also resulted from this conflict: vinyl chloride monomers 10,600 times in excess of acceptable levels being recorded, with dioxins spilling over the karsts of Greece and acid rain over the karsts of Romania. Lead, copper and cadmium levels were subsequently found to be dramatically elevated in border areas of Bulgaria (CERPLA 2001). Widespread pollution of air and water from the burning of oil wells during the 1991 Gulf War again highlights potential fallout issues for karst terranes.

Generation of refugee pressures

Caves and rugged karst terrain have long provided sanctuary for groups displaced by armed conflict or otherwise living in fear of raids by enemies. For example, Tham Jang near Van Viang in Laos provided sanctuary for local villagers against marauding Yunnanese in the early 19th century. In Virginia USA, settlers sought shelter in Melrose Cave during the French and Indian wars in the early 1750s (Halliday 1976). Bombing during the American War in Indochina induced many Laotian villagers to abandon their villages and seek long-term shelter in caves. There are numerous implications for caves and karst environments when they provide sanctuary for refugees, including waste disposal, deforestation of adjacent karst catchments, water pollution, pollution of cave atmospheres by smoke from fires, degradation of natural landforms, soil degradation and encroachment on ecosystems and protected areas to obtain emergency fuel, food or other materials. Some Indochinese villagers still harvest bats from caves and it is likely that such pressures on bat populations were particularly great during the American War, although in the absence of pre-conflict bio-data any such impacts cannot be quantified. Establishment of refugee camps also added to the environmental impacts on karst from the 1999 conflict in the former Yugoslavia (CERPLA 2001). As counter-terrorism became an increasingly prominent concern over recent decades the need for tools to address the particular risks in karst areas, by allowing enhanced catchment definition and prediction of contaminant arrival times, dispersal, dilution and arrival concentrations, has also been recognised (Field 2002).

Burying the dead

Cavers sometime bemoan the pollution caused by the dumping of animal carcases into caves and sinkholes. While it may seem insensitive to consider deceased humans in a similar vein, at a purely objective level, and for completeness in drawing-up the environmental account of conflict in karst, the disposal of human casualties is something that should also be considered. The massive numbers of human lives lost in some conflicts, perhaps 15 million during World War I (1914-1918), 9 million during the Russian Civil War (1917-1922) and 66 million during World War II (1939-1945), emphasizes the potential for considerable areas to be disturbed or contaminated through disposal of human remains. Human bodies have been dumped or secreted in sinkholes or caves in Slovenia, Cambodia and elsewhere, and even the digging of graves in karst may have some potential to impact on cave and karst environments in some circumstances. Analysis of records held in the Cambodian Genocide database suggests that in the western Cambodian karsts there were at least 15 killing fields, with 814 mass graves recognized to date containing 81,840 bodies. This includes thousands of bodies that were dumped into some individual caves (Figure 17). There were also at least 15 killing fields in the southern Cambodian karsts with 2,558 discovered mass graves thought to contain 69,824 bodies (Kiernan in press). To the environmental impacts caused by human casualties must be added that resulting from the corpses of livestock, wildlife and other animals that may be dumped into caves, sinkholes or watercourses.

Impacts during the transition out of active conflict

Deliberate removal of vegetation

In some cases deliberate removal of vegetation has been used as a tactic to reduce the capacity of an opponent to re-open hostilities. For example, following World War II, forests in Germany were clear-felled in the US occupation zone, the acknowledged purpose of which was the “ultimate destruction of the war potential of German forest”, those responsible anticipating that they could “be

Figure 17. (A) Vertical entrance to a cave in Battambang Province, western Cambodia, into which about 10,000 bodies were dumped during the genocide committed by the Khmer Rouge following its rise to power following US bombing and during later civil war; (B) Graphic explanatory sign to explain significance of the site to foreign visitors.

replaced only by long forestry development over perhaps a century" (Harmssen 1948; USOMG 1946, 1948; Balabkins 1964). Given that much of the timber was exported, the motivation may also have included an element of pillage. Policies of this kind pose severe risks for karst and caves given the now-acknowledged impacts that logging can have on caves and karst via changes to natural fluid flows and soil degradation.

Soil and sustainability

Often the damage that is inflicted upon soils and karst landforms during wartime does not end with the cessation of hostilities, because on-going damaging processes are triggered by the wartime impacts. Erosion is continuing to occur along some military trenches in the karsts of Laos and elsewhere. Erosion caused by overflow of ponds formed in bomb craters has also been recorded from Xieng Khouang province (Kiernan 2013a). Ongoing soil loss into the epikarst due to wartime devegetation and erosion can be pronounced (Figure 18). Based on the height at which karren species that originate

Figure 18. Ongoing soil erosion into the epikarst directly above an accessible cave in a heavily-bombed sector of Xieng Khouang province, Lao PDR, is indicated by the contrast between subaerially-formed karren on upper parts of bedrock outcrops and rounded karren originally formed beneath a soil cover and exposed by later soil loss.

beneath a soil surface are now exposed above the ground, coupled with recognition of accumulations of this eroded soil in caves, some 15-40 cm of soil appears to have been stripped from some karsts in southern Cambodia during and since the American War (Kiernan 2010b). This contrasts with virtually no exposure of subsurface karren types in some pockets of karst in neighbouring Vietnam where primary old-growth forest had not been destroyed during the war.

Once lost, re-establishment of a soil cover may take many millennia. Yuan and others (1991) have estimated that even in mild and moist Guanxi province in southern China, between 250,000 and 850,000 years are required to form 1 m of soil. It is precisely soils of this kind that were impacted by the wartime devegetation that occurred just across the Chinese border in Vietnam and Laos, and further south in Cambodia, during the 1960s and 1970s. While residual limestone soils are particularly vulnerable, damage to soils formed on allogenic materials may also have repercussions on vegetation and processes in underlying karst caves. For example, in south-east Asia many karst areas are mantled by alluvial materials that have often been heavily leached, with only active floodplains being "replenished" by flooding. Maintaining such productive soils as do exist on higher terraces and elsewhere in the landscape is critical for both environmental and social reasons. Any degradation of them is essentially permanent with respect to human time frames.

Impact and explosion craters produced by the relatively small armaments used during World War I persist in the European landscape today (Hupy & Schaetzl 2006) (Figure 19). The size of the craters produced during conflict has increased through subsequent decades due to advances in firepower. In addition to the area from which the most productive upper horizons of the soil profile has been blasted, a surrounding area is mantled by the mixed and inverted material displaced from the crater. Natural processes of soil formation are thus derailed (Hupy & Schaetzl 2008). Bomb craters that remain after the cessation of hostilities can also become artificial receptacles for run-off and sediment, and their overflow can trigger downslope erosion and transmission of sediment into waterways, including karstic conduits (Figure 20). Craters remain un-vegetated and unstable where ponded water facilitates wallowing by animals such as wild buffalo or livestock. In karst areas craters can

Figure 19. One of many craters dating from World War I that still remain extant in France.

Figure 20. Sheet and channel erosion of soils at a karst site in eastern Lao PDR due to drainage changes initiated by heavy bombing four decades earlier, overflow of water episodically ponded in craters being a major factor causing the on-going damage.

sometimes progressively evolve into sinkholes, examples of this having been recorded from both the Italian Alps (Celi 1991) and from Laos (Kiernan 2013a). The focusing of runoff into craters, and the thinner regolith left separating the surface from the eipkarst beneath a crater, probably facilitate this process. This might perhaps be coupled with some fracturing of underlying bedrock by the explosive impact.

UXO and ERW

UXO and ERW pose significant hazards for karst environments, whether due to the disturbance caused by excavation to remove it, or by *in situ* detonation to make it safe (Kiernan 2007). Impediment to use of sites otherwise most suitable for agriculture or settlement may also displace these activities onto more marginal, sometimes karstic, lands. Such issues loom large in the Lao PDR where the American War has left an estimated 13 - 78 million cluster bomb sub-munitions remaining unexploded, in addition to a vast array of other UXO and ERW. Some areas of karst were probably included in the infamous K5 (Bamboo Curtain) project that was established in Cambodia between 1985-1989 after Pol Pot's Khmer Rouge (KR) was driven into Thailand by Vietnamese forces. Because the funnelling of US and Chinese weapons to the KR by the Thai military (Global Witness 1996) allowed it to mount raids from the mountains, the new People's Republic of Kampuchea (PRK) government sought to seal the border and block re-infiltration by the KR. It embarked upon a gargantuan effort to clear vegetation from a strip of the previously pristine Cardomom Mountains and to establish a barrier of landmines. The K5 belt ultimately reached 700 km long and 500 m wide with a landmine density of approximately 3,000/km^2, but it proved unsuccessful in blocking KR infiltrators. The displacement of farmers, PRK use of forced labour in a manner reminiscent of conditions under the KR regime, and massive environmental damage entailed in establishment of the K5 belt, all proved counterproductive for the PRK. Many fled back to a KR base in Phnom Malai area, ~30 km south of Aranyaprathet and 40 km SW of Sisophon, where they were in turn forced to work for the KR. Ongoing processes of environmental degradation set in train by the K5 project, and by the massive volumes of UXO still extant, all continue to impact on the environment and on social and economic development today, many still being killed or maimed for decades afterwards (eg. Lieng 2014). Demining and removal of other unexploded remnants of war is a very expensive undertaking that is beyond the financial capacities of many developing countries. It has been suggested that in Kuwait demining cost up to US$67,000/km^2 (Anon. 2013c).

Impacts on social and economic development

The implications of war for subsequent social and economic development are diverse. Some of the implications of geomorphic damage and ERW for local people include degradation of land resources and resulting impacts on their livelihoods. Depleted soil productivity, increased pressure on marginal land and persisting endemic poverty, all imply further damage to any karst area in which war has occurred. The damage caused by war also compromises cultural heritage and cultural landscapes, ERW limiting the potential for tourism to assist in poverty reduction. It may also cause such safe sites as may be available to come under abnormally high visitor pressure, and there is commonly limited capacity for needed management responses. These latter factors have contributed very significantly to major degradation of caves used by tourists in Indochina, where the damage caused by short term "scenery mining" precludes longer term sustainable cave tourism as a more enduring component of poverty alleviation (Kiernan 2011, 2013b).

The development of military roads in northern Laos by Chinese authorities during the Indochinese anti-colonial wars facilitated improved communications for the civilian population during subsequent decades. But these apparent benefits were environmentally two-edged, implying additional environmental impacts generated by both subsistence and commercial enterprises that these roads facilitated. The social benefits were also unevenly spread, with many poorer people being unable to take advantage of new opportunities that allowed those who were already better off to leave the poorest further behind. Similarly, development of the US defence highway system facilitated useful economic development, but it also only directly impinged on karst areas in some cases and had the wider consequence of contributing dramatically to advent of the car culture so dominant in the US. Increased mobility of US citizens in turn facilitated increased expansion of towns, suburbs, pollution and new environmental pressures onto the karsts of the USA that are unlikely to have progressed so rapidly and comprehensively were highway development not adopted as a defence strategy.

When war interrupts civilian programs it often adds expense to their ultimate completion, and if engineering projects are involved public safety concerns may be generated. One karst-related case, in which war exacerbated construction problems rather than actually initiating them, concerns the Mosul Dam across the Tigris River in Iraq. This dam, constructed at an initial cost of US$2.6 billion to provide flood protection, hydro-electricity, irrigation and water supply, is 113 m tall, 3.4 km long and impounds well over 11 billion m^3 of water. (Al-Ansari and others 2015) The development went ahead contrary to the advice of specialists from several nations, who were concerned about it being sited atop gypsum and limestone. Commenced in 1981, problems with karst became very evident almost immediately upon its filling in 1985, including the formation of sinkholes and the eruption of new springs downstream from the dam. The potential for catastrophic dam failure was ultimately recognised around 1996. Subsequent downplaying of this risk by the national government, for political reasons, did not make the problem go away, with bathymetric surveys in 2011 revealing hundreds of sinkholes up to 20 m in size. It was soon being described as the most dangerous dam in the world, with the potential to overwhelm parts of Mosul within hours and reach Baghdad, 235 km downstream within days, potentially costing 1.5 million human lives (Al-Ansari and others 2015, Filkins 2017, Ingram 2019). Finally an urgent grouting program was initiated, but this was subsequently interrupted when the dam was seized by ISIL forces in 2014. Although Kurdish, US and Iraqi forces soon retook possession of the Mosul Dam, they found most of the key equipment had been stolen or destroyed. Perceptions of insecurity impeded engagement of the expertise and labour needed for re-establishment of the remediation program (Al-Ansari and others 2017), thus allowing continued acceleration of the karstification processes and considerably aggravating the likelihood of catastrophic dam failure. Eventually an Italian company commenced operations, guarded by 500 Italian and Kurdish troops (Bibo 2016). They ultimately needed to drill over 5200 drill holes, totalling 395,000 m, and grouted almost 40,000 m^3 into the subsurface, a process that took over three years and involved 8 million man-hours

(TREVIGroup 2021). These latest repairs cost US$530 million. While this has stabilised the dam for now it did not resolve ongoing concern regarding major construction flaws.

Persistent biological damage

Vietnamese authorities assert that as a result of US deployment of AO, several million of its citizens bear health legacies in the form of serious physical ill-health, mental retardation and multiple generations of children with birth defects. Although linkages between many of these conditions and dioxin exposure have been demonstrated, definitive proof of a link between AO exposure and individual victims is difficult to prove (Ngo and others 2006, Schecter & Constable 2006). Red Cross Vietnam estimates over 150,000 children have been born with deformities such as limbs that are missing or are twisted in characteristic manner, or with eyes that lack pupils. These deformities are concentrated around those parts of Vietnam where AO was handled or sprayed, and they are now affecting the second and third generation descendants of parents who were exposed to AO. Given such apparent impacts on the human organism, what unrecorded and hitherto unconsidered impacts may also have been inflicted on cave and karst fauna? Once again, in the absence of any direct evidence it is only possible to speculate on whether karst biota was impacted by reference to impacts on humans. Nevertheless, the persistence and mobility of dioxin from AO has been amply demonstrated in Vietnam where it has been shown to be moving through the food chain (Hatfield Consultants 2007). There is evident bio-accumulation, with residues detected in fish and ducks, and concentration in the food chain also militates against commercial export of foodstuffs from areas known to be affected (Ghalaieny 2013).

Contention persists as to the effects of AO, including suggestions by parties in the USA that some deformities may instead be the result of venereal diseases. Because Vietnam is an emerging economy with a testy relationship to its larger neighbour China, an emerging rival to US power, it is in US interests to foster improved relations with Vietnam while simultaneously seeking not to act in a manner that might be legally interpreted as acknowledgement of fault that could lead to a potentially massive liability for reparations. Hence, in 2008 the US Bush Administration provided funds to remediate dioxin contamination around its former base at Danang, not in any admission of a link between AO and the health issues and birth defects, but rather as a "humanitarian" gesture (Martin 2009). Such reticence persists despite the fact that in US veterans won a $197 million payout from the manufacturers of AO, and despite progressive acknowledgment by the US Department of Veterans Affairs that veterans suffering from a variety of conditions, including Hodgkin's lymphoma, ischemic heart disease, hairy cell leukaemia and Parkinson's disease, were likely to have acquired these from their exposure to AO, and evidence of a very high rate of spina bifida among their children, a condition associated with an AO ingredient (Wilcox 1989; USDVA 2012). About 10,000 US war veterans receive disability benefits for various cancers and other illnesses linked to dioxin exposure. New Zealand veterans collectively received some financial compensation about 20 years after exposure following a class action suit in the USA. But while some overseas veterans have been granted significant financial compensation payouts or regular benefit entitlements most Vietnamese families with a deformed child receive little or no government assistance. Similar contention exists regarding the harm possibly caused by depleted uranium (Priest 2001; Al-Hadithi and others 2012; WHOROEM 2012). The various direct and genetic impacts suggested in humans raise the potential for harmful legacies to also persist in impacted cave biota and karst ecosystems.

Environmental clean-up

Demilitarisation may involve stockpiling and perhaps defusing of armaments that are no longer needed, but all too often much material is simply abandoned. This may again include such substances as TNT, RDX, hydrazine and nitric acid, with other UXO and ERW including landmines and undetonated bombs being left more widely scattered. Leaking toxins from some 700,000 weapons abandoned in NE China by retreating Japanese forces towards the end of WWII have been implicated in at least 2000 deaths. Two decades after China intensified its efforts to force Japan to accept responsibility and remediate the area, Japan relented and after 1997 some clean-up occurred. However, the magnitude of the task was greatly underestimated from the outset, progress fell well short of total clearance, and the presence of scattered karst aquifers under some of these locations (Lu 1986) provides a less obvious potential complication. Corrupt diversion of funds by executives of a consulting firm that was engaged with the project added to the difficulties.

The high costs entailed in site clearance and healthcare for victims are major risks facing any party that acknowledges its accountability for the results of its previous military activities, and fear of establishing a legal precedent is generally strong. In the few cases where any responsibility has been accepted it has generally involved situations in which it was in the interests of the guilty party not to antagonise another politically valuable party, such as commitments by the US to clean-ups in Canada and Panama, and Japanese efforts in NE China. In this regard the international laws of war have been left replete with vague definitions, and are made all the more difficult to enforce by exemptions for military "necessity" (Austin & Bruch 2000; UNEP 2009; Bothe and others 2010; Risen 2010). Efforts by many nations to comply with the Chemical Weapons Convention has resulted in their ridding their own territories of such weapons, but typically they have not removed the weapons they have left behind following their overseas military adventures.

Commercial opportunism involving premature diversion of wartime technology

Through the period of World Wars I and II considerable effort was put into development of chemicals as weapons of war and of various means for dispensing them against enemies who were sometimes dehumanised by wartime propaganda that portrayed them as being "pests" or "vermin". With the cessation of hostilities in 1945, this large body of expertise and equipment potentially lay idle, but was instead rapidly recruited into civilian use in agriculture and forestry as a means of spreading biocides against agricultural rather than human "pests" and for spreading fertilisers. Many of these substances remained poorly understood at the time (Russell 2001; Russell & Tucker 2004) but widespread indiscriminate spraying occurred nonetheless.

The resulting environmental harm provoked the concern of writers such as Rachel Carson, who in her landmark book *Silent Spring* (which revealingly was originally entitled *The War Against Nature*) included reference to the consequences of forest spraying on karst-rich Vancouver Island, Canada. Here a Canadian biologist who witnessed spraying in 1957 reported that coho salmon subsequently developed an opaque white film over their eyes and moved only sluggishly. Subsequent laboratory analyses by the Canadian Department of Fisheries revealed that all fish not actually killed by exposure to low concentration DDT showed symptoms of blindness (Carson 1962). Given this dramatic impact on salmon, it seems reasonable to assume there were also detrimental impacts upon other organisms, including organisms in karst caves and aquifers on Vancouver Island and in other karst areas subject to similar spraying – salmon are known to migrate through karst caves in south-eastern Alaska to spawn. The vast areas of forest cleared during World War II to aid the US war effort led to large scale post-war replanting programs which in turn led directly to the advent of industrial-scale forestry. There were especially large impacts on the Atlantic coast and the karstic Appalachian Mountains from which the war industries had removed the best pine, leaving mostly lesser value species. This sowed the seeds for massive expansion of the paper industry, and major fires that subsequently occurred in parts of the Appalachians, from which fire had been largely absent for millennia, and resulted in erosion and sediment transmission in karstic catchments.

Conclusions and discussion

The impacts of war in karst represent, in microcosm, the impacts of war on the wider environment. A legal basis for attempts to protect the environment during armed conflicts has traditionally been sought under international humanitarian law, but this approach imposes some significant limitations. For example, the anthropocentric focus that underpins humanitarian law overlooks the more ecocentric perspectives that commonly underpin nature conservation initiatives, such as the Convention on Biodiversity, the preamble to which records that its signatory parties are conscious of the "intrinsic" values of biodiversity. Nevertheless, additional Protocol I of the Geneva Conventions prohibits means or methods of warfare that will cause, or may be expected to cause, environmental damage that is severe, widespread and long-lasting. However, these terms are not precisely defined, there is seldom any pre-conflict baseline data available for comparative purposes, and the few post-conflict environmental assessments thus far undertaken have been very narrowly focused on biota and water chemistry alone, and even then have been relatively superficial. No consideration has been given to geodiversity apart from perhaps occasional non-specific references to possible soil erosion, and karst has never featured.

It is not just in karst environments that some forensic geomorphology, programmed such as to capture not only the immediate impacts of conflict but also longer term damage caused by geosystem readjustments such as the long-term consequences of drainage derangement, would doubtless demonstrate that war has caused “severe” environmental impacts that will take far longer than mere human generations for recovery (if it can ever occur) and is thus “long-lasting”. A karst site might well offer the opportunity for a useful test case, focusing not just on the immediate destruction but also on such longer term impacts as the progressive loss of destabilised soil into the epikarst that is today so evident in Laos, Cambodia and elsewhere (Kiernan 2010a, 2010b, 2013a). But unfortunately, the criteria “severe”, “widespread” and “long-lasting” are presented collectively rather than singularly, and meeting only two may not be sufficient for successful prosecution of any party charged with such an environmental war crime. The vague term “widespread” would also doubtless be contested, notwithstanding the fact that any human community faced with the despoliation of all the productive land accessible to it might consider that to constitute “widespread”.

The United Nations’ International Law Commission (ILC) is mandated to develop and codify international law, and it has recently adopted a set of draft principles designed to improve environmental protection during conflicts. These allow for designation of important environmental and cultural places as protected areas, something that might conceivably be invoked to safeguard special karst places. Protection of features held sacred by indigenous people would also be consistent with the UN Declaration of the Rights of Indigenous People. Unfortunately, one of the new ILC draft principles limits such protection to sites that do not contain a military objective (Kiernan 2021). This limitation is also contained in the 1954 Hague Convention for the Protection of Cultural Property in the event of Armed Conflict (Chamberlain 2004). Given the extent to which karst terrane has so deliberately and consistently been utilised for the siting of guerrilla and other bases, convincing protagonists not to use the cover that karst offers would likely be a considerable challenge.

Worldwide military expenditure in 2019 totalled US$1922 billion (2.19% of world GDP) (SIPRI 2021) – this equates to over US$5.26 billion every day spent on the business of war at the expense of other environmental and social programs. The US$330 billion/year that has been estimated (von Grebmer and others 2020) as the cost of eliminating world hunger by 2030 could be covered in just a little over two months if world military expenditure could instead be diverted to this task. The environmental degradation that results from war, from the rudimentary farming techniques of many still-impoverished peasant villagers in the karstlands of Indochina even four decades after the American War and our limited understanding of contamination in karst aquifers following armed conflicts, all highlight how much more usefully the resources currently devoted to militarism could otherwise be expended. But while peace and the prevention of wartime environmental harm may be a better option that attempting to cure the damage once inflicted, the harsh reality is that war continues to occur in karst and other natural environments. Reduction of the harm it generates is a very complex challenge, but one that demands greater attention by researchers, educators, policy developers and legislators.

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Investigation into the geoconservation significance of the Lost World boulder caves, Mt Arthur, Tasmania

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Abstract

This report outlines the geoconservation significance of the Lost World boulder caves of Mount Arthur in Wellington Park, Southern Tasmania. The study carried out an investigation into the geodiversity and the geoconservation significance of the site, analysed current and possible future threats to the site, and also recommended some potential management approaches for the site. It is hoped that this study will motivate further research into the role of these caves as a unique habitat, whilst also prompting the application of more targeted environmental management approaches to the area.

1.0 Introduction

Geological and geomorphological conservation, or geoconservation, is the effort to manage change in geodiversity - the diversity found within abiotic nature. Although geoconservation has been recognised as being of some importance for over 100 years, there has always been an imbalance between the biotic and abiotic elements of nature when it comes to conservation policy and practice (Gray 2004). Conservation of geodiversity is in itself important, as many of the processes that formed the present landscapes are now inactive. Once disturbed, these sites may never recover (Pemberton 2007).

Geomorphology controls physical conditions, which in turn control biodiversity. Management of biodiversity is therefore highly dependent upon management of the landscape on which it resides. The emergence of the geoconservation concept in recent decades has prompted many environmental management bodies to focus increased attention on research into the geological and geomorphological aspects of the sites that they are managing, thus adopting a 'total ecosystem perspective' (NRM South 2003; Pemberton 2007).

1.1 Site Description

1.1.1 Location and access

The study site is situated approximately 9 km directly west of the city of Hobart on Mount Arthur and is easily accessible from The Big Bend on Pinnacle Road via the Lost World walking track (see Figure 1).

The walking track leads to a spectacular lookout at the top of a natural amphitheatre formed by dolerite cliffs. At the base of this escarpment lies an extensive boulder field which can be accessed via a rough track created by rock climbers that leads down the northern margin of the cliffs. There is also a less complexly developed boulder field situated above the cliff line (see Figure 2). Numerous caves are present in the boulder fields, with many chambers connected by easily accessible passages.

The Lost World lies within Wellington Park, which is reserved under the *Wellington Park Act 1993*. It is not officially classified as a national park under Tasmanian legislation, though the applicable regulations are virtually identical. The reserve is managed by the Wellington Park Management Trust and local city councils, one aim of management being preservation (Wellington Park Management Trust 2010).

1.1.2 Previous studies

Although the site is readily accessible and lies within the Wellington Park, there has been very little investigation or detailed recording of its features.

Skinner (1973) appears to be the only person to previously attempt to document any of the caves in detail, surveying three: "Lost World Grotto" (305 m long), the 360 m "Dolerite Delight" (which he suggested might be joined) and "Campers Cavern" (135 m), and referring to a fourth as "only about 100 metres long". Skinner noted the existence of *Hickmania,* another (unidentified) spider and a cave cricket he thought was of the genus *Parvotettix.* Unfortunately, lack of locational details has not,

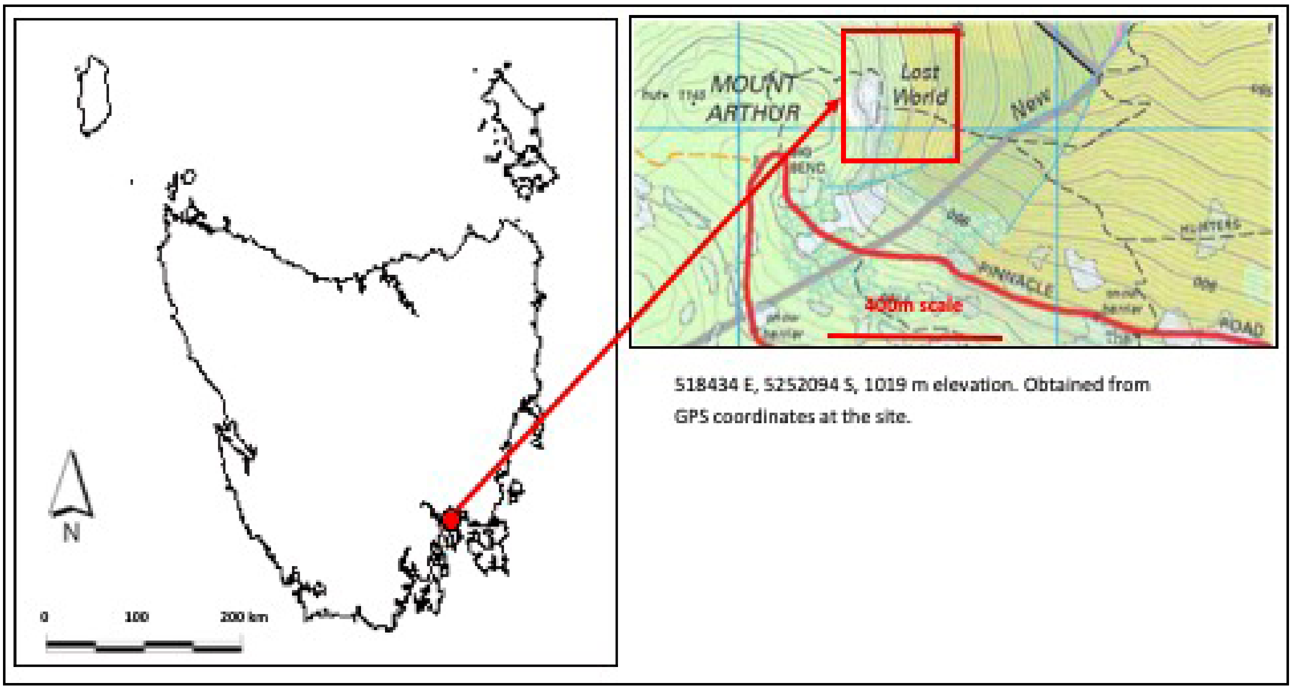

Figure 1. Map of Tasmania, showing the approximate position of the study site, together with an enlarged (1:25000) topographic map with coordinates and elevation. Topographic map obtained from LISTmap version 1.2, Department of Primary Industries, Parks, Water & Environment, accessed 19th March 2010 <www.thelist.tas.gov.au/listmap>.

to date, facilitated identification of these particular caves. They may, in part, overlap the caves described here.

Banks (1981, quoted in Dixon 1995) attributed the lack of major disruption among the fallen columns to "paucity of fractures across the columns, to lowness of the cliff in the early stage of its development during the Last Ice Age and to a cushioning effect of a thick bed of snow in the hollow adjacent to the cliffs supporting and slowly lowering the columns after they were wedged out."

Kiernan noted the existence of this substantial system of talus (boulder) caves in discussing talus, joint and fault caves in Tasmania (Kiernan 1982).

Bradbury included 'Lost World boulder caves' in his inventory of sites of geoconservation significance in Tasmania. He regarded them as 'Outstanding for Tasmania' (Bradbury 1995, p. 27).

In 1995, Dixon included the 'Lost World dolerite boulder cave complex' among 'Additional features of geoconservation significance which should be considered for National Estate listing'. He considered the cave complex might be significant at the national level, given the lithology and form.

Leaman (1999) was impressed by the site, suggesting its "tumble of dolerite columns" were the result of ice activity and, possibly, seismic activity. He described the "extensive caverns beneath the jumble" as being due to "removal of much of the debris which can accumulate between boulders" but refrained from further comment, except to warn "this is a dangerous and awesome place".[1]

The geomorphology of the study site is strongly controlled by the geology of Wellington Range, which is comprised primarily of dolerite emplaced during the Jurassic period approximately 170 Ma BP (Seymour and others 2007). This dolerite is an intrusive igneous rock found extensively throughout Tasmania. It originally intruded the surrounding host rock as a magma at a temperature of approximately 1100°C. As it cooled and crystallised, the rock contracted, causing jointing within the body of rock and forming the polygonal columns that are exposed in several places on Mount Wellington and Mount Arthur. The boulder deposits situated at the base of the dolerite cliffs of the study site represent a landscape created by slope failure and mass wasting. Figure 2 shows the strong trend in the orientation of the collapsed dolerite columns, suggesting a mass wasting event that caused simultaneous toppling of the weathered columns away from the cliff. This

1 Editorial addition: Lost World Boulder Caves has been listed as a geoconservation site in the Tasmanian Geoconservation Database (accessed through https://www.naturalvaluesatlas.tas.gov.au/#GeositePage:2224) where it is stated that there are passages in excess of 300 m length and 40 m depth. The (official) Statement of Significance for this site is: "Notable example of type, the most extensive network of boulder caves known in Tasmania" (the listing originated in March 1995; accessed 26 June 2021)

event has preserved cracks and crevasses within and between these dolerite columns which now present as boulder caves.

Boulder caves may incorporate morphologies resembling karst, and may even have a predominance of subsurface drainage through conduit-type voids, but they differ from karst caves by lacking long-term evolution by solution and physical erosion.

1.2 Aims

The aim of this report is to assess the geoconservation significance of the Lost World boulder caves. The caves are the most extensive of their type known in Tasmania (Wellington Park Management Trust 2005), and as such have considerable potential geoconservation significance. By investigating the physical conditions of these caves, their role as a special habitat can be better understood. This study will broadly document the geodiversity and biodiversity of the cave systems. These data will provide greater understanding of potential threats to the site, allowing a targeted management plan to be utilised to protect these unusual karst-like systems.

1.3 Methods

1.3.1 Cave mapping

A limited but concise cave mapping exercise was carried out in one of the largest cave systems within the boulder field at the base of the cliffs (see Figure 2). These particular caves were chosen for their ease of access, representative morphology and large extent. Three people were required in the cave system at all times to carry out the mapping exercise; two people acted as surveyors, and the third person acted as the sketcher. Surveyors carried a laser range finder to obtain accurate distance measurements, and a clinometer to measure slope angles. The mapping exercise encompassed cavern and passage morphology, as well as noting signs of anthropogenic disturbance. Cave surveying and sketching was conducted in a manner that conforms to the Australian Speleological Federation's Cave Survey and Map Standards (Grimes 1997).

1.3.2 Identification of geodiversity values

Identification of geodiversity values was achieved with the use of a table adapted from Gray (2004, pp. 131-132), which lists a summary of common geodiversity values and examples of each. The table was modified to suit the site being surveyed, and a copy given to each volunteer who visited the site during data collection field trips. Each volunteer attempted to identify as many values as possible whilst at the site. Their responses to the values listed were compiled, and are summarised in section 4.1. This was a valuable exercise as it encompasses the views and opinions of people from different backgrounds and with differing attitudes towards the subject of the study. Whilst the study would have ideally included more people, the opinions given by the available volunteers are believed to be sufficient.

Figure 2. Photos of the study site. The photo on the left shows the two scree deposits surveyed, separated by jointed dolerite cliffs. The photo on the right, taken from the top of the cliff line, shows a strong trend in the orientation of the collapsed dolerite columns. Scale bars shown are approximate.

1.3.3 Analysis of threats

Analysis of current and future threats to the study site was carried out with reference to Murray Gray's text *Geodiversity: valuing and conserving abiotic nature* (2004). Gray dedicates an entire chapter to common threats that geodiversity faces. A brief insight into current threats was achieved through observation of current physical conditions at the site, such as signs of anthropogenic disturbance.

1.4 Limitations and challenges

This investigation was highly dependent upon volunteer availability and weather conditions. For safety reasons, at least five people were required at the site during data collection field trips. This allowed the three people required for mapping to enter the caves, with at least two people remaining on the surface to carry out extra data collection and to act as a safety presence in the event of an accident or emergency. Weather conditions were another limiting factor during this study, as they impact significantly on the safety of the study site. Mount Wellington commonly experiences sudden changes in weather conditions, with field trips being postponed due to rain and fog on several occasions. Slippery conditions caused by rain or snow proved to be dangerous, as considerable rock-hopping was required along the access route.

The most significant challenge when conducting this study was the lack of both theoretical and empirical knowledge regarding the site. Apart from the brief listings and survey mentioned in section 1.1.2, the Lost World has never been comprehensively documented, so there was little opportunity to consult literature during planning stages or prior to data collection. The most appropriate literature offered insights into comparable environments, but nothing provided preparation for the overwhelming amount of information potentially available for collection at this very complex study site. It was easy to become 'bogged down' in excessive data collection. As such, compilation of this report became focussed upon giving a broad overview of the site, leaving scope for more specialised, targeted studies in the future.

2.0 Cave Environments

Caves are complicated landforms both structurally and environmentally. Environments outside and inside the cave are highly differentiated due to their structural complexity (Russell and MacLean 2008). This section will outline the geodiversity of the Lost World by describing the geomorphology of the site, as well as suggesting several possible formation scenarios.

2.1 Cave morphology

There are two primary boulder fields at the study site. While caves within each deposit show many similar characteristics, there are significant structural differences between the two boulder deposits. This is primarily caused by their different modes of formation (see section 2.2).

2.1.1 Cave systems above the cliff line

The boulder field situated above the cliff line consists of dolerite blocks up to approximately 5 m in size, with the majority being 1 - 2 m in size. This deposit shows signs of long-term stability, with all block faces observed being both chemically and physically weathered (though not extensively), and most blocks being covered with lichens and mosses. Boulder caves in these deposits are abundant, but lack both the vertical and lateral extent, and the structural integrity of those in the boulder deposit at the base of the escarpment. The structure of these caves is controlled by the various and chaotic orientations of the blocks within the deposit, and hence of the resulting interstices between these blocks. With no preferred orientation of the blocks within this deposit, the caves can be very difficult to navigate. Caves also showed a far greater tendency to be isolated from each other above the cliff line than those in the amphitheatre where more consistent block orientations allowed greater continuity of interstitial space.

The cave systems above the cliff line are well ventilated and contain a significant diversity of cave fauna (see section 3.1). Despite a short-term lack of rain preceding the first data collection field trip (conducted in March), the caves in this area appear consistently damp and humid. Moss is present on many moist boulder faces, and mud is common at the base of the caves. This suggests that these cave systems are likely to provide a damp environment even throughout the drier months of the year, whilst also discounting the possibility of a significant drainage system with high volumes of water flow, as this would have washed away the mud.

2.1.2 Cave systems below the cliff line

In contrast to the deposits above the cliff line, those situated at the base of the escarpment contain dolerite blocks up to 20 m in size, and possibly even larger. The morphology of this deposit is primarily controlled by the form of the polygonal dolerite columns of the cliff, as it has obviously been created during a toppling process in which the columns toppled simultaneously, thereby providing lateral support to one another that allowed the columnar form of adjacent columns to be retained (see Figure 2). This deposit shows the same signs of long-term stability as discussed in section 2.1.1, with the addition of trees growing from the interstices between rock masses. Boulder caves within this deposit are very well developed, with significant lateral and vertical extent, as well as considerable connectivity between caverns. The morphology here begins to resemble that of fissure caves, with parallel walls and narrow passages (Striebel 2008), as a result of the strong structural alignment of the dolerite columns. The structural integrity of these caves is robust due to the structural control of the collapsed columns.

The cave systems at the base of the escarpment have multiple entrances, and are very well ventilated. A significant diversity of cave fauna occurs in these systems (see section 3.1), which are very damp and humid. The floors of most passages in these systems consist of mud and gravel (see Figure 3), while the floors of caverns are typically covered in rock piles and large boulders. Very little organic matter is present within the caves.

Figure 3. Narrow passage, showing the entrance of a near-vertical shaft to a lower level, and the typical vertical walls controlled by the structure of the toppled boulders. This image also tries to show the damp, muddy floors that contain high amounts of gravel and cobblestones.

Cracks and crevasses between the dolerite blocks are controlled by the orientation of the collapsed columns. The largest caverns within this boulder field occur where a column has fallen onto uneven ground and formed a void, or where larger blocks have fallen subsequent to the columns. Most passages between caverns are controlled by the structural planes of the columnar jointing (east-west), or by the strike of the cracks within the columns, which is perpendicular to the orientation of the columnar jointing (north-south). Caverns are up to 6 m in height, ranging from a few metres in width and/or length to over 30 m. Passages are typically 1- 2 m wide, with vertical walls and a planar roof (see Figure 3).

The cave systems surveyed and mapped for this report, informally named ‘Multistorey Cave’ and ‘Lost World Labyrinth’, have several levels that are controlled by the way in which the columns fell. The maps (Figures 4, 5 and 6), provide an insight into two of the largest and most easily accessible cave systems at the study site. These cave systems are highly representative of the area, displaying most of the geodiversity values discussed in this report.

2.2 Cave formation scenarios

The chaotic arrangement of the boulder deposit above the cliff line suggests a gravity-driven mass movement event, with the boulders originating from upslope (allochthonous). The structural trends of the caves below the escarpment suggest a more complex origin, formed by toppling from the adjacent cliff face (autochthonous). While the scope of this project did not allow for thorough investigation into the exact mode of formation of these caves, literature review has revealed some possible scenarios that may suit the site. The first scenario, inspired by Colhoun’s research into periglacial landforms and deposits in Tasmania (2002), involves *in situ* frost and ice wedging of the dolerite columns on the cliff face. This process involves continual expansion and contraction of water trapped between the joints in the rock as it freezes and thaws in this elevated environment. Freeze/thaw cycles do not account for the seemingly simultaneous collapse of the columns though, so may only be considered a contributing factor, rather than the primary cause, of the cave formation.

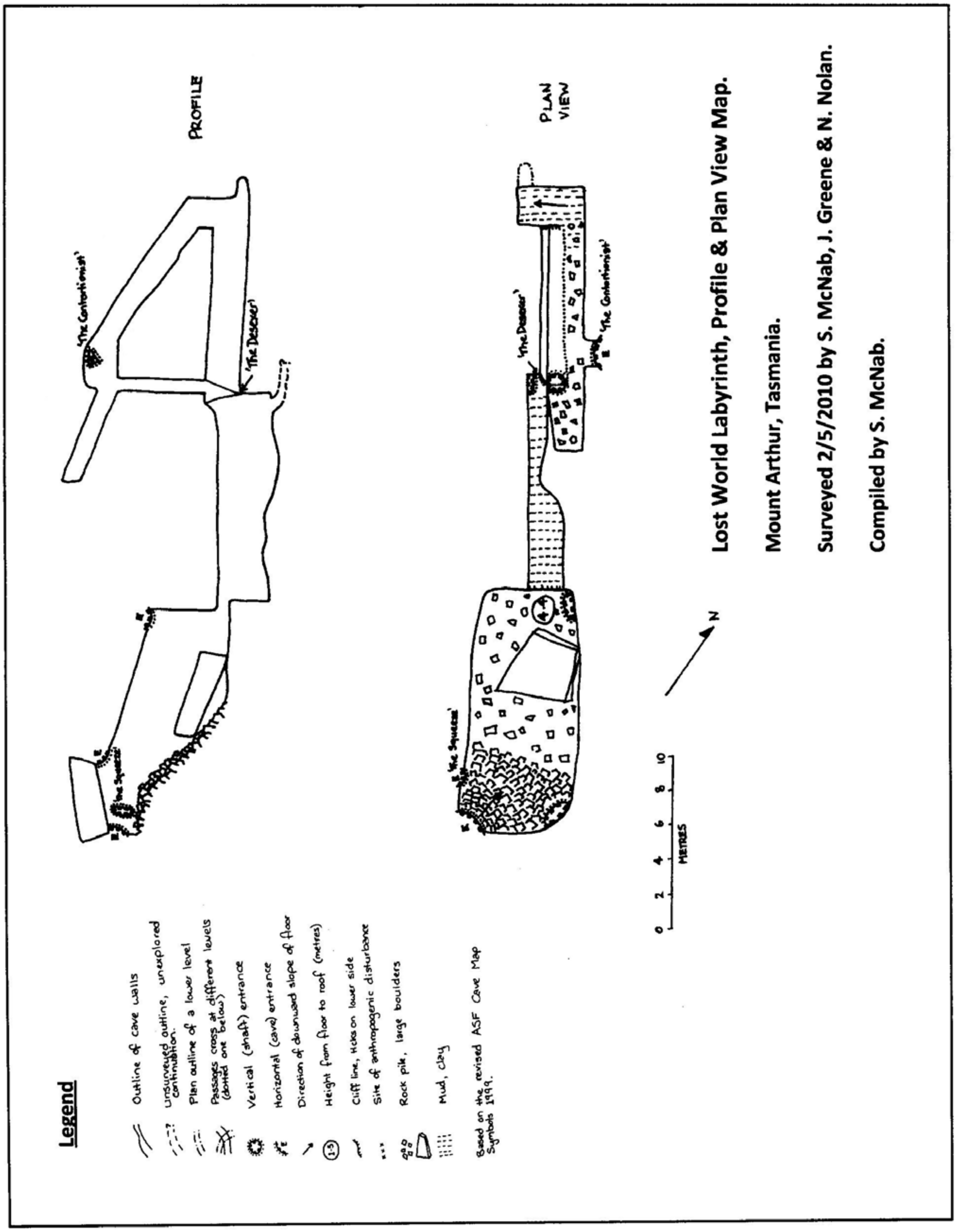

Figure 4. Plan and profile / longitudinal section of Lost World Labyrinth, Mount Arthur.

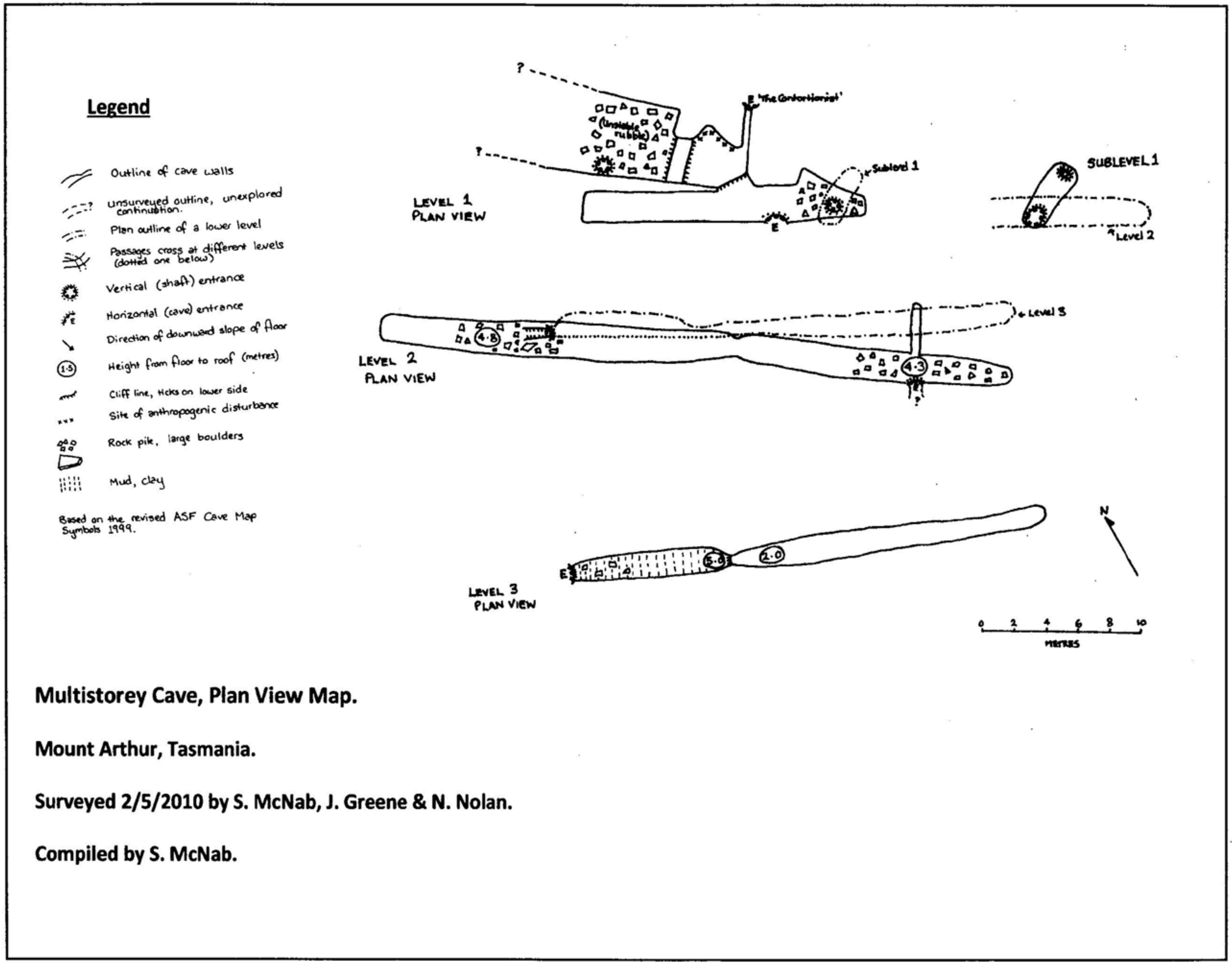

Figure 5. Plans showing three levels in Multistorey Cave, Mount Arthur.

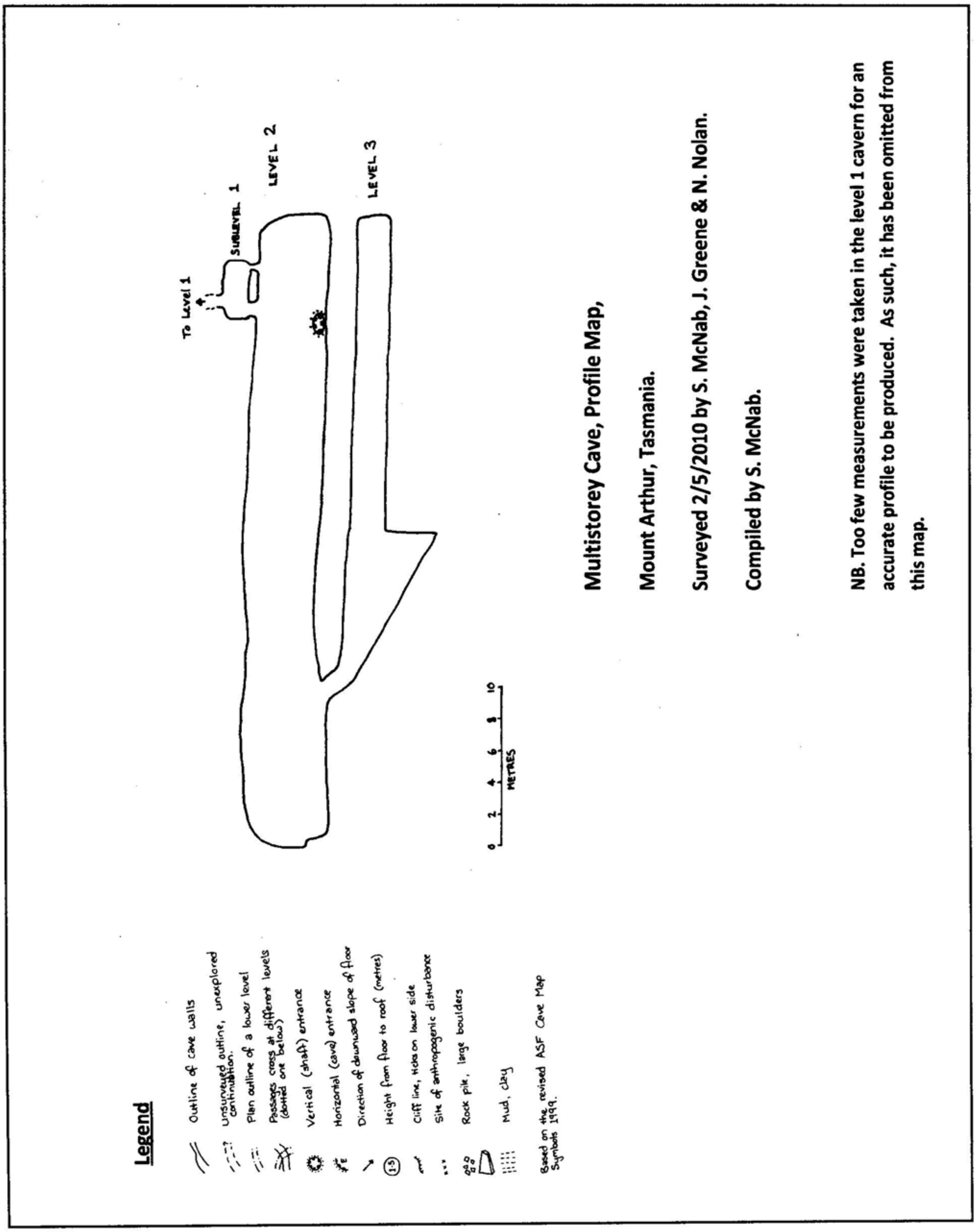

Figure 6. Profile / longitudinal section of Levels 2 and 3 of Multistorey Cave, Mount Arthur.

The second scenario is partially based on the proposed origin of the extensive talus caves of Sweden, described by Sjoberg (1986). Sjoberg describes talus (or boulders) on collapsed mountain slopes creating “more or less vertical caves with big grottos connected by narrow passages” (1986, p. 396), concluding that the stacking of the boulders is evidence of momentary collapse caused by a neotectonic event. A similar earthquake event is not impossible at the study site, given the fault-bound geological setting of Mount Wellington (Stacey & Berry 2004), and may have caused the cliff face (already weakened by jointing within the rock) to collapse in a single event to form much of the boulder field at its base.

The final scenario, suggested initially by Kevin Kiernan (pers. comm.) and developed with reference to Caine (1982, 1983) and Smith (2007), involves basal slipping of the dolerite on the lubricating sedimentary rocks below it. Smith describes caves on Pilchers Mountain in NSW that formed from massive sandstone block separation aided by “the presence of underlying shale and coal bands which acted as slip planes when lubricated by groundwater” (2007, p. 15). Colhoun (2002) explains that the rock unit underlying the dolerite sill on Mount Wellington is composed of weak sandstones and mudstones that are conducive to slope failure. Considering the damp environment of Wellington Range, a scenario similar to that proposed by Smith (2007) is plausible.

3.0 Biodiversity

Subterranean habitats are characterised by complete darkness in most cases, resulting in the absence of green plant life (Eberhard and others 1991). The extent of microclimatic variation is controlled by a combination of cave structure and the physical conditions within the caves. Multiple entrance caves, such as those of the Lost World area, have highly variable microclimatic conditions due to increased ventilation, allowing constant exchanges with the outside environment (Russell and Maclean 2008). Sources of nutrition are scarce, meaning that only highly specialised species are able to survive in subterranean environments (Eberhard and others 1991).

Cave ecosystems are generally small, highly specialised, and relatively isolated, resulting in an island-like geographic range of cave-dwelling species (Eberhard and others 1991). This attribute lends itself to endemism, which is a significant factor in the conservation of cave biology. The functional role of caves as an ecosystem is an important value of geodiversity, and this section will briefly outline the biodiversity observed at the Lost World that may increase the geoconservation significance of the site.

3.1 Fauna

The classification of cave-dwelling fauna, or cavernicoles, is based on their association with various zones within the cave (Doran and others 1997):

- *Troglobites* are adapted to subterranean environments, and cannot survive outside them.
- *Troglophiles* typically live and breed within the cave environment, but are not confined to it.
- *Trogloxenes* regularly inhabit caves for shelter, generally staying close to the entrance as they require access to the surface to feed.
- *Accidentals* are surface-dwelling animals that cannot survive in a subterranean environment, but unintentionally find themselves trapped within a cave system.

Cavernicoles observed at the Lost World consisted only of invertebrates. The scope of this investigation did not allow for further research into evidence of vertebrates.

3.1.1 Invertebrates

The most abundant cavernicole observed within caves at the Lost World is a large arachnid, confirmed by Niall Doran (pers. comm.) to be the Tasmanian Cave Spider (Figures 7 and 8). *Hickmania troglodytes* is a troglophile (Doran and others 1997, 1999), primarily residing in the entrance and twilight zones, and is known to inhabit caves on Mount Wellington (Eberhard and others 1991). *H. troglodytes* is the largest spider in Tasmania, and is endemic to the state. The species displays physical traits of both primitive and advanced spider groups, and as such is considered to be highly significant in evolutionary terms. Doran and others (1999) also recognised the species as being ecologically important as a top-level cave predator, and zoogeographically important, as it has been discovered that its closest relatives are found in South America. This spider is the only known species in the *Hickmania* genus (Doran and others 1997).

Figure 7. *Hickmania troglodytes*, found in the twilight zone of Multistorey Cave. Maximum leg span of approximately 15 cm.

Figure 8. *Hickmania troglodytes*, found in the twilight zone of a talus cave above the cliff line, with a maximum leg span of approximately 18 cm.

H. troglodytes is particularly susceptible to any alterations in the availability of food. As these spiders feed primarily on crickets of the genus *Micropathus*, which are also found in the Lost World boulder caves, food availability is highly dependent upon events outside the cave, as that is where *Micropathus* feeds (Doran and others 1997, 1999). External conditions and disturbances can therefore indirectly affect the survival of the Tasmanian Cave Spider.

Cave crickets are widespread in Tasmanian caves, with the *Micropathus* genus most common in the western and southern parts of the state that receive more rainfall. Most cave crickets are omnivorous, sourcing their food from outside the cave system. *Micropathus* is endemic to Tasmania (Eberhard and others 1991). *Micropathus tasmaniensis* was recorded from a "fissure cave in dolerite, Mt. Arthur" (Richards 1968); it was collected in August 1967 by A. Goede. Niall Doran (pers. comm.) believes the cricket shown in Figure 9, observed by us in several caves at the Lost World, to be a species of the *Micropathus* genus. This appears to be a reasonable assumption, given earlier records and the presence of *H. troglodytes*, whose primary food source is *Micropathus* spp.

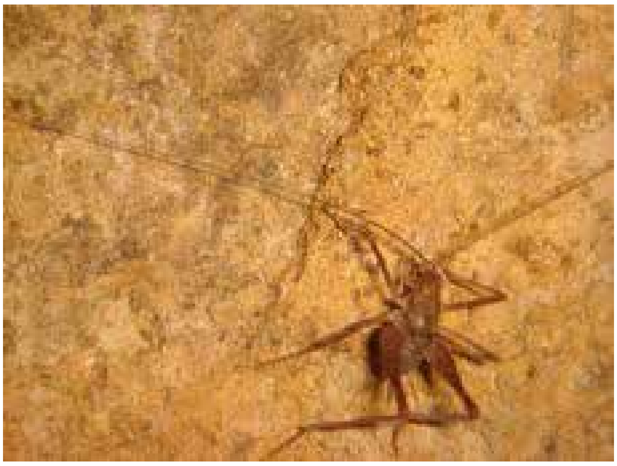

Figure 9. Unidentified specimen of the *Micropathus* genus, found in the twilight zone of Multistorey Cave.

Tasmanian glowworms are the larval stage of the fungus gnat *Arachnocampa tasmaniensis*, which is endemic to Tasmania (Driessen 2009, 2010; Eberhard and others 1991). Larvae hatch in spring and summer, emitting bright blue light and producing silk threads covered with droplets of sticky mucus to catch their prey (Driessen 2009, 2010). *A. tasmaniensis* is not confined to cave systems, but also occurs in moist and sheltered surface habitats such as forests. The species is most commonly found near the entrances to stream caves (Eberhard and others 1991), which is why it was a surprise to observe them in one of the caves above the cliff line at the Lost World (see Figures 10 and 11). Situated on the base of a damp boulder approximately 10 m below the surface in the twilight zone, the glowworms are luminous, and their silk threads are easily observable. The presence of *A. tasmaniensis* at the study site makes preservation of the surrounding forest essential, because it provides additional refuge and allows continuous colonisation of the caves (Eberhard and others 1991).

3.2 Flora

Photosynthesis depends upon the presence of light, so the absence of light within cave systems means that the vast majority of plant species are not able to survive in this environment. While there are consequently no plant species entirely unique to the subterranean environment, some surface-dwelling plant types are able to adapt to living in

Figures 10 & 11. *Arachnocampa tasmaniensis* colony found in the twilight zone of a boulder cave above the cliff line.

a cave system. Common subterranean plant types include fungi, cyanophyceae and algae, as well as mosses, liverworts and ferns typical at the entrances of caves (Vandel 1965). While mosses and lichens are common around the entrances, the only plant type present within the deeper reaches of the cave systems at the Lost World is algae. Algal growths are common on consistently damp cave walls in the twilight zone, and present in caves both above and below the cliff line at the study site, though not in significant amounts in the deeper reaches experiencing total darkness.

The role of the Lost World boulder deposits as a habitat for woody shrubs and several tree species is a research topic beyond the scope of this report, however the high moisture levels held by these deposits may prove to play a significant role in the distribution of several plant species. Many eucalypt and myrtle species are concentrated in damp depressions throughout the boulder fields, with the entrances to caves providing a moist environment inhabited by a vast diversity of species, particularly ferns (see Figure 12). Myrtle clusters are concentrated along the base of the cliff line, while eucalypts are more evenly spread out in the landscape. These trends could prove to be significant. Further research is required in· this area.

Figure 12. Shaft-type cave entrance, characterised by a depression in the boulder field, and colonised by a variety of plant species. High moisture levels and ample shade provide favourable conditions for fern species, which are the dominant plant type in these environments at the Lost World.

4.0 Geodiversity and Geoconservation

4.1 Geodiversity values

Geodiversity can be valued in a number of ways, from encompassing an entire community's attitude, to being valued by a single individual. Gray (2004) describes geodiversity as being valued intrinsically, culturally, aesthetically, economically, functionally and educationally. Table 1 outlines the values that I believe to be applicable to the Lost World boulder caves, and those identified by study volunteers.

As with any landscape, the Lost World should be valued for its integrity and right to existence. The geological processes involved in the formation of this landscape are no longer active as Tasmania has become a relatively tectonically and geologically stable land mass. The physical processes that contributed to the morphology of the landscape, such as gravity-driven mass wasting and slope failure, are still active. However, this study indicates that the landscape shows signs of long-term stability, hence if it were to be artificially altered or damaged in any way, recovery over a human time scale is likely to be unattainable.

Table 1. A summary of geodiversity values that are applicable to the study site, and a brief explanation of each. Adapted from Gray (2004, pp. 131-132).

Value Type	Specific Value	Explanation of Value
Intrinsic Value	- Intrinsic and existence value	The landscape has integrity in its own right (NRM South 2003a,b). If disturbed, recovery may be unattainable due to the time scale of the natural processes that maintain the landscape, and the sensitivity of the geosystem and ecosystem as a whole.
Cultural Value	- Spiritual	While the exact link of the study site with Tasmania's Aboriginal cultures is unknown, their spiritual beliefs and understandings create an important connection to the land that must be considered when assessing the geodiversity of this site. This is outside the scope of this project.
	- Sense of place	Local landscapes are an important aspect of contemporary communities, playing a significant role in our sense of place and in our health (NRM South 2003a). Individuals' attachments to the landscape stem from interrelationships between aesthetic values, cultural values, intrinsic values, and functional values. Areas where the landscape is being heavily degraded have an ill effect on the health of some residents, and can cause anxiety amongst communities that leads to a loss of sense of place (NRM South 2003a; Gray 2004)
Aesthetic Value	- Local landscape	Local landscapes often have high visual appeal. Simply referred to as "The Mountain" by most residents, Mt Wellington (and by association Mt Arthur) is one of the most prominent and aesthetically pleasing features of Hobart's landscape.
	- Geotourism	Recreational activities, such as caving and climbing, are highly valued on natural landscapes in Tasmania. Leisure activities can be strongly linked to geotourism, as well as contributing to a sense of place for many locals (Gray 2004).
	- Leisure activities	Recreational activities, such as caving and climbing, are highly valued on natural landscapes in Tasmania. Leisure activities can be strongly linked to geotourism, as well as contributing to a sense of place for many locals (Gray 2004).
Functional Value	- Geosystem functions	Physical systems in dynamic equilibrium, such as that at the Lost World, are extremely important for the continuing function of environmental systems (Gray 2004). It is essential for the health of the ecosystems reliant upon these landscapes that the Integrity of the natural landforms and processes is maintained on all scales.
	- Ecosystem functions	The physical landscape provides the template on which ecosystems reside and function (Gray 2004; Pemberton 2007). The link between geodiverslty and biodiversity is finally being recognised (Pemberton 2007), which means that the role of the physical landscape in the continuing function of ecosystems is achieving a high level of value.

Value Type	Specific Value	Explanation of Value
Research and Education Value	- Earth history and processes	Geological and geomorphological features have allowed scientists to reconstruct much of the planet's history, including the changing geography of land masses (Gray 2004). Dynamic sites such as the Lost World are also important for research into on-going processes, and understanding how they may change in the future.
	- Environmental monitoring	Current and potential future human impacts on the use of landscapes can be ascertained through environmental monitoring (Gray 2004), which allows for the production of a targeted conservation management plan.
	- Education & training	The role of geological and geomorphological landscapes in education of children and the training of future geologists, geomorphologists and pedologists is invaluable. Sites that can be used to demonstrate principles, as well as past and current processes, are essential in order for this to be achieved, and are highly valued as a result (Gray 2004; Pemberton 2007).

The community of Hobart associates a strong sense of place with the landscape of Mount Wellington, and by association, Mount Arthur. The aesthetically pleasing nature of this dominant feature in the local landscape adds to this sense of place. Many individuals experience an emotional attachment to their local landscape, enhanced by interrelationships between aesthetic values, cultural values, intrinsic values and functional values (NRM South 2003a). While the average annual number of visitors to the site is difficult to determine, rock climbing is known to be popular in the area, and anthropogenic disturbance indicates that the caves have been explored in the past. Caving would likely be a popular leisure activity, with the potential for a geotourism venture in the future. Degradation of this landscape would not only impact upon such future economic opportunities, but would also adversely affect many peoples' sense of place, as suggested by NRM South (2003a).

The functional value of the Lost World boulder caves is immeasurable. As the largest group of boulder caves known in Tasmania (Wellington Park Management Trust 2005)[2], these caves host a fragile ecosystem that is highly sensitive to change, and they provide a habitat for several species endemic to the state. This functional value gives rise to research and education opportunities. Despite its small area, the potential for significant scientific discovery at such a site is immense. Environmental monitoring is also important, both to maintain the integrity of the landforms and processes at all scales, and to ensure the continued success of the diverse ecosystem that the caves sustain.

4.2 Threats to geodiversity

Many people would consider geodiversity as being robust and unthreatened, not needing any form of management (Gray 2004; Pemberton 2007). However, as many geomorphological features were created by relict processes, their capacity to recover from disturbance is severely limited, and in some cases extinguished (Pemberton 2007). Some systems are able to repair themselves more readily and at a faster rate than others, which is a factor that must be carefully considered when planning management strategies for sites being threatened. NRM South believe that "some geological sites, for example Mt Wellington, are robust and do not need active management while others, like the karst around Hastings, and many of the sand dunes on the south-east coast need careful management and protection" (2003a, p. 5). Such a belief involves the ill-informed assumption that Mount Wellington is a homogeneous geosystem. This is clearly not the case. Stringent environmental monitoring and targeted management plans are required to maintain the geodiversity of the Lost World.

Direct anthropogenic threats are already having an effect on the boulder caves at the study site. In one of the more easily accessible caverns, graffiti has been carved into several of the walls (see Figures 13 and 14). A lack of public information

2 The current (2021) Geodiversity webpage (https://www.wellingtonpark.org.au/geodiversity/) refers to: "the Lost World boulder cave system (including the longest non-carbonate terrestrial caves known in Tasmania) –Eds.

Figures 13 & 14. Photos showing the excessive amount of graffiti in one of the main entrance caverns of Multistorey Cave (exact position indicated on the map in Figure 5).

and inadequate conservation measures will allow such damage to continue. These disturbances not only affect the aesthetic and intrinsic value of the site, but also threaten the cave environment and the biodiversity sustained within the system. Doran and others (1999) explain that *H. troglodytes* is prone to deserting webs and even egg sacs if disturbed too frequently, and such a state of agitation is detrimental due to the amount of energy it requires in view of the scarcity of food sources. This may account for their rarity in caves developed for tourism (Doran and others 1997).

While it may not necessarily directly impact the Lost World boulder caves, the threat of climate change has implications for the future of the subterranean environment and biodiversity sustained within this system. The role of the caves as a habitat during climate change would make an interesting research topic; however, a changing environment would put the survival of several species inhabiting these caves at risk. Doran and others (1999, p. 259) found that "*H. troglodytes* is itself very intolerant of desiccating conditions and high temperatures". In addition to temperature variations, the availability of water in all forms is important for the maintenance of this ecosystem. Glowworms are apt to shrivel up and die if there is a significant reduction in humidity and moisture availability (Driessen 2009).

Indirect threats to the entire catchment area have profound implications for the geosystem and ecosystem functions of the Lost World boulder caves. Caves are entirety dependent upon outside sources for energy input, and as such are vulnerable to external events, even if they occur at some distance from the cave system (Doran and others 1997). Land clearing, though unlikely within the boundaries of Wellington Park, would adversely affect each of the invertebrate species described in section 3.1.1. Cave crickets rely on forests outside of the cave system for their food supply, and they in turn are the primary food for *H. troglodytes*. Additionally, glowworm colonies often live in the surrounding forests as well as inside cave systems. The preservation of these forests is essential, as they provide a refuge for glowworm populations, and allow continuous colonisation of the caves (Eberhard and others 1991). Forestry and road-building in the catchment area of the Waitomo Caves in New Zealand was proved to cause a decline in the resident glowworm population, which was further exacerbated by changes to the cave entrance to suit the ever-increasing number of tourists entering those caves (Eberhard and others 1991; Driessen 2009, 2010).

Future proposals to expand the geotourism industry must not be overlooked either. Caves effectively have no carrying capacity, and visitors contribute extra fluxes of energy and mass into low energy systems that may not be able to sustain such conditions (Russell and MacLean 2008). Caves such as these would require modifications for ease of access, which would also alter the input of energy and mass. While the structural integrity of these caves suggest that this is a more robust site than many karstic tourist caves, the geosystem as a whole would be put under enormous pressure if these caves were to become a popular tourist destination.

4.3 Geoconservation significance

The intention of this report is to build a case for the geoconservation significance of the Lost World boulder caves by outlining the geodiversity of this site and the threats to that geodiversity. The appropriate human response to threats regarding features that hold some form of value is conservation (Gray 2004). The Lost World boulder caves deserve significant geoconservation measures due to the following reasons, which have hopefully been made clear throughout this report:

- The inability of this system to recover from disturbance as a result of the time scale and complexity of the processes that created it.
- The intimate link between geodiversity and biodiversity at the site.
- Both direct and indirect threats that are already affecting the integrity of the site.

Being situated within Wellington Park, the Lost World already receives some level of conservation afforded by management by the Wellington Park Management Trust. However, as pointed out by Doran and others, "where caves do fall in large reserves, this has mostly occurred as a by-product of protecting other faunal or natural values in the area" (1999, p.261). This is almost certainly the case for this site. The Lost World boulder caves lie within the boundaries of both Tasmanian Geoconservation Database listed 'Wellington Range Periglacial Terrain' (DER18, sensitivity 2) and 'Lost World Boulder Caves' (DERl5, sensitivity 8). These regions are considered to be significant only at the state level, according to the database, and the boulder caves are considered to be 'robust' with a sensitivity of 8 (DPIPWE 2009)[3]. While this may be true structurally speaking, it has obviously not taken account of all aspects of geodiversity, such as ecosystem function, that suggest it is a fragile site and must be afforded active protection.

3 This page has been modified since the original investigation; its replacement appears to be: https://dpipwe.tas.gov.au/conservation/geoconservation/tasmanian-geoconservation-database/geoconservation-sites-listing-process.

5.0 Recommendations

Based upon the findings of this investigation, my initial recommendation is that more research be conducted at the study site. A lack of scientific publications suggests that the scientific community is largely unaware of the geodiversity of this site, and of its geoconservation significance. This report has only provided a broad overview of the site, but the discoveries made thus far encourage further, more specialised studies.

In order to monitor and maintain the Lost World boulder caves, a management plan targeted specifically at the study site must be adopted. In terms of geodiversity, there are no comparable sites in Tasmania that have been the subject of a unique management plan. While other boulder caves throughout the world have been documented and studied (Smith 2007; Sjöberg 1986; Striebel 2008; Kastning 2009), none of these authors have outlined suitable, comprehensive management plans. Management of the site should have a holistic approach, encompassing protection of the abiotic components, so as to save them from further vandalism, as well as management and monitoring of the biotic components. An appropriate starting point for the planning of such an approach would be to consider the analogy with karst landscapes and their management strategies. The management of sensitive karst landscapes is well-documented, and could serve as the basis on which management of this boulder cave system is planned.

In accordance with the holistic management approach, conservation of these caves is essential. While the abiotic structures themselves are robust and show signs of long-term stability, the ecosystem they support is fragile and sensitive to disturbance. Legislation to protect geological and geomorphological sites does exist (NRM South 2003a), but the inclusion of these specific landforms within the partially protected Wellington Park is likely to be incidental. While Doran and others (1999) stress the importance of conservation of the cave's catchment as a whole, the Lost World boulder caves do not appear to have an integrated hydrological system. Nevertheless, as water is likely to feed in from multiple sources, the environs need to be protected from polluting materials and disturbing activities. Further, as Section 4.2 outlines, conservation of the surrounding forested area is essential for the survival of the cave fauna.

6.0 Conclusions

In terms of conservation management, there has always been a strong imbalance between the biotic and abiotic elements of nature. However, the growing recognition of the importance of geoconservation is prompting a more holistic approach to modern environmental management. The Lost World boulder caves, although recognised to be the most extensive cave system of this type known in Tasmania, have received scant attention in scientific literature.

The two boulder deposits surveyed show many structural differences, however the cave systems in both play host to similar faunal assemblages. Caves above the cliff line are characterised by chaotic boulder alignments, are less extensive and tend to be isolated. The environment within the caves is very damp, and hosts *H. troglodytes*, a species of the *Micropathus* genus, and a colony of *A. tasmaniensis* still in its larval stage. These caves likely formed from a gravity-driven mass wasting event.

Cave systems below the cliff line are structurally controlled by toppled dolerite columns, and show significantly more connectivity and extent than those above the cliff line. This damp environment also supports the existence of *H. troglodytes* and the *Micropathus* genus, but the presence of glowworms has not been observed in these caves during this study. Several theories have been proposed in this report and elsewhere for the formation of these caves, however further research would be required before a firm conclusion could be made.

The Lost World boulder caves are valued intrinsically, culturally, aesthetically, functionally and for their research and education potential. The boulder caves hold considerable geoconservation significance, and if damaged or disturbed, may not be able to recover. These cave systems host a fragile ecosystem that is sensitive to disturbance, in many ways similar to that of a conventional karst. Human presence is already impacting upon the integrity of the caves, with graffiti observed in one of the surveyed caverns.

Based on the findings of this report, further research must be conducted into this unique system. The development and implementation of a targeted management plan is essential to prevent further damage to this environment, and must adopt an approach that recognises the importance of incorporating both the biotic and abiotic components of the landscape. While the caves are situated within the boundaries of Wellington Park, more specific conservation measures must be adopted so that these unique caves are preserved well into the future.

"Everything we have, we inherited from the past, and everything we use or lose deprives future generations of it. That, in a nutshell, is the case for valuing and conserving abiotic nature." - Murray Gray (2004, p. 368).

7.0 Acknowledgements

I would like to express my thanks to Kevin Kiernan, who supervised my project, offering opinions, suggesting theories and inspiring enthusiasm for the subject. I would also like to thank Rolan Eberhard for his encouragement, interest and references, and to Niall Doran, for his expert opinion on the Tasmanian Cave Spider. But most of all, I must thank my friends and project volunteers: Joshua Greene, Jarod Harris, Megan Abbott, Nicholas Nolan and Geoff Lewis. They provided shoulders to stand on, inspired ideas when I needed them most, and remained enthusiastic, even when it snowed on us.

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[Editorial Note: This paper originated as part of geomorphology coursework and fieldwork towards a Bachelor of Science degree at the University of Tasmania in 2010. Because of the potential interest in the subject features and the relative lack of documentation of these caves the editors have been pleased to accept this paper for publication in *Helictite*. Some updating and minor text changes have been deemed necessary.]

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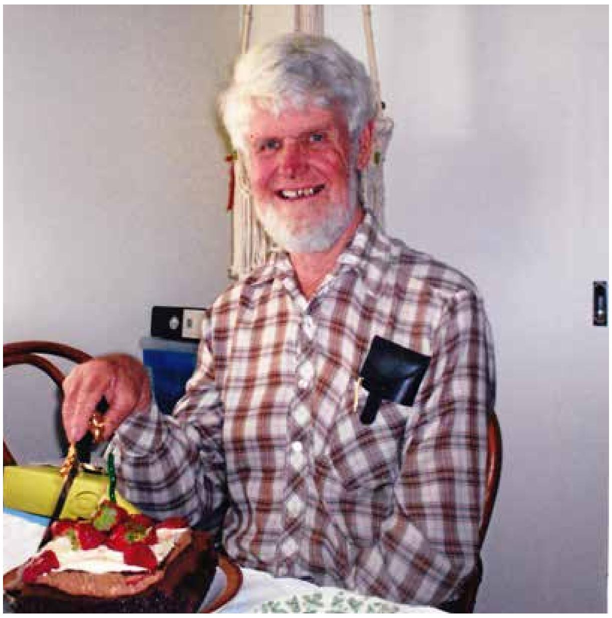
Vale Dr Philip Holberton

13 March 1935 - 27 December 2020

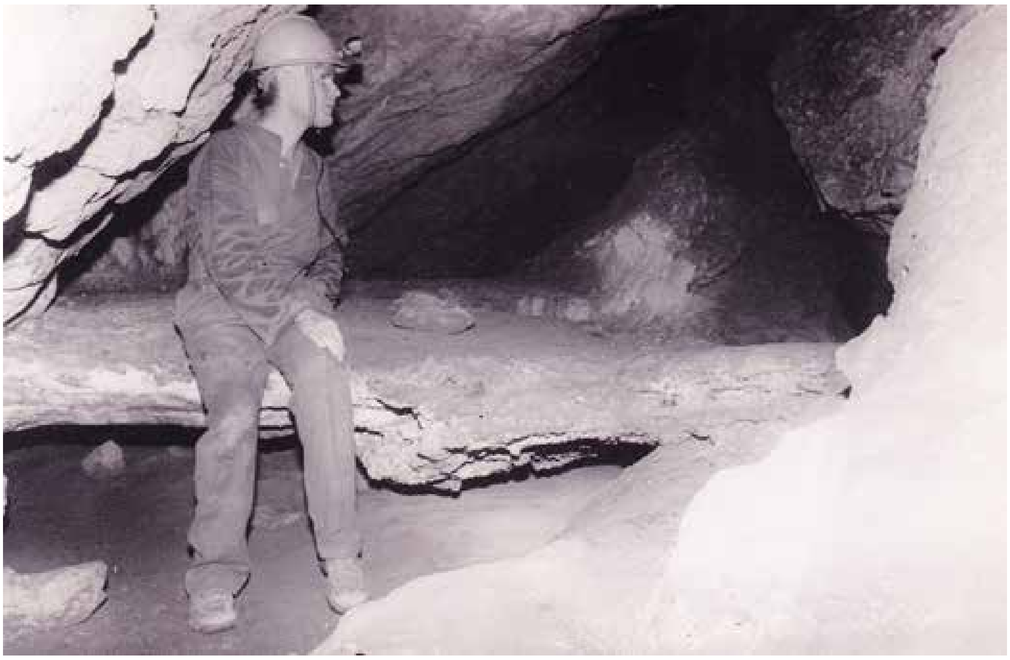
Phillip Lardner and Martin Holberton



Philip was born in 1935 in Burma, where his father, Nelson, was employed by the British Forestry Service. He was taken to the ancestral home in England when two years old and subsequently undertook his education at Cambridge University. After completing a Bachelor of Medicine, he continued on to add a Bachelor of Surgery – M.B. B.S. – in 1959. He married Anne, who was also a doctor, in Plymouth in September 1961. After practising medicine for a few years in the UK, they spent a period of four years on Christmas Island in the Indian Ocean where their first children, Clare and Brian were born. He returned for further studies in the UK, gaining membership of the Royal College of Obstetricians and Gynaecologists (M.R.C.O.G.) and sons Jim and Martin were born.

The family moved to Australia in 1969 and settled in Kempsey. They celebrated the arrival of another son, Peter, in 1971, strengthening their ties with the area.

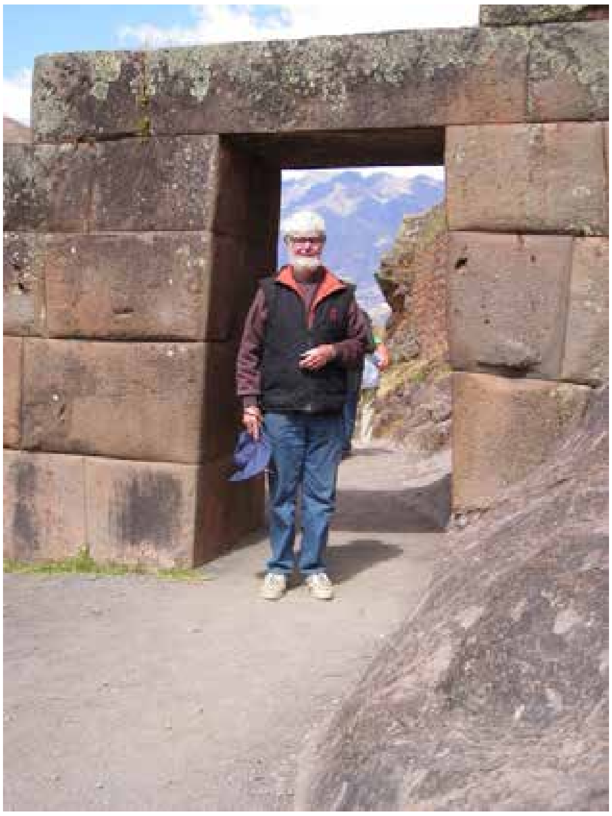
In 1970 Philip joined Kempsey Speleological Society through his love of bushwalking and developed a very keen interest in caves. He became Secretary of Kempsey Speleological Society in 1983; a position he retained until 2020. He was also editor of the group's newsletter, "Trog", one of the most reliable and regular cave-group newsletters in the country – and the last to be published on (folded) foolscap. Philip also took an active interest in the Australian Speleological Federation and attended some of its conferences.



Early days at Yessabah

Philip was very knowledgeable about the Macleay Valley and its surroundings, keeping updated maps of caves and records of their locations and numbers and through his extensive dealings with National Parks Wildlife Service was recognised as the cave tagging authority throughout the Macleay Valley, New England and surrounding coastal areas.

Philip was involved with NPWS in an advisory capacity and steered them in the right direction on many occasions on many issues in the Macleay Valley and its surrounding coastal districts.

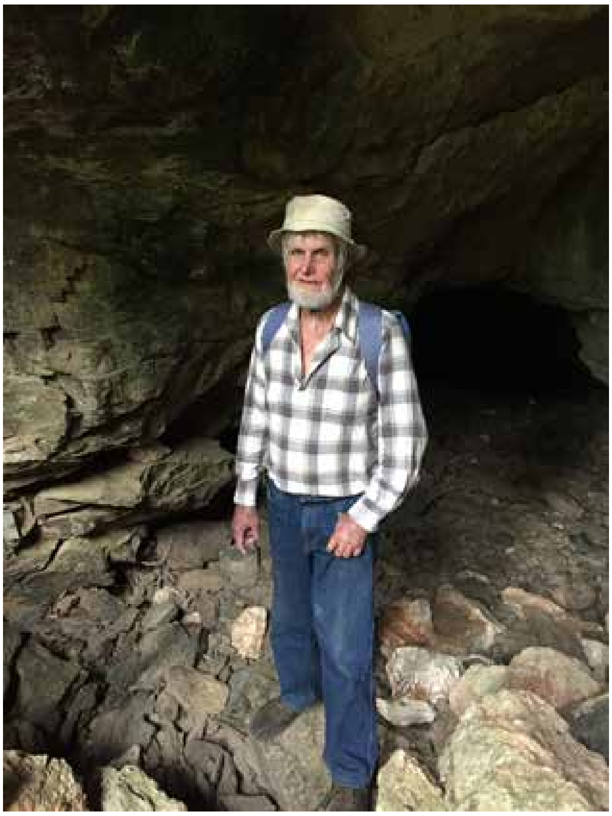


Philip loved to travel – here, to Machu Picchu, Peru, in 2008

Philip was President of West Kempsey Rotary for some years, and Secretary and active member of the Cattlemans Union for many years.

In 1978 Philip and Anne moved to the lovely property they named *Pindah* at Hickeys Creek in the upper Macleay where they ran cattle and Philip maintained climate recording equipment as part of a joint venture between Kempsey Speleologial Society and researchers at the University of New South Wales.

Philip enjoyed and contributed to Letters to the Editor of the local paper and was recognised for his clear thinking and common sense approach.



In 2017 Philip guided some visiting caves through Carrai Arch in the Macleay Valley karst.

Philip joined the Kipling Society in 1998, and there was soon the first of many thoughtful and carefully researched letters to its journal. It was clear that this particular member had wide interests, from classical music to speleology. His guiding quotation was apparently "The cure for boredom is curiosity. There is no cure for curiosity."

Philip was keenly aware of injustice and had little tolerance of bureaucratic incompetence. This at times put him at odds with both church and state. One of the last letters he sent was to his local federal MP stating that the proposed National Integrity Commission was totally unacceptable and that "for an integrity watchdog to be effective, everyone must be equal before it."

Philip retired from the medical profession in 2004 but continued with his many community activities. He was shattered by the sudden loss of his partner, Anne, in 2007.

Philip Holberton will be greatly missed by very many people and a range of regional and community organisations.

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Helictite, (2021) 46**:** 67-68

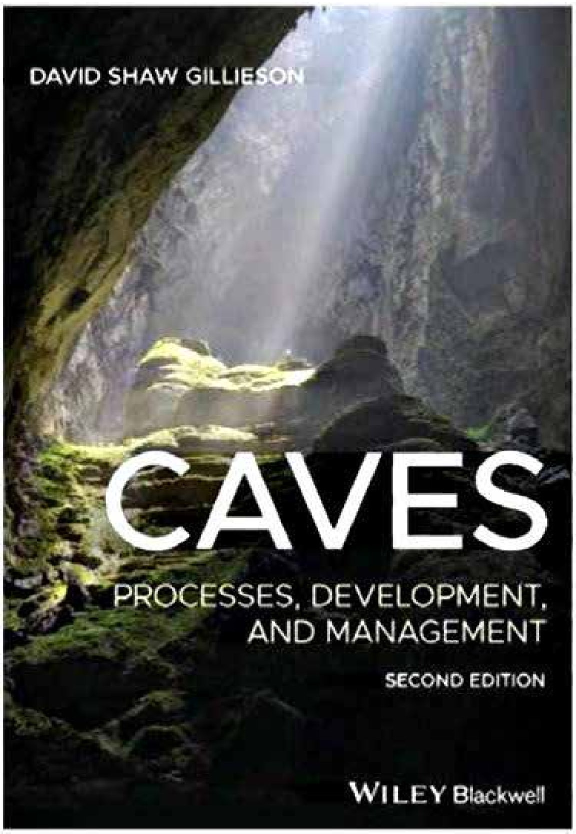
Book Review

Caves. Processes, Development and Management. Second Edition.

David Shaw Gillieson

Wiley Blackwell, Hoboken NJ. 2021 508 pages

This very impressive revised edition of Gillieson's 1996 book will be an invaluable addition to the library of today's cave scientists, karst area managers, recreational cavers and anyone else with a serious interest in caves and karst. It pulls together many key elements of all the knowledge of caves and cave management that has been gained by researchers world-wide over the two and a half decades since the original edition was published, and presents it in a readily digestible form. The result is a particularly fine contribution to cave and karst literature.



The volume commences with an introduction to caves and karst in broad terms. It then zeroes in on various fundamental elements of cave science – karst hydro-geology, rock dissolution processes, modes of speleogenesis, speleothem formation, cave sediments and various other matters. Anyone seeking to broaden or update their understanding of caves, karst and how they work, will be admirably served by these excellent chapters.

One of the great strengths of Gillieson's volume is the breadth of its coverage. For instance, he devotes two chapters to the techniques currently available for dating cave deposits and for deducing past climates from them, including examples of how this has contributed to emerging knowledge of the past. Other chapters explore cave ecology, cave archaeology and historic uses of caves. These topics are addressed comprehensively and impressively well.

Having clearly enunciated the many values of caves, Gillieson goes on to examine some of the threats to which these values can become subject, and means by which risks to these underground treasure troves can be minimised. The impacts and management of recreational caving, including cave rescue operations, are included in a chapter entitled "Cave Management", which also addresses cave classification and reviews aspects of tourist cave management including lighting, engineering concerns, interpretation, guide training, radon gas and the impacts of cave cleaning.

As the old adage goes, it is not possible to conserve the holes in the cheese without also considering the cheese. Notwithstanding that it has become commonplace for caves to be spoken of colloquially as some sort of hidden underground world, in reality they are of course part of a single world of which the surface environment forms part. Protection of caves requires appropriate management of the surface components of their environment. A lengthy chapter on catchment management ranges across such matters as the importance of karst catchment definition, the need to protect soil, vegetation and water quality, and risks associated with groundwater lowering. Among the threats considered are soil erosion, microbial contamination of groundwater, pollution of karst groundwater by fertilisers, herbicides and pesticides used in agriculture, and golf course management. The potential conflicts that can arise in karst management decision-making are faced squarely. Responding to the fact that sound decisions require access to a solid and reliable information base, Gillieson concludes his book with a chapter on the documentation of caves, including geoheritage assessment.

Southern hemisphere readers are particularly well-served by the inclusion in this book of numerous examples of cave science and cave management topics drawn from this side of the globe. The previous *Karst* tomes by Joe Jennings, and also the New Zealand perspectives so effectively injected by Paul Williams into Ford and Williams' *Karst Geomorphology and Hydrology* did much to help sensitise the karstic centres of intellectual gravity in Europe and North America to the fact that the southern hemisphere exists, but to some extent that conversion remains a work in progress, and in any event much new knowledge has arisen since those authors wrote.

An excessively northern hemisphere perspective seldom serves southern hemisphere readers well (I still chuckle at the memory of an International Geomorphological Congress in Europe when one researcher's conclusion that features on the southern side of a particular mountain in southern Africa were potentially of glacial origin was immediately and resoundingly denounced by a prominent northern hemisphere glacial "expert" who dismissively asserted that "everyone knows glaciers form on the more shaded northern side of mountains, not their sunnier southern sides". This led me to always use an "upside down" map of the world when presenting any contributions of my own at international conferences thereafter, despite the problems I usually then had trying to concentrate on what I was saying without giggling as I saw much of the audience continually trying to turn their heads upside down without being noticed… but I digress…). There are no such flat earth blind spots in this Gillieson volume. More strength to his arm.

Gillieson's greatly improved coverage of southern hemisphere karst and caves does not come at the expense of the northern hemisphere, to which he still gives ample and necessary attention, including insights into important new advances in understanding from southeast Asia. Rather, he supplements the more traditional karst fare with considerable new and valuable material from New Zealand, Australia and elsewhere in the southern hemisphere. The result is a much more rounded overview of world cave and karst science and management than any other volume of which I am aware. Partly this relates to his material on how caves and karst work and the values they hold, but just as importantly it also pertains to the threats they face in an increasingly over-crowded and over-corporatized world, and what needs to be done if they are to remain healthy living natural geo and bio systems.

Gillieson's emphasis on some of the unique characteristics and global significance of the Nullarbor karst is particularly timely given a recently proposed massive new putative "green energy" project that would entail visually intrusive and highly water-dependant heavyweight infrastructure erected across hundreds of square kilometres of this iconically flat, dry and brittle hollow karst landscape. Responding to the challenges that this and many other developmental proposals pose requires the very sort of information that this book delivers so effectively. No cave or karst scientist, manager, thinking recreational caver or other serious cave enthusiast should be without it. A few copies gracing the shelves of Australia's parliamentary libraries wouldn't go astray either.

Reviewed by Kevin Kiernan

Information for Contributors to Helictite

Aims and Scope of Helictite.

Contributions from all fields of study related to speleology and karst will be considered for publication. Fields include earth sciences, speleochemistry, hydrology, meteorology, conservation and management, biospeleology, history, major exploration (expedition) reports, equipment and techniques, surveying and cartography, photography and documentation.

Our main geographic focus is Australasia: Australia, New Zealand, New Guinea and the Malay Archipelago, but we also invite studies from the Pacific and Indian Oceans and Antarctica.

Papers should not exceed 10,000 words, plus figures. Contributors intending to write at greater length or requiring any advice on details of preparation are invited to correspond with the Editors at ozspeleo@iinet.net.au. Short notes or 'Letters to the Editor', expressing a personal view or giving a preliminary report of interesting findings, are also welcomed. Discussions of published papers should be received within six months of the publication date, and will be passed on to the original author for response.

All submitted papers will be peer reviewed. The editors reserve the right to determine whether any particular contribution will be accepted for publication.

The process of submission, review and publication.

1. Consultation with the editors in relation to a proposed contribution.
2. Submission of the manuscript, including graphics.
3. Peer Review.

   Decision upon tentative acceptance (possibly subject to minor corrections, major corrections or resubmission).
4. Revision by the author(s).

   Papers with major corrections or resubmitted papers may be subject to a second review.
5. Submission of the final version.
6. Layout, proof reading and publication on Helictite website.
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