

Are the orthoquartzite towers and caves on the Borradaile Plains, Tasmania, formed by dissolution and arenisation?

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Abstract

The discovery of significant cave and karst landscapes formed in quartzites and sandstones in South America, Africa and Australia has led to a debate among scientists over the definitions of karst and the processes forming karst in quartzites. In the past these caves were listed under the ambiguous definition of ‘pseudokarst’ landforms. It is now generally agreed that the chemical dissolution of silica within massive quartzite or sandstone units plays a significant role in the development of certain types of quartzite caves and the term syngenetic karst may better describe non-carbonate landscapes where dissolution and sediment transportation by erosion processes both play major roles in karst development. The recent discovery of towers formed within Precambrian orthoquartzite rock adjacent to Tertiary basalt on the edge of the Borradaile Plains in northern Tasmania poses questions regarding the processes of quartzite dissolution and karst development in silica rich rocks in an area that has had a subalpine or glacial climate for much of the Quaternary. It is suggested that the overlying basalt has been stripped from around the towers by Quaternary erosion and the caves have formed by arenisation induced by acidic upland soils.

Introduction

In the scientific literature, karst has been recognised by landforms produced by the dissolution of carbonates (Ford and Williams 2007). However; recent studies of major karst landscapes containing sizeable caves formed in quartzite and sandstones (Piccini and Mecchia 2009; Uagoda and others 2011; Wray and Sauro 2017) have challenged this definition. For example the discovery of very extensive cave systems formed in quartzite and associated meta-sedimentary rocks including the 300 m deep Sistema Auyantepuy Noroeste (Piccini 1995) and Guacamaya Cave (Sauro and others 2013) on the Tepuis of northern South America and documentation of other significant quartzite karst areas in southern Africa (Marker and Swart 1995; Fabri and others 2015) and northern Australia (Grimes and others 2011) has made clear that over long time periods quartzites can produce karst landscapes. The most impressive quartzite karst landscapes in Australia are extensive tower karst and “ruined city” landscapes widely distributed across the Australian tropics (Young 1987; Wray 1997a; Grimes and others 2011), which display many landforms formed by dissolution such as pinnacles, street and block landscapes, and caves including the impressive 300 m long Whalemouth Cave in the Kimberley (Jennings 1983; Young 1987; Grimes and others 2011). Drainage conduits including caves several tens of metres long in sandstone have been described in the Carnarvon Gorge

area of central Queensland (Wray 2009). Elsewhere, outside the tropics, small meander cut-off caves including the Underground River and Ross Cave formed in Sydney basin sandstone sequences have been identified as largely formed by karstic processes (Wray 1995, 1997; Dunkley 2011). The largest caves formed in siliceous rocks in Tasmania are Wet Cave near Sisters Beach on the north coast (Kiernan 1995) and Iron Maiden and Blister caves on the south-western coast of King Island in Bass Strait (Goede and others 1979). These caves have passages up to 120 m long. However, they are raised sea caves eroded in quartzite and are not of karstic origin, although carbonate speleothems derived from overlying dune limestones are present in the King Island caves (Goede and others 1979). Away from the coast in southwest Tasmania small quartzite fissure caves have formed on the Frenchmans Cap Range (Kiernan 1995) and have been observed by the primary author on the Needles Ridge near Maydena. At Mt Wright two large arches have formed in Ordovician sandstone and conglomerate (Middleton 2015). Like the previous examples none of these features appear to be of karst origin, but near Quamby Bluff on the lower slopes of the Great Western Tiers in northern Tasmania a cluster of caves formed in Triassic sandstone display some characteristics of solution weathering (Middleton and Sharples 2014). This paper describes newly discovered caves and associated surface landforms formed in orthoquartzite on the Borradaile Plains in northern Tasmania and discusses their mode of formation.

Study area

The Borradaile Plains, an extensive dolerite-capped plateau at 800–900 m above sea level (asl), form the drainage divide between the deep glaciated troughs of the Forth Valley to the west and the Mersey Valley to the east (Colhoun and others 1996) (Figure 1). The plateau is mostly underlain by a sill of flat-lying dolerite and areas of Tertiary basalt. However small areas of Precambrian basement documented on 1:250000 geologic maps outcrop as greenschist-quartzite sequences and related rocks around the perimeter of the plateau, particularly at its northern end (Mineral Resources Tasmania 2010). The study site is located on a westerly facing spur of the Borradaile Plains at an elevation of 810–840 m asl immediately upslope and east of the steep defile of the Borradaile Creek gorge that drops 400 m to the floor of the Forth Valley. Most of the Borradaile Plains have only been geologically mapped at a reconnaissance scale and the study site is mapped as greenschist quartzite rocks. However, during a field reconnaissance vesicular basalt of probable Tertiary age was noted immediately southeast of the study site where it forms two bedrock benches clearly visible on the hillshade map of the site (Figure 1). In the south of

the study area flows of vesicular basalt are found on top of, and adjacent to, quartzite outcrops.

The Forth Valley has a temperate maritime climate with short mild summers. The nearest weather station of comparable elevation is at Waratah, 56 km west of the site, at 609 m asl. Here summers are short and mild with temperatures rarely rising above 30°C and winters are cold with average daily minimums of 0–2°C (BOM 2017a). On the Borradaile Plains temperatures are likely to be lower. Precipitation is around >1500 mm a year based on data from the Liena (Old School House) weather station 10 km to the northeast (BOM 2017b). Heavy snowfalls are common during winter. The natural vegetation cover is cool-temperate wet forest dominated by *Eucalyptus delegatensis* and shrubby grasslands. During the most severe glacial periods the Borradaile Plains may have been overrun by the extensive central plateau ice cap (Hannan and Colhoun 1987; Kiernan and Hannan 1991; Colhoun and others 1996). During the less severe last glaciation the Borradaile Plains were probably treeless with low alpine grasses and herb fields (Colhoun 2000; Hopf and others 2000). Under significantly colder but drier climates than at present the Borradaile Plains would have experienced extensive landscape

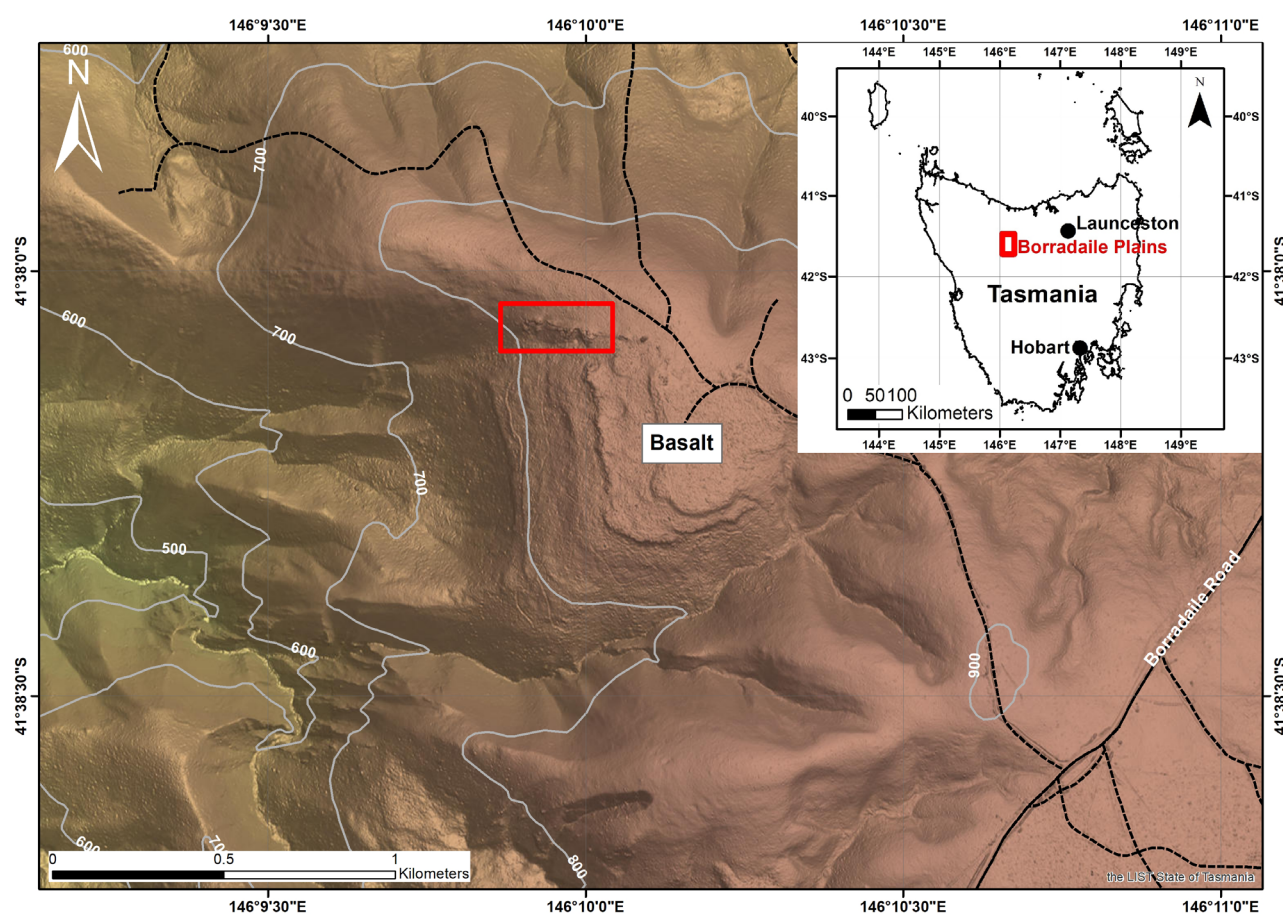


Figure 1. Location map and hill shade (LiDAR-derived) map available on LIST Tasmania (<https://maps.thelist.tas.gov.au/listmap/app/list/map>), showing the topography in the immediate vicinity of the towers and study area (red outline). The towers and the flat lying basalt flows capping the plateau are prominent features in the landscape.

modification by periglacial processes such as frost shatter, solifluction and nivation (snow melt) (Slee and Shulmeister 2015).

The study site covers an area of approximately 3 ha enclosing a line of massive rock towers that rise steeply above the surrounding surface and resemble small “ruined city” forms common in tropical quartzite areas such as those described in the Northern Territory (Grimes and others 2011). The two main outcrops have been designated the East and West towers and contain most of the major karst features. However, karst landforms are also present within the smaller isolated towers. The towers are composed of folded massive orthoquartzite beds separated by schistose units.

Methods

The study area was surveyed in 2011 using compasses and tape measures by the authors with the aim of developing a sketch map of the landforms and listing the landforms present, so that management plans for an adjacent forest coupe could be developed and a proposal written for future listing of the landforms on the Tasmanian Geoconservation Database (TGD), which formally recognises sites of geoconservation significance in Tasmania (Comfort and Eberhard 2011; DPIWE 2019). This site was formally listed on the TGD in April 2018. In February 2016 a bushfire burnt through the site and destroyed the vegetation. Consequently, the initial survey was updated in 2017 and the impacts of the bushfire on the caves detailed (Slee 2017).

Description

The outcrops extend east-west for 300 m on the top of a south-west facing spur of the Borradaile

Plains. The two main towers are surrounded by steep cliffs up to 8 m high and rise up to 12 m above the surrounding undulating plains (Figures 2 and 3). The towers are surrounded by smaller outliers that rise abruptly up to 4 m above the land surface. Unlike typical scarp-retreat cliff faces that form cliffs and drop-offs at the edges of plateaus as a result of weathering and cliff face collapse, the towers rise above the surrounding landscape on all sides. The linear trend of the outcrops striking to the west-north-west suggest that they may be the remnants of a single hogsback strike ridge that projected above the general elevation of the Borradaile Plains.

Karst landforms are common throughout the study area. Landforms identified include numerous grikes and solution hollows in the base of the cliffs, rudimentary sinkholes on the summit area of the eastern tower and small enterable caves.

Surface landforms

The towers have steep cliff-lined profiles with massive smooth walls and rugged domed to turreted summits (Figure 4). No karren were observed on the towers; however the East Tower is broken by large smooth bedrock ridges with the result that the quartzite projects several metres out from the tower. These landforms are reminiscent of karst grike fields in Ordovician limestone outcrops observed elsewhere in Tasmania.

No sinkholes were observed on the plateau surrounding the outcrops but several small circular bedrock depressions up to 1.5 m deep occur on the upper part of the East Tower in the vicinity of cave 5 and at the far eastern end of the mapped outcrop.

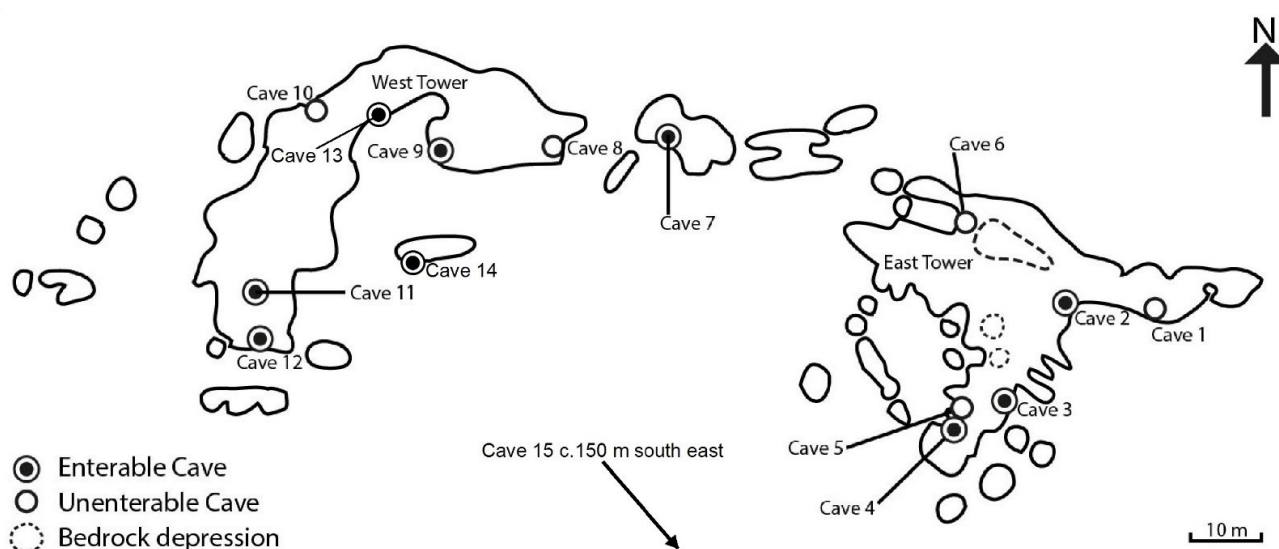


Figure 2. Map of the quartzite towers derived from detailed field mapping and observations.

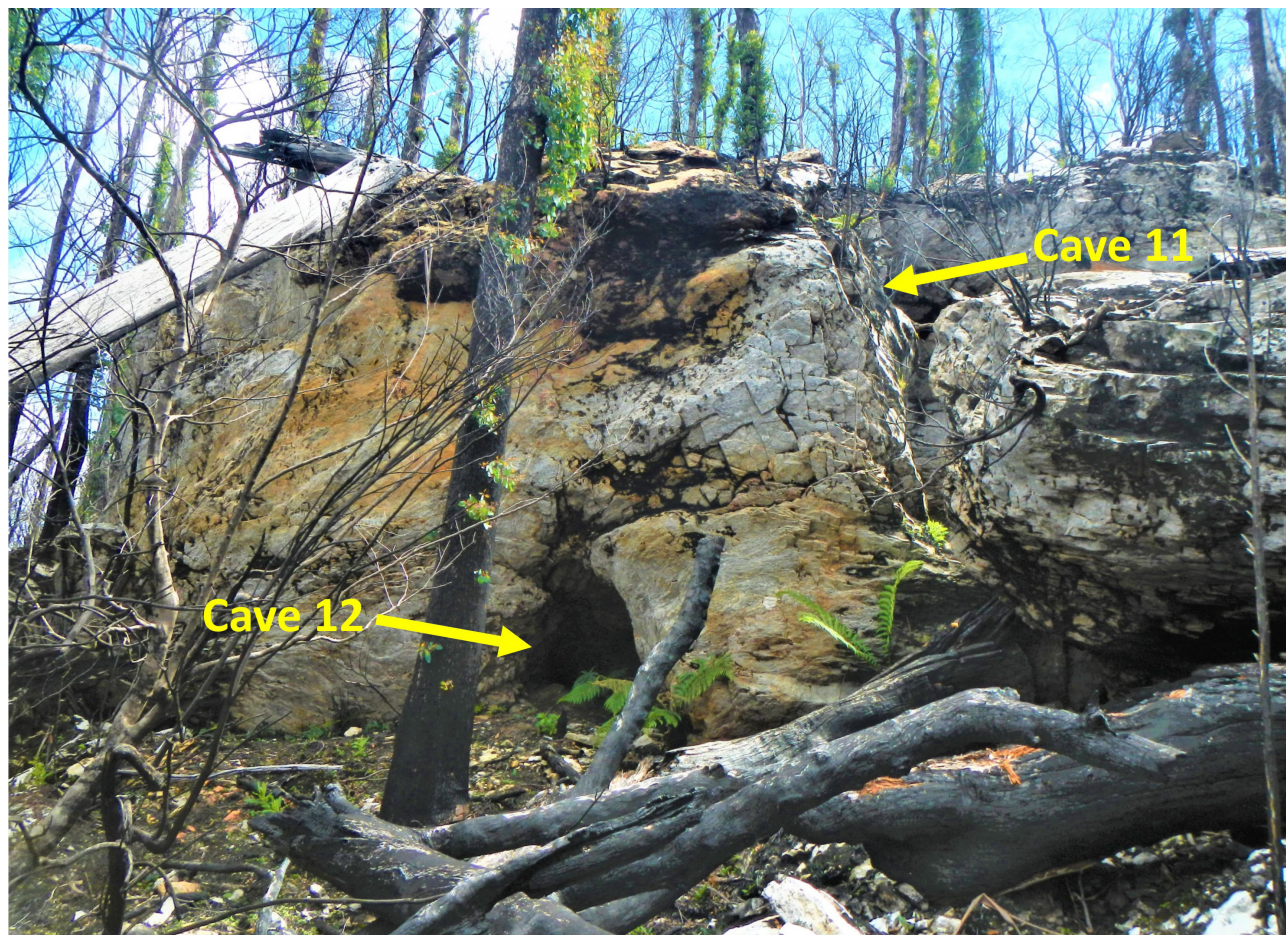


Figure 3. View of the southern face of the western tower, caves 11 and 12 are arrowed.



Figure 4. The rounded summit of the western tower.

Although many of the outlying towers appear to be formed in solid bedrock some large boulders are present down slope of the towers, hinting at past tower collapse. Two notable cave-collapse features are present in the East Tower. Cave 4 appears to be a former tunnel cave with a partially collapsed outer wall, which has promoted development of an unstable breakdown area. A 6 m long and 2 m deep grike is a major feature of the western end of the East Tower. The straight walls of this feature, the large angular talus blocks lying on the floor of the grike and a tight 5 m long cave passage (cave 6) at the end of the grike, all suggest that this feature formed by roof collapse of a more substantial cave. In contrast to the East Tower, the West Tower presents a massive profile with straight-sided vertical to overhanging cliffs up to 8 m high and no surface sinkholes. Grikes are only weakly developed. The most notable surface landforms on the summit of the West Tower are a series of 2-3 m tall rounded summit tors.

Caves

Fifteen caves were located; of these eleven were accessible. Six caves are located within the East Tower, six within the West Tower and three are located in outlying smaller bedrock bluffs. The caves have been divided into three categories:

Tube (Figure 5): Single or double rounded tunnels that end in pools of water. These caves appear to be subsurface continuations of surface grikes penetrating the edges of the towers. Four caves display this morphology, and two of these are >10 m long; all contained small standing pools of water in their inner reaches during visits in 2011, but were dry during the 2017 observations after the bushfire. The presence of standing pools of water coupled with these caves' rounded phreatic style of development suggest that these caves may have formed by the slow dissolution of quartzite by ponded rainwater acidified by the organic-rich upland soil. This deduction is supported by the observations of Hill and others (1995, p. 283) that soils formed in Ordovician quartzites in the Forth region have extremely acid peaty topsoils of pH 3.8, and subsoils have pH of 4.5. In addition, Bennett and others (1988) demonstrated that dissolution of quartz in water is greatly accelerated by the presence of organic acids. Dissolution is likely to have been initially associated with pits in the bedrock surface and over time developed along grikes and elongated tunnel caves. In cave 9 a seepage displays well developed runnels and small stalactites are present on the nearby roof (Figure 6).



Figure 5. View towards the back of the tube-shaped passage of cave 9.

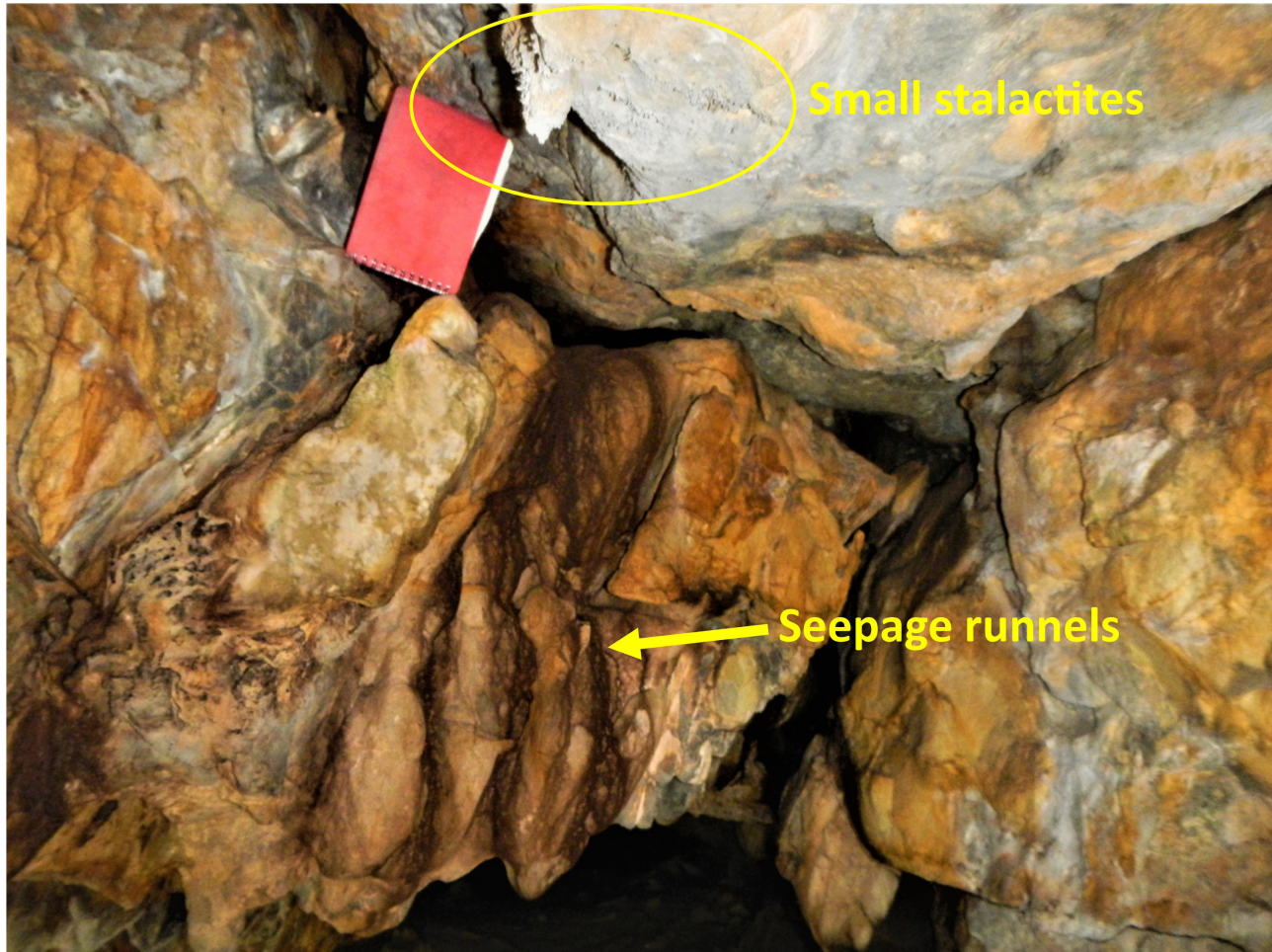


Figure 6. Location of small seep and solution runnels (arrowed) in the roof of cave 9. Also note miniature stalactites adjacent to the note book. The seep dried up after the 2016 bushfires.

Wide and low (Figure 7): Caves with wide passages have formed at the soil/bedrock contact. Caves 7 and 14 feature low tight entrances leading to more extensive low tent-shaped passages of unknown length. These caves have similar morphology to that of caves formed by basal dissolution of tropical karst towers by surrounding swamps, producing “swamp notches” (McDonald and Twidale 2011). Cave 12 on the West Tower appears to have a similar origin however it has an inner chamber 2.5 m tall.

Open tunnels (Figure 8): Cave 11 is a single 2.5–3.5 m tall arch in the West Tower and forms an 11 m long walk-through cave. No pools were observed in this cave. The cave follows a structural weakness in the bedrock (a band of thin schistose beds) and the cave probably developed along this weakness. Cave 15 lies within a small outlying bedrock bluff (not shown in Figure 2); it features approximately 10 m of passage that extends the width of the bedrock outcrop and features three entrances to a small inner chamber.

It is notable that the caves appear at two elevations within the towers; the swamp-notch

caves lie topographically below other caves. This difference in elevation is most obvious in the West Tower in which the entrance of cave 12 lies 2–3 m below the base of cave 11 and cave 12 has a N–S passage alignment as compared to the E–W alignment of cave 11.

Discussion

Caves formed in quartzite and sandstone bedrock in Tasmania are usually formed by mechanical processes. The most common process for forming caves in sandstone is wind erosion or less commonly landslides and localised slope unloading processes (see Sharples 1997) or caves possibly associated with fault zones (e.g. Slee and Stoios 2019). In drier and coastal parts of the state, salt weathering is likely to be a factor in the mechanical breakdown of sandstones (Rodriguez-Navarro and others 1999) and may play a role in the formation of tafoni on cliff faces in eastern Tasmania (Williams 2007). Sharples (1990) notes that salt weathering is more prevalent in sandstones containing clay minerals rather than in sandstones composed purely of quartz. Salt weathering is unlikely to be active on the high-rainfall Borradaile Plains or to affect indurated orthoquartzite and is discounted as a process forming the described



Figure 7. Left, The low entrance to cave 14 (circled) with the main West Tower beyond. Right, View into the western passage of cave 14. This passage extends for at least several metres out of sight. Note the lack of coarse rubble on the floor of the cave, as in cave 3 (Figure 9). We suggest this cave formed as a void partially or wholly filled with acid soil, and that it is slowly being exhumed.



Figure 8: Cave 11 is an 11 m long and 3-4 m high tent-shaped passage. Note the recent angular shards of rock at the entrance and burnt eucalypt produced by the intense bushfires that impacted the site in January 2016

landforms. Caves formed elsewhere in Tasmania due to mechanical weathering processes generally have breakdown deposits on their floors and angular faceted walls resulting from the mechanical fracturing of beds within the host rock. In contrast the caves on the Borradaile Plains have vegetated soil-covered floors with smooth walls and limited evidence of breakdown (Figure 9).

An alternative process for cave formation at Borradaile is slow dissolution of quartz along rock fractures by meteoric water, generally in the soil saturation zone, a process widely accepted as initiating quartzite caves and known as arenisation (Piccini and Mecchia 2009; Grimes and others 2011; Sauro and others 2012; Sauro 2014; Wray and Sauro 2017). Dissolution and preferential breakdown of massive quartzite occurs along lines



Figure 9. Left: The twin entrances to cave 3 are separated by a column. Note these entrances lie on the sheltered easterly aspect of the Eastern Tower which is not exposed to the prevailing westerly winds. Right: Back passage of cave 3, note the smooth rounded walls of this passage.

of weakness in the rock to form voids of loose sands and remnant silcrete. If the overlying soil is removed, physical weathering processes including wind deflation and stream/water erosion can rapidly remove the loose grains in the rock mass leading to cave formation (Wray 1997b; Grimes and others 2011; Sauro 2014). If feldspars are present in sandstones or quartzite their chemical breakdown under acidic meteoric weathering regimes may also be a factor (Aubrecht and others 2011, 2013).

In Australia, karst development in quartzite has been mostly documented in tropical and sub-tropical environments and within the humid temperate zone (with warm to hot summers and mild winters) in Sydney basin sandstones (Wray 1995, 1997; Dunkley 2011). The climates there are significantly different from the cool-temperate Borradaile Plains. The processes that formed caves within the Fell Sandstone of Northumberland Britain (Self and Mullan 2005) may provide a closer analogue for conditions that formed the caves on the Borradaile Plains. Several small caves in the Fell Sandstone appear to have formed by arenisation: the largest is the 10 m long Routin Lynn Cave that has a similar morphology to a number of the caves present on the Borradaile Plains. Self and Mullan (2005) postulated that surface karst landforms and most of the caves they describe must have formed since the retreat of the Younger Dryas ice cap that buried the area 13,000 years ago, and that most features in the Fell Sandstone developed rapidly during the warmer, more humid, Holocene.

The juxtaposition of Precambrian quartzite and Tertiary basalt immediately east of the towers hints

at a process that may have produced the rounded quartzite outcrops. In the past the host quartzite bluff is likely to have been buried by basalt (Figure 10). The deeply incised but rounded nature of the quartzite outcrops contrasts to the elongated sharp quartzite ridges visible on the shade map downslope in the Borradaile Gorge, and suggests that most or all of the outcrops may have once been buried by weathered basalt. We note that the Tertiary climate was warmer than at present and the pH of deep subsoils may have been higher than in present-day basaltic soils due to faster mineral weathering rates. Quartz dissolution is quicker in high pH solution than in low pH solution (Henderson and others 1970) so leaching of the quartzite by water percolating through basaltic soils could have formed much of the rounded topography of the quartzite outcrop.

Summary

Most quartzite and sandstone caves showing evidence of dissolution and arenisation in Australia are located in tropical or sub-tropical environments but the caves in orthoquartzite on the Borradaile Plains are in a cool temperate climate that would have been sub-alpine or alpine in character throughout much of the late Quaternary. We suggest the landforms evident today have been formed by two processes. During the Tertiary the underlying quartzite was weathered by high pH solutions percolating through deep weathered basalt, forming the rounded topography of the outcrop we see today. Subsequently, chemical weathering by acid soil solutions rich in organic acids and arenisation processes have eroded caves at soil level. At present



Figure 10. One of the entrances to cave 15. The GPS lies on a boulder of vesicular basalt of likely Tertiary age that lies immediately upslope of the quartzite outcrop where it forms a low escarpment.

many caves are found near the present soil surface, but caves higher in the outcrop may have formed when the soil surface was higher, i.e. the outcrop and its caves are slowly being exhumed by erosion driven by cold-climate processes, fire, ground ice and sheet wash.

The recent discovery in north western Tasmania of the Borradaile towers and associated landforms indicative of karst processes are significant not only for their geomorphic isolation from similar landforms but also for their deduced mode of development in a region that has been heavily modified by glacial and periglacial processes throughout the Quaternary. The authors support the notion that the Borradaile towers and caves are primarily of solution origin and therefore should be classified as karst rather than ‘pseudokarst’, as discussed by Eberhard and Sharples (2013).

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