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Iron springs, environmental changes, accelerated weathering and cave development in quartz sandstone in the Blue Mountains, New South Wales, Australia: preliminary studies

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Abstract: After a series of extreme weather events (drought, bushfires and floods), iron flocs were seen at ephemeral springs in quartz sandstone in the Blue Mountains National Park, New South Wales, Australia. Naturally burnt areas allowed better viewing of small sandstone caves. This paper discusses some of the processes operating within the quartz sandstone, leading to the attractive and unusual shapes, and how extreme weather led to the mobilisation and re-deposition of iron minerals.

Key words: sandstone, iron, flocculants, climate, caves

Introduction

Preliminary study sites were selected on a plateau of mainly quartz sandstone in the northern part of the Blue Mountains National Park, New South Wales, Australia. Between 2017 and 2019 were drought years; at the end of 2019 and the beginning of 2020, lightning-induced severe bushfires impacted the Blue Mountains, including the study sites. Flooding rains from 2020 to 2023 caused considerable denudation. Rusty orange-coloured springs appeared along the road as well as in the bushland. Closer inspection allowed us to see iron minerals being deposited by transient springs. These springs were ephemeral, previously clear, and covered by vegetation, but the more recent weather extremes appeared to have initiated a process of accelerated iron mineral deposition. Roadside springs looked rusty, with bacterial iron flocculants (flocs) and flowstone-like patterns. Naturally burnt areas allowed us to view some of the smaller sandstone caves which were previously hidden by vegetation.

This paper discusses some of the processes operating within the quartz sandstone, leading to attractive and unusual shapes, and how extreme weather led to the mobilisation and re-deposition of iron minerals. The aim of this study is to document transient rust-coloured springs in the study area as a result of extreme weather conditions, what may have caused them, and whether there was any relationship between iron banding and caves in the sandstone.

Study area and environment

Mount Banks is a raised area of a plateau located in the Blue Mountains National Park, 115 km west of Sydney, Australia (Fig. 1, site 2). The area is famed for its rugged scenery set in Triassic quartz sandstone, deeply dissected by creeks and sheer cliffs (for example, see Fig. 2). The area features ironstone bands and little caves in quartz sandstone. Distinctive ironstone weathering patterns occur in exposed areas of the plateau which is mainly Banks Wall Sandstone at this study site. One source of iron for the ironstone could be the Miocene basalt cap rock on the top of Mt Banks (Pickett et al. 1997), although others suggest that the source of iron is within the Banks Wall Sandstone itself (Goodwin 1969, Jacobs et al. 2014).

Within the study area, the village of Clarence lies about 20 km northwest of Mt Banks along the highway Bells Line of Road. This study site included a road cutting at Clarence, between Chifley Road and Petra Avenue (Fig. 1, site 5). The geology is similar to

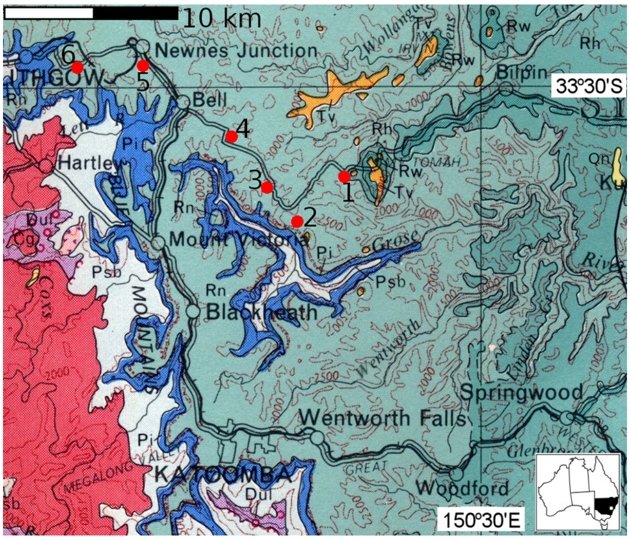

Fig. 1. Geological map of the study area (based on Brunker and Rose 1967) showing positions of study sites 1-6. Colours and Codes to mapped units and relation to the study sites: Qn (yellow) – Quaternary gravel, sand, silt and clay (eastern part of the region); Tv (orange) – Early Miocene basalt (tops of highest points); Rw (darker green) – Triassic shale; Rh (mid green) – Triassic quartz sandstone; Rn (green) – Triassic Narrabeen Group sandstones (the main deposit on the plateau and cliff edges); Pi (Blue) – Permian Illawarra Coal Measures (at the base of the cliffs); Psb (nearly white) – Permian marine mudstones (lower slopes and valleys); Dul (violet spots) – Devonian Lambie Group conglomerate, sandstone and shale (lower valleys); Cg (Red) – Carboniferous granite and granodiorite (western part of region). The inset map of Australia is from Geosciences Australia. Contour intervals are in feet

Mt Banks, a sandstone plateau with deeply dissected gorges. Other sites visible along the same highway with similar geology and distinctive orange-coloured springs include Mt Tomah, Mt Bell (Fig. 1, site 1), an area about 1 km south of the Mt Wilson road turnoff (Fig. 1, site 3), 3 km south-east of Bell (Fig. 1, site 4), Ida Falls Creek south of Chifley Road (Fig. 1, site 6).

The sandstones of the Blue Mountains are generally horizontally-bedded, with occasional cross-bedding, yet iron-stained banding occurs independent of bedding (Goodwin 1969). In a study of quartz sandstones of the Sydney Basin, Wray (1995, 1997) indicated that sandstones near swamps were frequently more porous due to dissolution. He discussed the importance of organic acids in their dissolution and noted the presence of iron also increased sandstone dissolution, including the development of runnels on the surface. Arenisation, the formation of “ghost rock”, as well as the formation of goethite and limonite deposits in sandstone were discussed by Wray and Sauro (2017), leading to the development of sandstone caves and ironstones. The overall appearance of surface ironstone outcrop patterns at Mount Banks is similar to ironstones described from the Bohemian Cretaceous Basin (Adamovič and Cílek, 2002a, b). The formation of small caves in quartz sandstone is reminiscent of mixing corrosion seen in porous limestones, for example, Dreybrodt et al. (2009), although with very different chemistry.

Thin soils near cliffs and steep sites at Mount Banks comprise mainly sand with organic material. Migoń et al. (2023) described a process of arenisation in jointed sandstone, forming sand cones downstream of the joints and development of large rocky blocks. A similar process may be happening in the Blue Mountains, especially near cliffs.

The Blue Mountains National Park has abundant sclerophyll vegetation dominated by eucalypts. Transpiration keeps the water table low, especially during long droughts such as 2017–2019. It is this act of transpiration which also releases eucalyptus oil into the air, making the Blue Mountains appear blue. Swamps are a feature of the study area, including both headwater and hanging swamps on the sandstone. Jacobs et al. (2014) offer a good general introduction to the swamps of the Sydney region, including the Blue Mountains, their classification and their relationship to the landscape. Swamps in the area also contain at times bacterial iron mats, called flocculants (flocs). There are several common, harmless microorganisms found around the world which can slowly convert ferric oxide to iron oxyhydroxides. These microorganisms thrive in wet anoxic environments such as those found in these swamps. Other organisms operating in wet, oxygen-rich, near-surface environments can further alter the iron chemistry. This can be seen sometimes as an iridescent floating deposit on the water. Microorganisms associated with these types of films were summarised by Chi Fru et al. (2012).

Bushfires in Australia are not unusual and are often initiated by lightning. During the major natural bushfire of 2019–2020, a large area was burnt (5.5 million hectares according to the NSW Government Department of Environment and Heritage) including much of the vegetation in the study areas between Mt Banks and Clarence. The heat from intense fires may alter rock surface minerals: when subject to the high temperatures of a bushfire, surface goethite can dehydrate to ferric oxide. The temperatures required to do this are at least 500°C (Beuria et al. 2017) which can easily be achieved in bushfires such as the one during 2019–2020.

After the bushfires, there were flooding rains. A La Niña wet weather event lasting from 2020–2023 brought significant rain and floods to the region. Without vegetation to draw down the water table, springs were seen in the area, coloured red-orange from apparent iron oxides. One of the closest weather stations to the study site is Mount Wilson. For the years 1970–2023, the published median annual

Fig. 2. A hanging swamp discharges a rusty-coloured stain on exposed sandstone on Mt Banks (Fig. 1, site 2), with the Grose River valley beyond

rainfall is 1268.7 mm. For the drought year 2017, the total rainfall including hail, snow and drizzle was 785.5 mm. In contrast, the totals for flood year 2022 were 2310.7 mm. For more detail, see Table 1.

Groundwater monitoring bores (boreholes), operated by agency WaterNSW, are located at Wentworth Falls to the south of the study area on the other side of the Grose River valley in similar geology. The bore logs cover the time period of the study and indicate that the groundwater levels in the bores respond quickly to rainfall with very little time lag. Data is available from the Australian Government Bureau of Meteorology, using the interactive software tool Australian Groundwater Explorer (BoM 2024). The movement of groundwater can be confined to discrete regions of an aquifer. A percolation model for groundwater movement has been developed by Masihi and King (2012). Nearer to the study site, perched water tables were described in the Banks Wall Sandstone (Jacobs et al. 2014).

Methods

Fieldwork was done from January 2023 through to April 2023, and all sites were accessed from public roads and walking tracks. Photographs were taken

Table 1. Rainfall at Mount Wilson (weather station Clarine 063246, BoM 2024)

Year	Total rainfall [mm]	Notes on rainfall for particular months	Other notes
2017	1242.7	Much lower than mean rainfall: April–May, July–September	
2018	1093.4	Much lower than mean rainfall: April–August	
2019	785.5	Much lower than mean rainfall: April, May, July, August, October–December	Bushfires began by lightning in November
2020	1810.2	Much higher than mean rainfall: February, July, August, October, and December	Bushfires were stopped by significant rain in February
2021	1743.7	Much higher than mean rainfall: February, March, August, and November	
2022	2310.7	Much higher than mean rainfall: July–October	
2023	1047.7	Much higher than mean rainfall: April, November, December	

using a Canon EOS 400D camera with Canon EF-S18-55mm f/3.5–5.6 lens. This was a preliminary visual analysis: no sampling was done and no chemical analyses were performed.

Results of observations

Springs and swamps

When active after rain, episodic springs could be seen on rounded rock faces below hanging swamps and in road cuttings at the study sites. Rainfall on the sandstone generally soaked into the rock except for puddles on ironstone outcrops, where water persisted a little longer. Gradually, as vegetation returned naturally from a combination of epicormic buds and seed, the springs became less obvious, although an orange-coloured stain remains. During the period of study, other sites in sandstone around Sydney also developed iron springs, but they have not been investigated. It should be noted that the presence or absence of iron springs appears to be quite independent of fire events.

During the bushfires, parts of some swamps burned completely through the peat subsoil right down to the sandstone but others stayed wet. After flooding rain, water levels in the swamps rose and flowed over the sandstone as shown in Figures 2 and 3 at Mt Banks. Some swamps had iron staining but others were clear.

Closer inspection near the springs revealed small features similar to flowstone, comprising sand grains and organic material as well as bacterial iron flocs at the air/water interface making iridescent patterns (Fig. 6). Gradziński et al. (2010) reported a similar deposit, called siliciclastic microstromatolites, caused by an interaction between microorganisms and siliciclastic materials, from near-vertical surfaces in a sandstone cave in Poland. Low nutrient levels near the springs allow swamp species such as the carnivorous plant, *Drosera spatulata*, to grow well in the area, and were among some of the earliest plants to recover after the fires.

Exposed sandstone plateau after fire

Apart from swamps and occasional igneous intrusions, the sandstone plateau of the Blue Mountains generally has very thin soils, mainly composed of sand, quartz sandstone and ironstone clasts overgrown by a mat of interlocked roots of several plant species. The bushfires burned some of these mats,

Fig. 3. Iron oxyhydroxide from a hanging swamp forms a smooth, rusty-coloured coating on sandstone above a small cave on Mt Banks (Fig. 1, site 2)

which subjected the soils to high temperatures close to the surface. Near Mt Banks picnic area, it was possible to see some of the effects. After the fires and the first rains, the ash bed became a thick, foul-smelling black paste. This may have prevented some of the soil from being simply washed away and was still present three years later. Reduced vegetation allowed us to see ironstone bands which formed resistant shell-like patterns in the sandstone outcrops at Mt Banks.

Iron springs and ironstone patterns

The delicate ironstone patterns exposed on the sandstone outcrops, especially near cliffs and older road cuttings are most likely goethite with some haematite on older surfaces. Some areas of exposed sandstone on the plateau subjected to the bushfires appeared rusty, which could happen if the fires burned off lichen and other plants previously growing on the rock. Temporary iron springs occur in areas of the plateau above small caves (e.g. Fig. 3), leaving distinctive smooth orange-coloured deposits.

Analysis

The small sandstone caves seen near Mount Banks appear to have been formed by a process of arenisation, producing a softer, more easily eroded "ghost rock". The softer rock becomes more concave due to erosion (such as piping, insect burrowing, gravity acting on loose grains, surface and subsurface water erosion and other mechanisms). As these concave shapes develop, they become niches, slots and eventually caves. Extreme weather has allowed us to see some of the processes in action. It would be worthwhile to look out for other iron springs in sandstones around the Sydney region and note the geology and conditions under which they become active.

Denudation of Mount Banks and the plateau (both the basalt and the porous Banks Wall Sandstone) allows iron oxyhydroxides to be redeposited in joints and hanging swamps, where it can be re-worked by soil chemistry and biology, dissolving or precipitating iron oxyhydroxides downstream from the original source. The presence of iron ions assisting quartz dissolution would be ongoing, especially in porous sandstone below hanging swamps. Once the sandstone pores are more open, iron migrating through the sandstone becomes channelised, most likely due to percolation. This percolation process then acts to block some of the pores, especially around the outsides of the percolation channels where the groundwater flow rate would be reduced. This may lead to tubular shapes and shell-like patterns of ironstone where swamp water in the sandstone meets oxygenated groundwater derived from rainfall. Denudation preferentially removes the softer sandstone "ghost rock" first, leaving the harder ironstone exposed.

Heat, acids and microbes on iron deposits

Another process which may liberate iron oxides may be natural bushfires, which are relatively common in the Sydney region. There is possibly some small-scale iron reduction in low-oxygen situations. Heavy rain following a bushfire washes a lot of material, including charcoal, sand and iron oxides, from their original position into cracks and swamps. Here the iron oxides can be dissolved slowly by soil acids, such as humic and fulvic acids. The long-wet period, post-fire (2020–2023), would have allowed the water table to rise sufficiently to overflow the swamps, allowing iron bacterial flocs to coat surfaces (Fig. 3). The material can also be lodged in rock joints forming dyke-like deposits and coatings on the sandstone, as shown in Figure 4 above a small cave. Whether sandstone joints become permanently filled or not by

Fig. 4. Dark reddish crenulated ironstone banding forms the ceiling of a small cave in cross-bedded sandstone near Mt Banks (Fig. 1, site 2)

this process would depend on whether bacterial flocs were able to cement the sand and charcoal before the next rain storm washes the debris out of rock joints.

Groundwater mixing

The quartz sandstone is generally porous, except where ironstone banding occurs, as the ironstones appear to be mostly aquicludes. Rain falling on the plateau is readily absorbed into the sandstone, as indicated by the groundwater monitoring boreholes. Rainwater sources tend to have relatively neutral pH. On the other hand, water in the hanging swamps tends to be very acidic, often with low oxygen and can dissolve iron oxides. Where two different groundwaters meet within the porous sandstone, there may be some mixing corrosion, depending on the groundwater chemistry.

Iron oxyhydroxide deposition may occur near the groundwater mixing front within the sandstone, later exposed as shown in Figures 4 and 5 above small caves in sandstone. The shell-like patterns can appear roughly circular, tubular, and repetitive as the groundwater levels change. In general, the ironstone patterns at the study sites are formed valley-side as this is the general direction of groundwater flow. Runnels such as shown in Figure 3 may be initiated near the swamp edges by a similar process and enhanced by denudation.

At the study sites, the ironstones exhibit brighter reddish colours close to the surface, presumably because there is plenty of oxygen. Deeper in the rock, the patterns are sometimes less distinct, and more yellow in colour. This may be due to different bacterial species acting at lower oxygen levels. The process can be seen in road works where newly exposed rock tends to have a lighter colour than older exposed rock.

Formation of caves and ironstone layers

Within the sandstone, either impervious ironstone zones close to the surface or impervious shale layers redirect groundwater as springs. Generally, the area just above the impervious layer is a softer sandstone where the grains are poorly cemented and frequently burrowed by insects. The quartz in the softer sandstone is only held together by a small amount of silica (probably common opal). This layer exhibits more concave features on steep surfaces and sometimes appears whiter than the rest of the sandstone.

Above the soft layer, one may see a layer of ironstone, caused by a mixing of acidic and neutral waters. The sequence can repeat in some areas, depen-

Fig. 5. Tubular, dark ironstone bands in sandstone above a small cave at Mt Banks (Fig. 1, site 2), with surface water seepage

ding on groundwater sources. Near steep areas such as cliff edges, the iron-rich layer sometimes forms the ceiling of small sandstone caves depending on how eroded the soft layer becomes. A small cave is shown in Figure 4 which has a fretting pattern in the walls, similar to tafoni weathering.

Relationship between iron springs, ironstones and small caves in sandstone

The following is a suggested ongoing and repeating sequence of weather and groundwater events leading to the formation of iron springs and their relationship to small caves in quartz sandstone in the study area:

1. The existing surface has ironstone patterns in the quartz sandstone, with iron derived from either weathered basalt or ferrous minerals in the host sandstone.
2. Severe bushfire removes vegetation, including some of the local peat in swamps, and dehydrates some earlier ironstone surfaces.
3. Rain washes loose particles of iron oxides and oxyhydroxides into joints and swamps.
4. A long period of unusually wet weather, coupled with a lack of vegetation allows the water table to rise considerably and allows springs to discharge groundwater (both clear and iron-stained) from joints and swamps (Figs 2, 3).
5. Acidic and biochemical reactions in swamps dissolve particles containing iron in the groundwater and re-deposit iron oxyhydroxides as flocs (Fig. 6).
6. Mixing of fresh (rain) and acidic (swamp) water layers within the sandstone dissolves some of the silica and deposits iron oxyhydroxides near the mixing boundary, typically a curved layer (Fig. 5).
7. Arenisation results in a softer, more easily weathered sandstone, leading to the development of small caves (Fig. 4), as well as depositing small flowstone-like patterns (siliciclastic microstromatolites) with flocs downstream of swamps (Fig. 6). Silica may redeposit downstream, case hardening of the sandstone surface. Also, below the small caves, loose quartz sand particles add to the thin soils.
8. Over time, near-surface iron oxyhydroxide flocs block the pores in the sandstone, forming impermeable layers of ironstone. Silica and iron oxyhydroxide may be deposited on surfaces and in joints further downhill, causing local surface hardening.
9. As the vegetation re-grows, the water table drops and the temporary iron springs dry up. Swamps re-develop and peat again deposits.
10. Hardened surfaces become more prominent over a longer period of denudation, becoming the roofs of small caves and the tubular ironstone shapes seen on surfaces, due to the removal of loosened sandstone grains near the sandstone surface. Some caves can be quite large, e.g. tens of metres wide and high, although typically lack depth.

Fig. 6. Flowstone-like siliciclastic microstromatolites with colourful bacterial iron flocs, Mt Banks Road (Fig. 1, site 2)

Conclusions

Preliminary research carried out in the Blue Mountains by the author would suggest the following generalisations about the formation of iron springs and cave development in quartz sandstone at this stage:

At Mount Banks, curved shell-shaped ironstone crops out on the surface of Banks Wall Sandstone near hanging swamps in steep areas. Small sandstone caves, commonly below the ironstone at the study sites, are caused by arenisation: leaching of silicic cement downstream of hanging swamps, initially by groundwater mixing (pH, iron and biochemistry) to weaken the rock and later, once exposed, assisted by insect burrowing and tafoni weathering of the undersides of overhangs. The formation of these interesting ironstone shell-shaped patterns is ongoing on the surface, as slow denudation of the landscape exposes the iron banding. The ironstone shell-shapes are most likely emplaced within the sandstone following mixing corrosion: percolation of iron-rich water derived from swamps, travelling through the porous sandstone and reacting with rain-derived groundwater in the bulk sandstone, with varying amounts of oxygen. Iron oxyhydroxides, derived from a nearby basalt cap, or from minerals in the Banks Wall Sandstone, can appear as flocs in the hanging swamps. Extremes in weather (fires and flooding rain) accelerate the processes, allowing one to see bacterial iron flocs, normally deep in the swamps, rise as iron springs and redeposit iron oxyhydroxides in the landscape.

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Author's contribution

Jill Rowling organised the field work, wrote the article and took the photographs. This article expands on concepts which she presented to the International Union of Speleology, 14th International Symposium on Pseudokarst in Karłów (Poland) on Thursday 25th May 2023. More colour images are available by emailing the author.

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