The Geoheritage and Geomorphology of the Sandstone Pagodas of the North-western Blue Mountains Region (NSW)

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Washington, H.G. and Wray, R.A.L. (2011). The geoheritage and geomorphology of the sandstone pagodas of the north-western Blue Mountains region (NSW). *Proceedings of the Linnean Society of New South Wales* **132**, 131-143.

The towered 'pagoda' rock formations of the north-western Blue Mountains, west of Sydney, have a heartland of about 600 km^2, mostly at around 1000 metres altitude in Banks Wall and Burra Moko Head Sandstones. The pagodas are of two types: the 'platy pagodas' are generally stepped-cones in shape, with semi-regular ironstone bands, whereas the 'smooth pagodas' display less ironstone bands and are similar to many slickrock slopes found elsewhere. The platy pagodas however are an uncommon and significant geomorphic landscape feature, and are distinguished by the extent and regularity of their ironstone banding. The formation of the ironstone banding has involved the movement of iron in solution and its precipitation to form resistant bands, swirls and pipes. Questions remain as to how the ironstone banding formed, however 'roll fronts' of reaction between reduced Fe^{2+}-rich water and oxygenated water may best explain the amazing ironstone shapes. The geoheritage value of the pagodas is significant, but is threatened by activities such as longwall coal mining. The pagodas and the associated slot canyons of the Blue Mountains are ideal candidates for future geological and geomorphological research.

Manuscript received 1 November 2010, accepted for publication 16 March 2011.

KEYWORDS: Blue Mountains sandstones, geoheritage, geomorphology, ironstone banding, ironstone formations, Liesegang banding, pagodas.

INTRODUCTION

The 'pagodas' are a local name for distinctive sandstone formations in the north-western Blue Mountains region of NSW, west of Sydney (Fig. 1). These rocky cones are found in parts of three reserves of the Greater Blue Mountains World Heritage Area; the northern parts of the Blue Mountains NP, along the western edge of Wollemi NP, and in the Gardens of Stone NP. However much of the pagoda heartland is still found outside of reserves, principally on Newnes Plateau, Genowlan and Airly mesas in the Capertee Valley, and in Ben Bullen State Forest. The main concentration of the pagoda country covers around 600 km^2. Pagodas are conical rock formations formed by differential weathering and erosion of the local sandstones. They come in two forms. Smooth pagodas have relatively regular conical-shapes (without terraces), while platy pagodas are stepped and terraced cones that resemble Asian pagodas, ziggurats or step-pyramids. On platy pagodas, erosionally resistant ironstone bands from 1 to several cm thick project from the surface and form the hard surfaces of the terraces. These bands can project laterally from the underlying sandstone for tens of centimetres, and display detailed 3-dimensional forms that can resemble chairs and tables, pipes and pulpits. Pagoda complexes are part of wonderfully intricate, ruin-like, landforms that resemble lost cities and temples, and are also often associated with slot canyons and weathering caves. Their significance only started to be appreciated in the 1980s.

HERITAGE

Large sections of the pagoda region were incorporated into the Greater Blue Mountains World Heritage Area due to their biodiversity significance, particularly eucalypt diversity. However it is of concern that scenic, cultural and geoheritage values of the pagodas landscapes have not been fully appreciated or officially recognised.

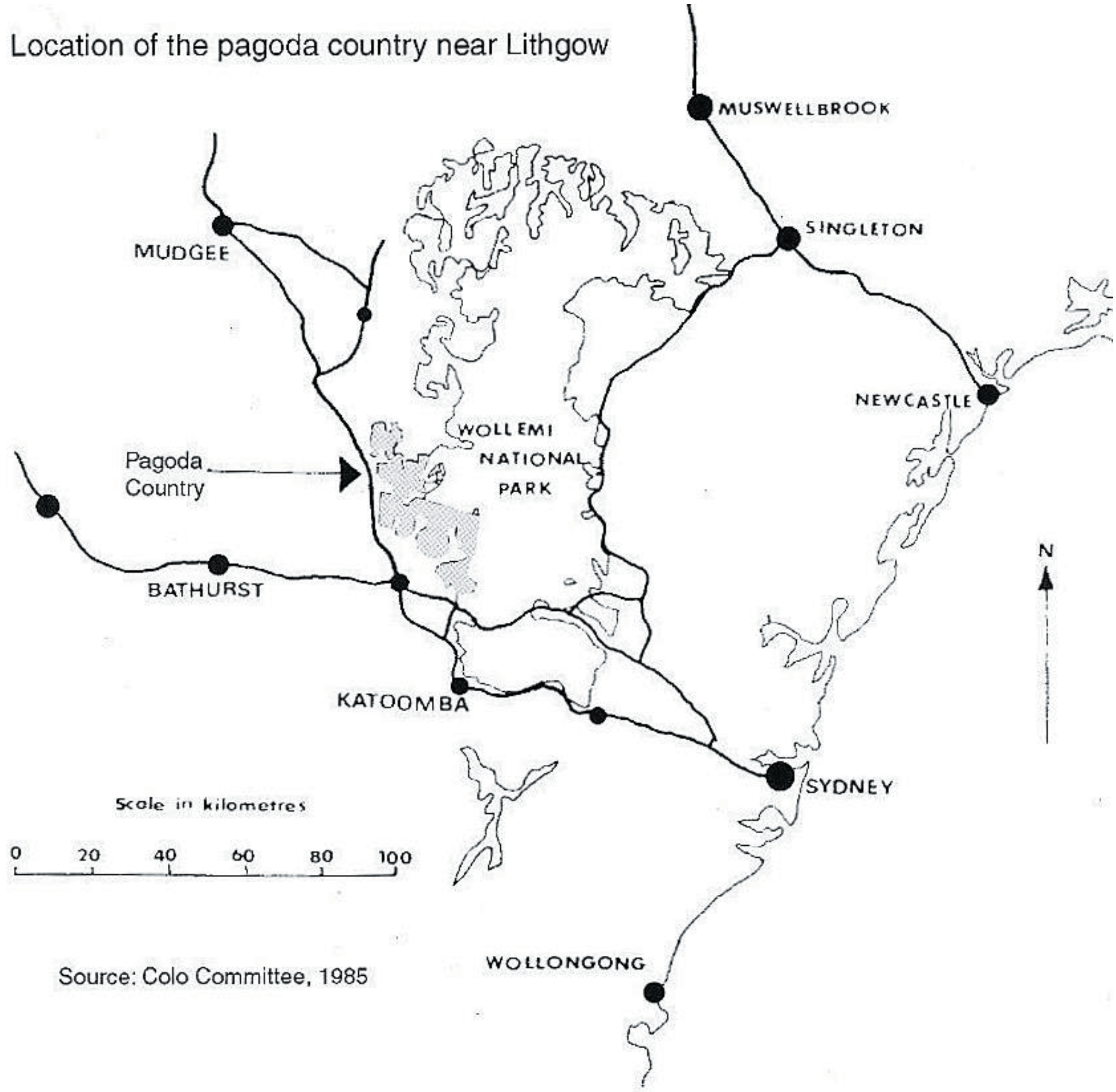

Figure 1. Map of the main distribution of the pagoda country in relation to Sydney, NSW (Washington, 2001a)

Geoheritage

The geoconservation significance of the pagodas has been recently recognised, but only to a partial extent. 'Geoheritage' as a term was originally only applied in Australia to *geological* features, not geomorphological or soil features (Sharples 1998). However, here we apply the broader usage of geoheritage (Washington 2001b), where the pagodas are geoheritage in view of the fact that they are uncommon and significant geomorphic sandstone landscape features.

The National Trust gave the first historical recognition of the visual and aesthetic significance of the pagodas when they proposed a Pinnacles National Park in 1977 (Washington 2001b). At that time these rock formations were called pinnacles, stuppas, beehives or just 'rocky outcrops', as on the 1:100,000 topographic maps. Although their visual beauty had been recognised by the National Trust, nobody had yet begun to appreciate their scientific values, such as geomorphology and botany. In the early 1980s a community non-government organisation the Colo Committee took up the campaign to conserve these rock formations, and along with the Colong Committee and the Federation of Bushwalking Clubs proposed the Gardens of Stone National Park (Colo Committee 1985). They focused on the term 'pagoda', which usage is now accepted for these smooth and stepped cones. At that time the pagodas locally were seen at best as interesting oddities, and at worst as sources of the 'black crinkly' bushrock that was sold on the Sydney market well into the 1980s.

Geodiversity – unlike biodiversity – is not alive, but it may be unique and significant and can be easily destroyed. The major impact on the pagodas has been subsidence due to longwall coal mining, where the ground surface can drop by up to 1.5 metres. While pagodas are quite geologically stable under normal conditions, the stresses of subsidence both crack pagodas and cause extensive cliff collapses. These collapses mostly occur along overhanging cliffs (often Aboriginal sites). This issue was highlighted at the Airly Commission of Inquiry in 1992, which investigated the proposal for coal mining of the Mt. Airly mesa in the then proposed Gardens of Stone National Park. At that time the Department of Mineral Resources (in response to a question by the Colo Committee) stated that in the Baal Bone Colliery area there had been 124 cliff collapses over 2-3 years, while in the adjacent Angus Place Colliery area there were 55 cliff collapses over the same period, some over 1,000 cubic metres (Washington 2001b). Significant cliff collapses have continued since (Muir 2010).

Mining subsidence can also impact on the Temperate Highland Peat Swamps on Sandstone (an endangered ecological community under the Commonwealth EPBC Act) through draining of aquifers and surface streams down strata shattered by subsidence. When the Colo Committee raised concerns in 1992 that the Department of Mineral Resources did not recognise the geomorphological value of these rock formations, the Department replied: 'That is not true, we do value the pergolas (sic)'. The confusion over the name, where 'pagodas' became 'pergolas', demonstrated that the geoheritage value of the pagodas was not being acknowledged at that time.

While Gardens of Stone National Park was proposed in 1985, a park by that name was not created till 1994, and covered only 11,780 Ha, later being extended to 15,080 Ha. The Park gazetted was the area of the pagoda country that did not overlie mineable coal (due to the thinning of the coal seams and 'bad roof' due to jointing). While some pagodas are found in the nearby Wollemi and Blue Mountains National Parks, and others are found in the Gardens of Stone NP, around half the core pagoda country is not protected in reserves. The main pagoda areas not protected are the Genowlan/Airly mesas, Newnes Plateau, and parts of Ben Bullen State Forest. Much of this area is covered by coal leases such as Airly, Baal Bone, Angus Place and Clarence.

The Gardens of Stone Stage 2 proposal of an additional 40,000 Ha was put forward in 2005 by the Colong Foundation for Wilderness, Blue Mountains Conservation Society and the Colo Committee. The proposal sought to form a State Conservation Area (SCA) over most of the area, which would have protected surface features but allows underground mining. Currently, the Department of Environment, Climate Change and Water (DECCW) has been working on a proposal to make the Genowlan and Airly mesas an SCA. This would allow 'bord and pillar' coal mining by Centennial Coal of the Airly Coal lease, but give protection to the surface features, including an extensive complex of pagodas, sometimes known as the 'Three Hundred Sisters'. The nearby Genowlan mountain is part of an area proposed for a future coal lease and contains an endangered ecological community (Genowlan Point Heathland) and a critically endangered plant *Pultenaea sp. Genowlan Point* (under EPBC Act), of which only 39 individuals were known in 2005 (Washington 2005), with only 26 being found in a recent visit in 2011.

The proposal to give SCA status to much of Newnes Plateau seems to have become bogged down due to a perceived conflict with forestry and popular 4WD and trail bike use. However, most of the pagodas on Newnes Plateau could be protected *without* conflict with these activities. There is an ongoing community campaign for the protection of Gardens of Stone II (Muir 2005).

Bioheritage

Given that biodiversity often is dependent on geodiversity, it is not surprising that the pagodas are a biodiversity hotspot for rare and threatened species. Pagoda areas offer many different habitats to species and also offer a refuge from fire and grazing to some plant species. Thus species survive there which may have gone extinct in the rest of the landscape. The rare Pagoda Daisy (*Leucochrysum graminifolium,* Figure 2a) is virtually restricted to pagodas. The rare *Prostanthera hindii* similarly is also mostly found on pagodas. In the northernmost part of the pagoda region, to the west of Nullo Mountain, a new species was found only a decade ago, now named *Leionema scopulinum*. It also is essentially limited to pagodas. Other rare or threatened plants often found on or near pagodas are *Pseudanthus divaricatissimus, Banksia penicillata, Acacia asparagoides, Epacris muelleri* and *Philotheca obovalis* (Washington 2001a). The 'regionally significant' *Eucalyptus oreades* is commonly found on and around pagodas. There are several threatened animals species found in and around pagodas. The Broad-headed Snake (*Hoplocephalus bungaroides*) is found on pagodas (as it lives under loose surface rock), while Glossy Black Cockatoos (*Calyptorhynchus lathami*) feed on *Allocasuarina* species found on and adjacent to pagodas. Raptors such as the endangered Peregrine Falcon (*Falco peregrinus*) use adjacent cliff habitats (e.g. Genowlan Point).

Cultural heritage

A number of Aboriginal art sites are found in sandstone weathering caves among pagodas, with Blackfellows Hand Aboriginal Place being the most famous. There are many other sites found in weathering caves in pagodas near swamps. There is also an extensive European coal and oil shale mining heritage associated with areas near pagodas, which dates from the 1880s (Colo Committee 1992). Oil derived from the kerogen in torbanite was used to replace sperm whale oil for domestic lighting. The western side of Wollemi NP contained narrow but rich bands of torbanite, and these were mined from Mt Airly, Newnes and Glen Davis. Mining heritage can be found at all these now-ruined sites, including steam winches, air shaft chimneys, and miners' cottages built into caves on Airly Mountain (Colo Committee 1992).

GEOMORPHOLOGY OF THE PAGODAS

These pagodas are an unusual landform type, and very little is known about how they form. What is clear is that pagodas are differential weathering formations found in the Banks Wall and Burra Moko Head Sandstones of the Triassic Narrabeen Group. The majority of platy pagodas appear to be found in the Banks Wall Sandstone, though smooth pagodas can be found in the underlying Burra Moko Head Sandstone. Both of these sandstones are fine to course-grained, porous sandstones, often with small pebble bands (Bembrick 1980). They were laid down in a massive river delta flowing from the north-west some 230 to 250 million years ago. Occasionally there are fine claystone bands intercalated amongst the sandstones.

Pagodas come in two forms – 'smooth' and 'platy'. Smooth pagodas (Figure 2 b and c) resemble cones or beehive structures found in the Bungle Bungles, Budawangs and other areas around Australia and the world (Young, Wray and Young 2009), such as the central-west USA where they would be called 'slickrock' slopes (Howard and Kochel 1988). Platy pagodas (Figures 2 d, e, f) however commonly have regular ironstone banding every 20 cm to a metre that can extend up to 60 metres in height. This banding is generally 2-5 cm in thickness and can, because of erosion of the surrounding friable sandstone, often project 20-40 cm from the sandstone (and in exceptional cases can project up to a metre). This ironstone plays a major protective role, and smooth pagodas appear to be eroding far more quickly than platy pagodas (we estimate at least 10 times faster, though this needs further research).

Platy pagodas are in our view distinct and significant features, as we are not aware of any other rock formations in Australia or overseas that mimic the geomorphology of platy pagodas (see Young, Wray and Young 2009). While there are many other rock pinnacles and beehives around the world, and while ironstone formations are found in other places, the regular stepped-cone shape of platy pagodas is a distinct geomorphic feature. The ironstone banding of the platy pagodas is thus significant in degree, not in nature, as ironstone is found throughout the Sydney Basin. However, the development of banding in platy pagodas forms a distinct geomorphic landscape unit. By analogy, limestone caves are significant, even though limestone is common. The reason why platy pagodas are virtually restricted to this area may be due to the friable nature of the porous bedrock itself, the amount of iron present in the sandstone, or aspects of former climate and associated hydrology. The exact formative mechanisms of platy pagodas remain unclear, but several hypothesis and suggestions for further research will be presented.

The erosional formation of the smooth beehive-shaped pagodas and similar 'slickrock slopes' elsewhere is fairly well understood (Howard and Kochel 1988; Young, Wray and Young 2009). Similarly, platy pagodas appear to result from the differential weathering of the resistant ironstone banding and the much softer, friable, surrounding sandstone. However, it is not known how the regular ironstone banding of platy pagodas has formed, and it is noteworthy that until now nobody seems to have asked these questions or published on this issue.

It has been suggested in community discussion over the years that the ironstone was possibly formed during deposition of the sediments. Given that these sediments were laid down in the delta of a large river,

Figure 2 OPPOSITE, a: Pagoda Daisy (*Leuco-chrysum graminifolium*); b: Smooth pagoda at Pt. Cameron, with platy pagodas in strata below; c: detail of b; d, e: Platy pagodas, Bungleboori Ck, Newnes Plateau; f: Platy pagodas at Gooches Crater.

a b c d e f

it is difficult to see how precipitated iron could have been deposited, which later reformed as ironstone in the 3-dimensional shapes seen within these sandstones. Whilst there is clear evidence that ironstone sheets commonly follow vertical cracks or joints in the sandstone (Figure 3a), the sub-horizontal ironstone layers are clearly not bedding-related features, as the 3-dimensional ironstone layers clearly cut across beds, and there are also ironstone piping (Figure 3b) and multi-dimensional ironstone sculptures (Figure 3c).

The iron thus appears to have reached its location through solutional processes, possibly when reduced Fe^{2+}-rich water precipitated out as ironstone. This was also the conclusion of Beitler et al. (2005) regarding the iron movement and ironstone formation within the Navajo Sandstone in the central US. Another suggestion for smooth pagoda formation has been that they are buried landscapes (e.g. dunes). This is not supported by the evidence, as while smooth pagodas may resemble dunes, they are rapidly eroding erosional landscapes that keep their shape not because they were buried dunes but because they are erosional features. The pagoda formation raises many questions, which are addressed in the following sections.

The Source of the Iron

The source of the iron remains a matter of debate. Some geologists suggest it is derived from former overlying basalt (as argued by Dr David Roots of Macquarie University in the 1980s). Remnant Tertiary basalt caps are found on Airly Turret and Mt Cameron in the north of the region, and on Mounts Wilson, Banks, Bell, Irvine, Tomah, Hay, and Tootie in the south, and these show that some small and localised basalt flows did occur near the pagoda region. Weathering of former overlying Tertiary basalt flows may have contributed locally to the iron content of the underlying sandstone. However, there is no definitive proof that basalt once covered the whole (or even significant parts) of this area, as noted by Dr John Pickett of the Geological Survey of NSW.

Others believe it originated from leaching of the iron coatings on sand grains and the iron cement in the sandstone itself (again noted by Dr Pickett). Leaching of 30% of the iron in coatings has been known from bleached zones in the Navajo Sandstones in Utah (Chan et al. 2006), which has then precipitated into ironstone formations that can contain 35% iron (Beitler et al. 2005). We agree with the second interpretation, that the iron comes predominantly from within the sandstone itself (possibly deep weathering during the Tertiary), but this needs further research.

Figure 3: a ABOVE, iron-indurated vertical crack; b OPPOSITE, ironstone tubing; c: ironstone sculpture on Wolgan/Capertee divide; d: Massive ironstone deposition above impermeable Wentworth Falls claystone (e) at Bungleboori Ck; f: 'dragon skin' ironstone nodule sheet (nodules c. 1 cm).

b

c

d

e

f

Hydrothermal hypotheses

Did the iron-rich water come from hydrothermal vents from basalt dyke intrusions, such as Varilova (2007) postulated for similar looking ironstone layers within sandstones of the Bohemian Switzerland National Park? While in that area there are nearby basalt dyke intrusions, no such intrusions have been found near the pagoda region. In any case, there is no evidence of how hydrothermal vents might have formed from such possible overlying basalt flows. Given the amount of ironstone present (which in places is rich enough to be an iron ore), evidence of hydrothermal vents should be more obvious.

Timeline of iron precipitation

It would be useful to know *when* the iron precipitated in the sandstone. Was this a single geological event, or were there a sequence of such events? Examination of oxygen isotope fractionation within authigenic clays in the ironstones may clarify this question. Palaeomagnetism of the ironstones may also reveal information as to the timing of ironstone formation. Determining the time of the formation of the ironstone banding may suggest how it was formed (e.g. whether it was associated with events such as volcanic activity in the Tertiary that may have shattered impermeable layers and allowed reduced iron-rich water to mix with oxidised surface water?).

Geochemistry of iron precipitation

It has been noted that oxygenated Fe^{2+} originally precipitates as polynuclear aggregates of Fe^{3+} hydroxides and ferrihydrite (Cornell and Schwertmann 1996), which are converted to a polymorph of FeO(OH) such as goethite, and finally to hematite (Berner 1980). Certainly a transition does occur with ironstone banding within sandstone bedrock on Newnes Plateau, as when uncovered (in sand quarries and road cuttings) the banding is light red and fairly soft. This then changes over a few months to become a deep purple colour and is much harder. Beitler et al. (2005) note that for Navajo Sandstone the presence of both iron oxide phases indicates multiple precipitation events with different geochemical conditions or progressive dehydration of goethite to form hematite. This may explain the change in colour and hardness of ironstone banding newly exposed to the Australian weather. Much more detailed geochemical investigation, including examination of iron-isotopes, may elucidate these aspects.

Three-dimensional ironstone banding

Platy pagodas contain extensive three-dimensional whorls, curves and pipes. While the ironstone formations in places follow cracks and other discontinuities in the sandstone where water might percolate, in the larger majority of instances it passes right *across* bedding planes. What can be responsible for this, to the extent that it can form piping, curves, and complex 3-dimensional sculptures formed by the coalescence of several ironstone bands? We believe the most likely explanation may be due to ‘roll fronts’ between reduced iron-rich water and oxygenated surface water. This has been postulated by Beitler et al. (2005) for the Navajo Sandstone (Fig. 4). Some concentric banding patterns have been called ‘ironstone roses’ and have been ascribed to Liesegang rings (Varilova 2007). We believe that the complex three-dimensional structures may reflect both vertical and horizontal movement of iron through the sandstones, leading to a complexity of formations not seen in the simple Liesegang banding in gel experiments in the laboratory.

Chan et al. (2006) note that precipitation of terrestrial concretions is thought to occur when Fe^{2+}-bearing (reduced) fluids intersect oxidizing groundwaters, where oxidation of iron at near-neutral pH would produce immediate precipitation of iron oxide at the mixing interface (Von Gunten and Schneider, 1991). Precipitation of iron oxide would be concentrated within a spatially-limited reaction front corresponding to this mixing interface. Beitler et al. (2005:556) note that ‘This combination of advective and diffusive processes could account for the complex mineralization patterns seen in the field’. Interestingly they also note that ‘Spatial relationships between bleached zones and iron-rich facies indicate that in some areas iron ions have traveled several kilometers before oxidation’. Concretions that precipitate within such a reaction front are commonly spheroidal in shape (Chan et al. 2006), and this might also assist in explaining the undulating nature of many ironstone bands, and possibly how tubular structures form? We recognise that while ‘roll fronts’ might explain how the amazing diversity of ironstone shapes could come about, it does not fully explain the process that leads to these formations, especially the regular banding of platy pagodas.

Regular ironstone banding

Apart from the 3-dimensional ironstone structures found in pagodas, there is also the regular sub-horizontal banding at a spacing of 0.2 to 2 metres, which can occur over heights of up to 60 metres. What best explains this? Is the regularity of the layering due to sequential events over geological time? Regular banding was *not* found in the Navajo sandstone, where Beitler et al. (2005:559) noted:

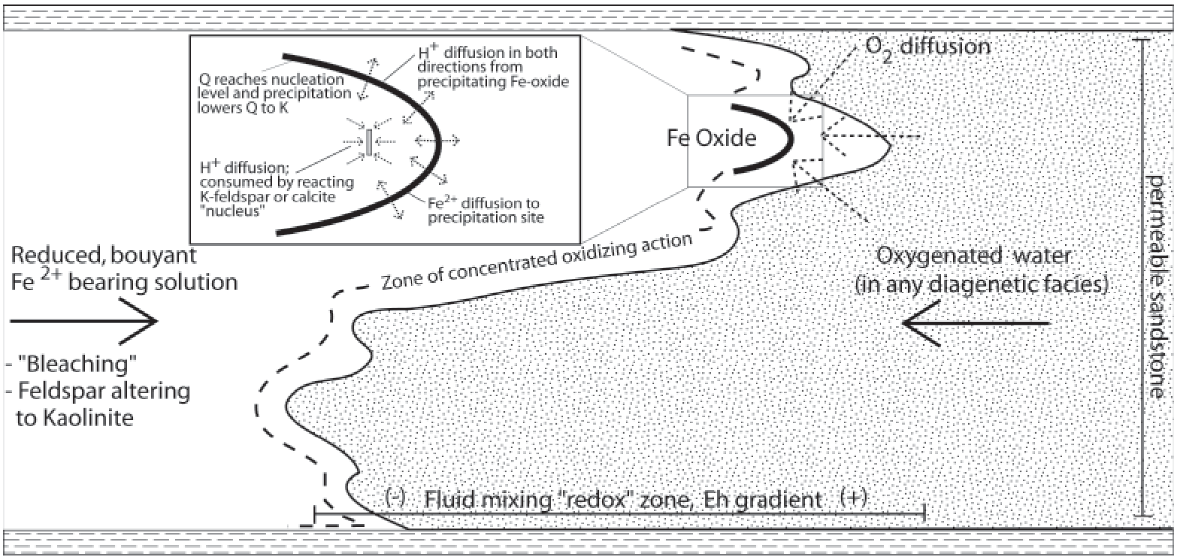

Figure 4 Generalized conceptual model of an oxidation-reduction front with precipitation of ferric oxide near the interface between oxidizing, O2-bearing water and reduced, Fe2+-bearing waters. A reduced, Fe2+-bearing solution moves to the right into a region of porous rock containing oxygenated water. (From Beitler et al. 2005, Fig. 12)

> 'The iron staining is commonly diffuse and permeates the sandstone on one side of the joint, and terminates abruptly on the other side of the joint, indicating directional fluid mixing and diffusion. The joints were likely conduits for oxidizing meteoric groundwater that infiltrated the sandstone and created a local oxidizing environment. If the sandstone was saturated with reducing iron-saturated fluid at the time of joint formation, the influx of this meteoric water would have resulted in precipitation of iron along this increased permeability zone.'

They thus found that joints were an important means of flow for oxidising water, but the ironstone was diffuse and not banded. What then causes the regular banding found in the sandstone of the platy pagodas? One hypothesis we have considered is that they are due to a series of wetting and drying events. It may represent a regular sequence where water moved through the sandstone as an aquifer, and ponded to a certain depth (e.g. on top of a claystone layer), then Fe^{2+} was precipitated out on the top of this water surface (due to higher oxygen levels, possibly due to arrival of oxygenated surface water) to form a new impermeable layer. More water then ponded to a similar depth on the new impermeable layer, which then precipitated Fe^{2+} to lay down another impermeable layer, and so on. This would suggest that under those conditions there was an optimum depth of water pooling in the sediments where the Eh and pH conditions were suitable for Fe^{2+} to precipitate out as Fe^{3+} in iron hydroxides in a horizontal 'roll front', which later formed into goethite (and then upon exposure, hematite). The banding may thus be a function of the properties of the porous sandstone itself, plus the climate and hydrology at the time, and the iron geochemistry associated with this.

As the distance between the bands varies from place to place (from 0.2 metres to 2 metres), this may reflect differences in the sandstone porosity, iron content, local hydrology and geochemical conditions. Field observations lend some support for this hypothesis, in that the most massively iron-indurated sandstone (Figure 3d) is often the layer immediately above a claystone band (Figure 3e). In places it seems these impermeable layers may only need to be quite thin to cause major iron induration. This may mean that the first leaching cycle extracted the greatest amount of iron, which was then indurated in that first layer. The presence of massive amounts of deeply weathered (> 60 metres) sandstone on Newnes Plateau (Peckover 1986) shows this region was subjected to major episodes of leaching and weathering. The question remains as to when this took place, given this area has been exposed to weathering since at least the early to mid-Tertiary (Young, Wray and Young 2009). Pickett and Alder (1997) also believe this leaching probably took place during the Tertiary.

Another explanation that may explain the regular banding is 'periodic precipitation', similar to the phenomenon known as Liesegang banding. This explanation for platy pagodas was suggested by geophysicist Prof. Marjorie Chan of Utah University. Hantz (2006) notes regarding Liesegang banding:

> Although the Liesegang phenomenon has been studied for over a century since its discovery in 1896, the mechanisms responsible for these structures are still under discussion. The models that try to explain the pattern formation can be divided into three main classes: supersaturation, sol coagulation and phase separation theories.
>
> All of these theories can reproduce the most important macroscopic characteristics of the bandings, but none of them is able to explain all the experimental findings. It is reasonable to assume that several mechanisms account for the Liesegang banding.

The complexity of the iron banding (with occasional gaps between banded areas) poses the question as to whether there may have been more than one precipitation event. This has been postulated in regard to small 'Liesegang blocks' in Iran (Shahabpour 1998). For this to occur in the platy pagoda banding however would mean that the bands formed are not immediately impermeable, and allow the reactant (e.g. oxygenated water moving down or reduced Fe^{2+} water moving upwards) to continue to pass through the rock. However, ironstone banding is often now observed to be impermeable, but this impermeability might possibly form later as the iron hydroxides later change to goethite and/or hematite. Horizontal flow of reduced iron-rich water between existing ironstone bands may possibly form other ironstone bands. This may explain the most heavily indurated ironstone areas above aquacludes. The regular ironstone banding of the pagodas remains one of the most difficult aspects of pagoda morphology to explain. Our above discussion details two hypotheses to be considered by future research.

Distribution Patterns and Controls

What determines where platy pagodas form? This may be due to three processes. Firstly, the faster erosion occurring along existing joints and valleys would allow platy pagodas to erode out in these areas. Secondly, the sites where one finds pagodas may be due to the fact that ironstone banding is not distributed uniformly across the strata that give rise to platy pagodas, so that the banding is *thicker* or more prevalent in some places. Certainly from field observation the thickness of bands varies from place to place. Ironstone banding can be seen in some of the friable sandstone quarries and road cuttings on Newnes Plateau, though this can be quite thin in places compared to that seen in pagodas. Thirdly, much of the pagoda country is deeply weathered (which presumably originally mobilised the iron). Newnes Plateau contains half a billion tonnes of friable sandstone (Peckover 1986). The degree of weathering may vary from place to place, so that in some areas the bedrock retains more cement between the grains. The formation of platy pagodas may thus be a function of enough protective ironstone banding, in addition to whether the bedrock between the bands is weathered to a greater or lesser extent. Even with banding present, if the bedrock is so weathered as to erode quickly, the pagoda may collapse and the banding be fragmented into ironstone debris. Such ironstone debris is commonly seen in places on Newnes Plateau, and near other pagodas. At this stage, we do not know which process is dominant in the formation of the platy pagodas we see today. Quite likely all three aspects are operating. Examination of drill cores and the friable sandstone quarries may provide further evidence as to the uniformity of banding, its thickness, the weathering of the sandstone, and whether such sites could form pagodas in the future upon differential weathering.

Impermeable bands

To what extent do claystone and ironstone bands determine water flow and hence where iron precipitates out? Claystone bands of various thicknesses are common within these sandstones, and begs the question whether these function as impermeable layers that have directed groundwater flow and ironstone formation? Claystone and ironstone bands function in the central Blue Mountains as impermeable layers that direct water along strata that feed hanging swamps (Pickett and Alder 1997), and they should function similarly in the north-western Blue Mountains. However, sometimes claystone bands in overhangs in the pagoda region can be seen to have been breached by cracks, and the iron-rich water has passed through to the strata underneath (and formed banding). In other places the impermeable claystone is intact and the ironstone banding is much thicker and more massive on top of these claystone bands (which in some spots may only need to be quite thin). This may account for the massive ironstone 'sculptures' which can be several metres high (Figure 3c) that are found in many places. The action of impermeable claystone bands may also explain why a strata under such a claystone band has extensive ironstone banding and platy pagodas, while the strata above the band is virtually free of ironstone and has only smooth pagodas (as observed at Point Cameron on the Wolgan/Capertee divide). In that location it would seem iron-rich water only had access to the lower strata, but not the upper. Similarly, massive iron-banding can be found in platy pagodas on top of the Wentworth Falls Claystone, while the Burra Moko Head Sandstone underneath contains mostly smooth pagodas (seen in the 'Lost World' on Bungleboori Ck). Claystone bands would thus seem to function as water barriers, where a strata that carries iron-rich water (due to water flow controlled by impermeable layers) forms iron banding, while another does not, as iron-rich water cannot reach it. This needs further research.

Bacterial influence

The role of bacteria in iron dissolution and precipitation needs to be clarified. as it is noted in the literature that bacteria are involved in both the reduction and oxygenation of iron in sandstone. Beitler et al. (2005:559) note in regard to the Navajo Sandstone that 'Bacteria commonly mediate iron mobilization and precipitation and could possibly be an important component of this system (Cornell and Schwertmann 1996)'. However, the complexity involved in the bacterial control of iron precipitation does not seem to have been adequately explained in the literature. Are the amazing ironstone shapes found in pagodas in part due to bacterial colonies in the sandstone changing Eh and pH and thus precipitating Fe^{2+}? Certainly cracks and weaknesses in the sandstone would allow greater water flow and hence may bring more food to bacterial colonies at these sites, hence Fe^{2+} may precipitate to a greater degree along with the higher bacterial density.

There is also the question of whether bacteria are present in nodular ironstone concretions found on ironstone sheets in pagodas, known colloquially as 'dragon skin' (Figure 3f). Nodular iron structures have been noted elsewhere in ironstone formations (Chan et al. 2006; Varilova 2007). However, no detailed study seems to have been carried out to date on the bacterial involvement with iron precipitation in ironstone. Chan et al. (2006) note that ironstone nodules also form on Mars, where bacteria may not be involved, and suggest that nodular sheets may just be a function of reaction fronts in active chemical systems. This is clearly an area in need of further investigation, where the possible application of iron-isotope studies may shed light on the action of bacterially-mediated iron precipitation.

Present day activity

Does ironstone precipitation continue today that will one day weather out to form pagodas? Iron is still being dissolved and is moving in solution across the landscape and precipitating out in swamps such as Long Swamp Creek (headwaters of the Cox's River). In such swamps it might then be reduced in the sediments and then move downwards and sideways through the porous sandstone, within the controls exerted by the impermeable claystone bands. In this regard iron induration of sandstone may still be continuing today, laying further ironstone layers that may form the pagodas of the future. Alternatively, was all the ironstone banding laid down in one key geological event? If it proves possible to date ironstone banding, it may answer this question. If ironstone banding is still forming, then it raises the question of how swamps may have been involved in the past iron induration of the sandstone. A casual examination of pagodas clusters shows a linearity evidenced in many places, but this may just be due to linear jointing and erosion along these joints. However, swamps also form along such joints (e.g. the shrub swamps of Newnes Plateau) where iron could seep into sandstone over many thousands of years. As such, the formation of ironstone banding may still be ongoing. This issue remains a fascinating hypothesis for future research.

CONCLUSION

The pagodas are a case-history of how difficult it can be for something to be recognised as geoheritage. It is also an excellent example of why the concept of geoheritage in NSW needs to be expanded beyond just geological sites to include geomorphological and soil sites. If geodiversity and geoconservation in the literature are seen as applying to all three categories (geology, geomorphology and soils), then so also should geoheritage. The north-western Blue Mountains pagodas were originally appreciated for their scenic grandeur, and only later started to be recognised and understood as 'hotspots' of biodiversity. However, science was slow to appreciate just how distinct and significant pagodas (especially platy pagodas) are as a distinct landform. Iron movement and precipitation within these sandstones seem to have been taken for granted as a process, and scientists have been slow to ask just how pagodas, particularly platy pagodas, actually formed. We conclude that they are distinct and significant geomorphological features, even by world standards.

Despite these significant values, the geoheritage of the pagodas is still under threat, largely due to underground longwall coal mining, but also due to damage by human trampling. There have however been advances over the years as recognition of their geoheritage value has increased. For example, the orientation of some coal mining longwalls have been changed, or terminated earlier, to protect particular pagoda formations (e.g. Oakbridge Colliery stopped a longwall short of the 'Artefact' pagodas in Baal Bone Colliery, Washington 2001b). Protection zones have also been created in coalmine operation plans to protect some areas containing pagodas and swamps. The use of 'bord and pillar' coalmining can reduce subsidence if the pillars are retained (as Centennial Coal has agreed to do in some areas), and hence can protect overlying pagodas. One coal company, Centennial Coal, has been willing to consider the idea of a State Conservation Area being created over their coalmining lease at Mt. Airly.

However, just as Australia has been slow to acknowledge its wealth of biodiversity, the pagodas show that we have been similarly slow to recognise the significance of our geodiversity, and the platy pagodas are certainly a distinct and significant part of Australia's geodiversity. The formation of platy pagodas has yet to be full explained, but their geomorphic significance is not in doubt. We believe that pagodas and their associated sandstone landforms (such as slot canyons) are important and significant parts of the sandstone geodiversity of the Greater Blue Mountains World Heritage Area and adjacent unprotected areas. This is of significance given the Commonwealth Government plans to renominate this World Heritage Area for geodiversity in the future (currently it is listed only for biodiversity). Pagodas deserve full and expanded recognition as a significant part of the geodiversity and geoheritage of the Blue Mountains region. Their natural aesthetic beauty, their biodiversity, and their significant geomorphological values mean they deserve enhanced recognition and conservation into the future.

ACKNOWLEDGEMENTS

We would like to thank Prof. Marjorie Chan (University of Utah), Dr John Pickett (Geological Survey of NSW), and Dr Robert and Ann Young (formerly University of Wollongong) for their comments on this topic. We would like to thank Dr Brenda Beitler for use of Fig 12 of Beitler et al (2005). We would also like to thank Jayne Thomas and David Blackwell for field assistance, and thank the School of Earth and Environmental Sciences Uni of Wollongong for laboratory analysis facilities. We would also like to thank the anonymous reviewers for helpful and constructive criticism.

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