Received: 11 November 2024 | Revised: 11 June 2025 | Accepted: 25 June 2025

DOI: 10.1002/esp.70124

RESEARCH ARTICLE

ESPL WILEY

The origin, evolution and life cycle of rock art shelters in the Kimberley Basin of NW Australia

Andrew Gleadow[1] | Helen Green[1] | Damien Finch[1] | Samuel Boone[2] | David Fink[3] | Réka-Hajnalka Fülöp[3] | Alexandru Codilean[4] | Augustine Unghango[5]

[1]School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Vic, Australia

[2]School of Geosciences, University of Sydney, Camperdown, NSW, Australia

[3]Australian Nuclear Science and Technology Organisation, (ANSTO), Lucas Heights, NSW, Australia

[4]School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, NSW, Australia

[5]Kalumburu Aboriginal Community, Kalumburu, Western Australia, Australia

Correspondence
Andrew Gleadow, School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Vic 3,010, Australia.
Email: gleadow@unimelb.edu.au

Funding information
Australian Research Council Linkage Projects LP130100501 and LP170100155; Rock Art Australia.

Abstract

The Paleoproterozoic Warton and Wunaamin Miliwundi Sandstones in the Kimberley Basin of NW Australia contain an abundance of rock shelters hosting a striking succession of rock paintings of immense cultural and archaeological significance. The evolution of these shelters has not previously been studied in detail, yet provides the ultimate control on the long-term survival of rock art within them. The rock shelters develop initially on near-vertical sides of remnant sandstone blocks on an etched landscape exhumed from a formerly pervasive deep lateritic weathering zone of probable Neogene age. The two nearly flat-lying sandstone formations are highly cemented orthoquartzites characterized by brittle behaviour revealed in a landscape-scale pattern of etched joint planes and small strike-ridge scarps along which shelters develop. Consistent features of these rock shelters reflect their mode of origin and subsequent evolution through a life cycle lasting tens of thousands of years or more. These include horizontal bedding-plane ceilings and fractured back walls cutting through sandstone beds, which host most of the rock paintings. Fractures mostly dip back towards the deepest part of the shelter near the floor. The first stage in shelter development involves undermining by crushing of a relatively thin incompetent bed to form a recessed bedding cave in the absence of normal erosional agencies. Overlying massive sandstone beds are left unsupported and progressively collapse in one or more intact slab falls. Further falls lead to gradual enlargement and a rocky floor piled with fallen slabs. The geometry of the fractured back walls suggests that both tensile and shear failure are involved in shelter growth in a series of mass wasting events. Subsequent spallation and dilational flaking on sandstone surfaces on the lowermost sandstone faces modify the shelter walls. Eventually, the shelter may be destroyed by toppling forward due to continued undermining at the base.

KEYWORDS

rock shelter, sandstone, rock art, life cycle, Warton Sandstone, dilation, shear stress

1 | INTRODUCTION

Rock art sites in various parts of the world occur in a range of geomorphic contexts from deep limestone cave systems, through large rock shelters to shallow overhangs and exposed rock surfaces. Preferred lithologies for the production and preservation of painted rock art (as opposed to engraved art) include limestone, sandstone and durable crystalline rock types such as silicic granites or volcanic rocks. The origin and evolution of caves, rock shelters and other landforms in limestone terranes are the subject of a vast research literature, whereas those formed in other lithologies, most notably sandstones, have received relatively much less attention, as noted previously by Young & Young (1992). The mechanism of formation of various sandstone landforms of relevance to the origin of rock shelters is often attributed, rather vaguely, to differential erosion. However, various authors have also implicated the distribution of stress in the rocks as a key factor in the localization of such erosion (e.g. Bruthans et al., 2014; Filippi et al., 2018; Filippi et al., 2024; Young, Wray, & Young, 2018). Here, we suggest that the stress distribution is the dominant mechanism controlling the evolution of the rock shelter, in the virtual absence of erosion.

The Kimberley region in the northern part of Western Australia is home to an extensive rock art province that is remarkable in the global context for several reasons. One is the sheer abundance of rock art sites estimated to number in the tens of thousands over an area of hundreds of thousands of square kilometres. Another is the well documented succession of rock art styles that show substantial changes in form, content and pigments (Harper, Veth, & Ouzman, 2020; Morwood, Walsh, & Watchman, 1994; Veth et al., 2018; Walsh, 2000; Welch, 1993, 2015) over an extensive time span estimated to stretch well back into the Pleistocene (e.g. Finch et al., 2019, 2020, 2021). A third is the fact that, unlike in many other parts of the world, there is a cultural continuity to the indigenous inhabitants, their belief systems and cultural practices in the region today.

Rock art across the Kimberley region is found largely within the relatively protected confines of sandstone rock shelters on small escarpments and sheltered rugged local surface environments (Figure 1) developed in the Wunaamin Miliwundi (formerly King Leopold) and Warton Sandstone formations (Donaldson, 2012a, 2012b) of the Paleoproterozoic Kimberley Basin. Massive sandstone beds within these formations produce excellent surfaces on which paintings can survive for periods of many millennia (e.g. Donaldson, 2012a; Finch et al., 2020, 2021; Roberts et al., 1997; Ross et al., 2016). However, relatively little is known about the mechanisms whereby the rock shelters themselves are formed or their ability to survive over similarly long periods. Understanding the origin and evolution of these shelters, and the rates of the processes involved, are of critical importance both to the preservation of rock art hosted within them and to relating these paintings to other archaeological records contained within the landscape.

The aim of this study is to consider the origin, mode of formation, and evolution of sandstone rock shelters in the north Kimberley region, specifically those found within the ca. 1,790 Ma Warton Sandstone (Tyler, Hocking, & Haines, 2012). Similar processes also operate within the Wunaamin Miliwundi Sandstone at a lower stratigraphic level within the basin stratigraphy. The work is based on detailed examination in the field and photographic documentation of many hundreds of rock shelters over a ten-year period.

Our findings pertaining to the mechanisms of rock shelter formation have a much wider relevance to sandstone terranes generally, and possibly other non-limestone lithologies. The results are therefore of importance to many other occurrences of rock art and diverse archaeological sites developed in similar sandstone environments found across northern Australia, especially in Arnhem Land in the Northern Territory, and other parts of the world.

FIGURE 1 The Pundawar Manbur rock shelter in the Warton Sandstone, north Kimberley (see Gunn et al., 2022 for a detailed description of this site and its rock art).

2 | GEOLOGY OF THE NORTHERN KIMBERLEY BASIN

The Paleoproterozoic Kimberley Basin (Figure 2) contains a succession of sedimentary and igneous rocks deposited on a passive margin at the western end of the North Australian Craton, whose stratigraphy and sedimentology have recently been detailed and revised by Phillips (2023). The geology of the entire basin has been described by Tyler et al. (2012) and of the north Kimberley, where this study is based, by Gellatly & Sofoulis (1969).

The Kimberley Group is a conformable sequence of shallow marine to fluvio-deltaic sedimentary rocks and mafic volcanics reaching a maximum thickness of c. 4,000 m (Phillips, 2023). Three major siliciclastic formations, the Wunaamin Miliwundi, the Warton and the Pentecost Sandstones, deposited between c. 1814 and 1740 Ma (Phillips, 2023; Sheppard et al., 2012), make up the main sedimentary fill of the basin and dominate the landscape. Common cross-bedding and asymmetric ripple marks throughout the sequence indicate that current directions were consistently from a northerly direction. Across the north of the basin, the rocks of the Kimberley Group are only very gently folded, forming very broad, open domal structures with dips generally <5° and bedding mostly close to flat lying.

2.1 | Lower Kimberley Group

The Kimberley Group is subdivided informally into lower and upper subgroups (Sheppard et al., 2012). The lower stratigraphic subgroup comprises the Wunaamin Miliwundi Sandstone and the Hart-Carson Large Igneous Province, dated to c. 1799–1791 Ma (Phillips, 2023; Sheppard et al., 2012; Wingate et al., 2018). The Wunaamin Miliwundi Sandstone consists mostly of massive coarse-grained quartz sandstones, mostly white in colour and thickly bedded up to 3 m or more. Much thinner interbeds of purple-coloured siltstone are also found. Some regional variation also occurs, and in a few places this formation is characterized by a finer-grained facies of pinkish sandstone with bedding generally <1 m thick.

Overlying the Wunaamin Miliwundi Sandstones is an extensive series of flood basalts with minor intercalated feldspathic sandstones and silicified stromatolites of the Carson Volcanics. Deposition of this formation was, at least in part, subaerial and the interflow sediments may represent ponding in minor lakes on the poorly drained flow surfaces. Presumed equivalent intrusives known as the Hart Dolerites are found mostly as sills intruding the lower subgroup and dated to 1799–1791 Ma (Phillips, 2023; Sheppard et al., 2012; Wingate et al., 2018). The Carson Volcanics reach a maximum thickness of >1,100 m elsewhere in the basin but are only c. 335 m thick in the north Kimberley (Gellatly & Sofoulis, 1969).

2.2 | The Warton Sandstone

The upper subgroup consists of, in stratigraphic order, the Warton Sandstone, Elgee Siltstone and Pentecost Sandstone. The Warton Sandstone conformably overlies the Carson Volcanics and is predominantly made up of white to pale purple-grey, well-sorted, medium to coarse quartz sandstones. The overall thickness of the Warton Sandstone ranges from 335 to 530 m in the north Kimberley,

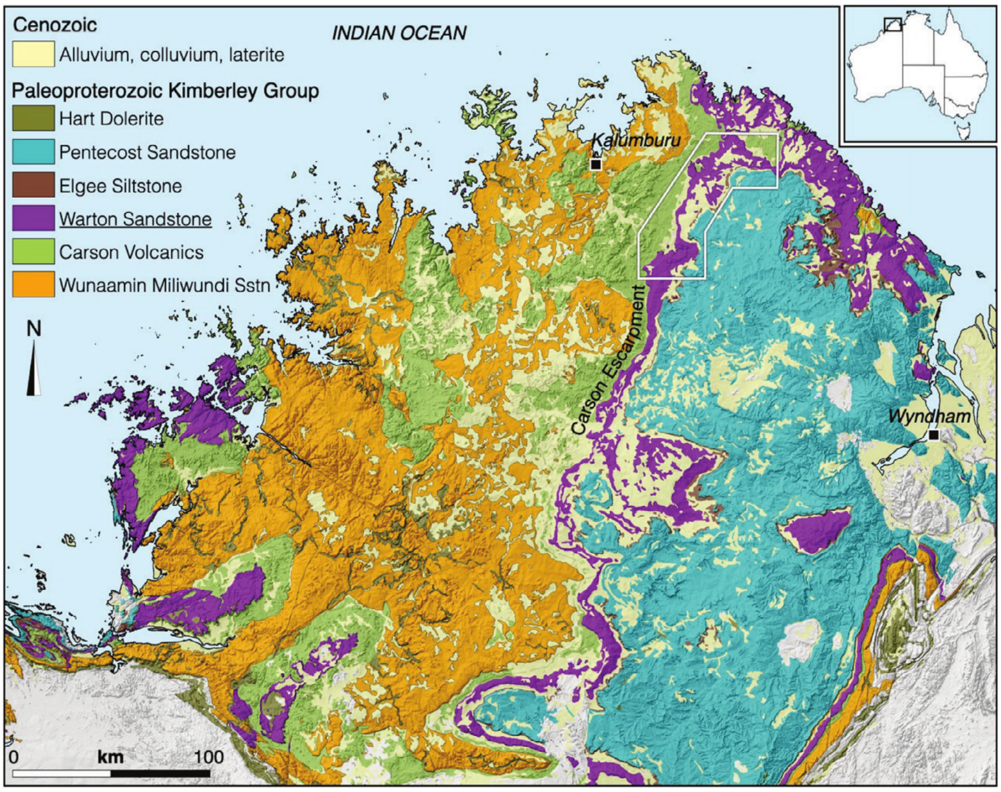

FIGURE 2 Geological map of the Kimberley Basin and Paleoproterozoic stratigraphic column (after Green et al., 2017). The band of outcropping Warton Sandstone running NNE–SSW through the middle of the basin defines the Carson Escarpment and separates the Elgee Siltstone and Pentecost Sandstone above, from the Carson Volcanics and Wunaamin Miliwundi Sandstone below. The white polygon shows the main study area.

and again represents a largely shallow marine to coastal paleo-depositional environment (Phillips, 2023).

Individual beds are massive to blocky in outcrop, typically 1–2 m thick and ranging between 0.5 m and 3 m. These are particularly massive in the lower 100–200 m of the formation and form the prominent 60–120 m high cliffs of the Carson Escarpment, running NNE through the centre of the basin (Figure 2). Along the escarpment, the Warton Sandstone shows some lateral variation over distances of tens of km from prominent, cliff-forming facies, which may represent large channel complexes, to areas where a finer-grained facies produces more subdued slopes with less massive outcrops.

Most outcrops of the Warton Sandstone are strongly cemented with siliceous cement, many being extremely tough orthoquartzites, forming a highly resistant substrate for the preservation of rock paintings. In thin section, the quartzites show epitaxial quartz overgrowths on the detrital grains and near-zero porosity (Green et al., 2017). The content of sulphides or other labile phases is very low, and the strength of the rock depends almost entirely on the cemented quartz framework.

Above the escarpment, a series of blocky strike ridges on a gently upwards sloping surface host many of the rock art shelters in massive sandstones that are still within the quartz-dominated lower Warton Sandstone but separated by finer-grained lithologies. Further up section the Warton becomes progressively more feldspathic (Phillips, 2023), forming smaller, less competent ridges that rarely host rock art sites. The surface becomes smoother and more plateau-like towards the top of the formation, where it is often covered by Cenozoic sands and patchy laterite remnants at increasing distances from the escarpment (Gellatly & Sofoulis, 1969). Much of this plateau appears as a gentle dip slope towards the overlying Elgee Siltstone and Pentecost Sandstone.

Throughout the sequence, much thinner (<0.5 m) white to purple-coloured siltstone and grey-green shale interbeds are found separating some of the dominant sandstone units. Ripple-marked surfaces and occasional desiccation-crack polygons are found on many bedding planes.

2.3 | Upper formations

The Warton Sandstone is in turn conformably overlain by relatively thin (c. 100 m, Gellatly & Sofoulis, 1969) soft red-brown siltstones and shales of the Elgee Siltstone, representing a dominantly intertidal mudflat environment (Phillips, 2023). The uppermost unit, the Pentecost Sandstone (760 m), represents a return to mostly shallow marine deposition and is divided into three members. The lithologies are mostly quartz-rich sandstones but appear to be more labile compared to the lower sandstone formations. They include friable sandstones containing prominent clay pellets, feldspathic sandstones and glauconitic sandstones (Gellatly & Sofoulis, 1969). Over most of its range, the outcrop of the Pentecost Sandstone is characterized by gently sloping, boulder-covered hillsides that do not host rock shelters suitable for preserving rock art.

3 | LANDSCAPE GEOMORPHOLOGY OF THE NORTH KIMBERLEY BASIN

3.1 | Regional joint pattern

The two sandstone formations characterized by abundant rock art shelters in the Kimberley basin, the Wunaamin Miliwundi and Warton

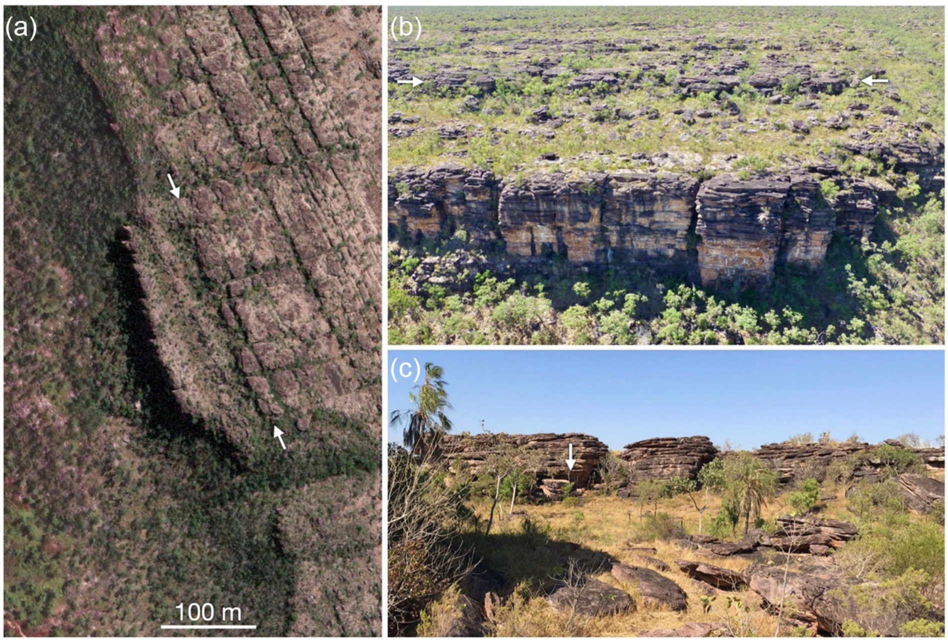

FIGURE 3 Major rectilinear and etched joint patterns in the Warton Sandstone as seen in (a) satellite imagery, (b) an oblique aerial view and (c) at ground level. (a) and (b) show the same area of the vertical escarpment edge of the Warton Sandstone that overlooks a plain of weathered Carson Volcanics to the left. The white arrows in (a) and (b) delineate the same strike ridge on the edge of a near-horizontally bedded sandstone unit above the escarpment. (c) Shows an almost identical context ~1.6 km to the SW of (b) at the same level above the escarpment. Several typical residual sandstone monoliths can be seen separated by narrow ravines produced by etching of the regional joints. The lower sides of these monoliths are the most common sites for rock shelters to develop, and the vertical arrow in (c) shows an example of such a shelter.

Sandstones, are both heavily and pervasively jointed, which is a striking feature of the landscape captured in satellite imagery (Figure 3a). Major rectilinear joints typically have a spacing of c. 10–20 m and are strongly aligned to three principal directions around bearings of 70 ± 5°, 100 ± 5° and 160 ± 5°. Often, two of the directions dominate in any particular area, although all three can usually be seen to some degree. Together, these joints impart a strong blocky fabric to the landscape, as shown at various scales in Figure 3.

Interestingly, this pervasive joint pattern is largely restricted to these two sandstone formations and is not characteristic of the other formations above and below them. Thus, the Carson Volcanics, the Elgee Siltstone and Pentecost Sandstone are largely free of this landscape-scale jointing pattern, suggesting a more plastic response to the same tectonic stresses, probably reflecting their higher clay content, compared to the extremely brittle behaviour of the two formations associated with rock art shelters.

The Warton Sandstone outcrops in large blocks, ridges and scarps with near-vertical edges defined initially by the regional jointing pattern. Although the joint pattern dominates the grain of the landscape at a scale of tens to hundreds of meters (Figure 3a), individual sandstone beds are often remarkably massive and relatively unjointed at the scale of individual rock shelters. Locally, individual joints do influence the development of some rock shelters, but jointing is rarely the major control on shelter-forming events at this scale.

3.2 | Landscape evolution

Poorly drained plateau surfaces, developed on the upper parts of the Warton, and parts of the Wunaamin Miliwundi Sandstone, preserve remnants of what was formerly a much more widespread, probably continuous, heavily lateritized surface (Gellatly & Sofoulis, 1969 p10). There is little direct evidence as to the age of this lateritic surface, but it is inferred to be of Cenozoic age and possibly older (Gellatly & Sofoulis, 1969). Similar pisolitic laterites, together with bauxites, are even more strongly developed on plateau surfaces on the Carson Volcanics.

In the study area, gradual dissection and stripping of this formerly extensive laterite surface have left a superimposed system of major rivers defined in part by broad flood plains, mostly developed on the Carson Volcanics, with narrow gorges and deeply incised, rocky riverbeds across the sandstone formations. Flood plains of the Drysdale, Barton and King George Rivers in the study area are mostly bordered by the overlying escarpment margin of the Warton Sandstone on one side and heavily dissected hills on the Wunaamin Miliwundi Sandstone on the other. Structural control on the major drainage pattern is significant in the sandstone areas, with the 16 km long entrainment of the lower reaches of the Drysdale River by the Barton River Fault being the most obvious example (Gellatly & Sofoulis, 1969). However, there are many smaller segments of these rivers that show strong alignment to the dominant joint trends, as do many of the minor tributaries.

Annual rainfall across the region averages >1,200 mm and is highly seasonal, falling almost entirely between November and April. High surface temperatures throughout the year, with average daily maxima of 30–38°C, contribute to evapotranspiration significantly exceeding rainfall throughout the year (>1800 mm/yr, Departmen oft Water & Environmental Regulation, 2023). Runoff is high during the wet season, but even major rivers are reduced to a string of pools in their rocky upper reaches during the dry season. Vegetation across the area is mostly tropical savannah, like much of northern Australia.

Perhaps surprisingly, given this tropical monsoonal climate of the north Kimberley region, catchment-wide average erosion rates, determined by cosmogenic ^{10}Be radionuclide concentrations in active stream sediments, are amongst the lowest measured anywhere on Earth, averaging between 1.8 and 7.7 mm/ka (Cazes et al., 2020). The highest basin denudation rates are found in the smallest catchments surrounded by sandstone cliffs, indicating that most of the sediment production is occurring at eroding rock surfaces exposed by the continuous mass wasting along bordering cliffs, gorge walls and escarpments (Cazes et al., 2020). Although these escarpments are retreating quite slowly overall and the exposed plateau bedrock surfaces at an even slower rate, evidence of relatively recent mass wasting events can be seen at many places along the cliff face.

In addition to stream sediments, Cazes et al. (2020) provide a set of ^{10}Be erosion rates sampled from a variety of exposed bedrock outcrops across the Kimberley region along and to the east of the Carson Escarpment. Of the 22 samples, two are from the 470 m plateau crest of the Cockburn Ranges, 150 km distant, and give the lowest erosion rate of 0.20+/−0.02 mm/ka, whilst six pertain to exposed, intact, roof bedrocks above our studied rock-shelters (elevation ~100 m) with a weighted mean and standard error erosion rate of 0.67 +/−0.03 mm/ka. The remainder are distributed across active ridge lines, river terraces and flood plain bedrock tors, which give a much higher and larger spread in erosion rates of 2–7 mm/ka that, as expected, are similar to that determined in stream sediments for catchment denudation rates. These bedrock results are consistent with other studies across the larger Kimberley region showing similar very low sandstone bedrock escarpment erosion rates at the Durack River, 150 km south (Fujioka et al., 2015) and Keep River, 200 km due east (Ward et al., 2005). Hence, taken together, these results suggest an extremely slowly evolving landscape over timescales similar to those seen in hyper-arid deserts or even polar regions.

What then can be inferred from cosmogenic erosion rates with respect to quantifying a denudation timescale? For example, how long does it take to reduce plateau elevations by, say tens of meters? To achieve steady state conditions, when a measured ^{10}Be concentration can be assumed to reflect constant erosion, the loss via decay and surface erosion is balanced by gain through production. The time required to do this, the so-called 'saturation integration timescale', is inversely related to the decay rate and the erosion rate i.e., the shorter the half-life and the higher the erosion, the quicker the system reaches equilibrium. For ^{10}Be whose half-life is 1.4 Ma, and a rock surface eroding at ~ 0.67 mm/ka, the ^{10}Be concentration reaches saturation after a minimum exposure time of 1.65 million years. Over this time interval, the bedrock surface has lowered by about 110 cm. This scale of denudation has most likely been the major driver of regional landscape evolution extending back at least for the past few tens of millions of years and attests to the unique antiquity of the Kimberley landscape. It is important to keep in mind that this extremely slow rate of landscape modification acts at a regional to continental scale – the construction and demise of rock-shelters respond to a range of different processes which are presented in the following sections.

3.3 | Etched sandstone plateau surfaces

Gradual retreat of the Carson Escarpment by sporadic mass wasting events has been accompanied by a pervasive stripping of much of the lateritic regolith and associated Cenozoic sands, which once existed above the Warton Sandstone, leaving an irregular, stripped etchplain surface (e.g. Migoń, 2004; Twidale, 2002; Ebert, 2009). Deep excavation of the regional joints into ravines and corridors from 1 to 2 m up to tens of meters wide has left remnant arrays of sandstone bedding stacks, blocks, columns and isolated monoliths, typically from around 3 m to as much as 8 m or more in height. Because of the very low regional dip, the sandstone blocks outcrop as dissected strike ridges broken up by labyrinth-like ravines and corridors (Figure 3).

The etched surface on the Warton Sandstone hosts the great majority of rock art shelters in the study area and occurs over a ~ 1–10 km-wide band above the escarpment. Local drainage is often poorly developed in this zone, and excavation of the larger joints is not closely associated with stream erosion. Thin remnant patches of pisolitic laterite are also often preserved on sandy floors between the rock stacks.

The question then arises as to how the relatively deep erosion of the larger joints and formation of the irregular etched surface have occurred in the absence of major stream erosion. We consider that most of the erosion occurred by subsurface chemical weathering at the interface between the sandstone bedrock and the former thick overlying lateritic regolith. Dissolution of silica along joints and bedding planes under the strong groundwater leaching conditions of lateritic weathering produced the landscape that has subsequently been exposed by stripping of the regolith (Young, Wray, & Young, 2018).

The Wunaamin Miliwundi Sandstone has very similar mechanical properties to the Warton but does not form a major regional escarpment. This is probably because, as the lowest widely exposed formation, its base is not exposed over most of the basin. However, like the Warton, it is exposed as a broad, undulating etch surface made up of prominent sandstone blocks and strike ridges, with very little soil cover. These blocky outcrops, typically 3–5 m high, have similar characteristics to those found in the Warton Sandstone above the escarpment.

3.4 | Geomorphic setting of the rock shelters

The Warton and Wunaamin Miliwundi Sandstones are both dominated by strongly cemented orthoquartzites forming very resistant outcrops containing rock shelters hosting the abundant rock art of the region. The distribution of the various styles of rock art occurs within different but overlapping cultural domains across the Kimberley Basin (Donaldson, 2012a; Walsh, 2000; Walsh & Morwood, 1999). However, within those broad domains, rock art is almost entirely restricted to these two major sandstone formations and strongly controlled by their geological characteristics (Donaldson, 2012a). These characteristics of similar mechanical behaviour and resistance to weathering control both the occurrence of suitable surfaces for painting and ensure their survival to preserve the art for millennia. Ultimately, it is the long-term survival of these rock shelters which is critical to the preservation of the rock paintings within them.

In the Warton Sandstone, rock shelters are most commonly found around the lower sides of large sandstone monoliths on the etched surface near the top of the major escarpment and on smaller nearby ridges above it (Figure 3c). Similar rock shelter forming environments also occur in outcropping sandstone beds in the incised valley sides of smaller streams draining the sandstone plateau and larger rivers cutting through it. Rock shelters may also form around large, transported blocks that have moved downslope from an

FIGURE 4 Typical rock shelters develop by the failure and collapse of sub-horizonal beds of Warton Sandstone of the Kimberley Basin. The primary features of the shelters include rocky floors, often consisting of fallen slabs, whilst the deepest parts of the rock shelters are invariably near the base. The back walls, which sequentially step outwards towards the top of the shelter, have high-angle faces sloping inwards towards the rear and base of the shelter, and show relatively sharp upper contacts with flat ceilings defined by bedding planes. Lower edges of the sandstone beds are often rounded. Arrows point to examples of spallation scars (also see section 5.2 and Figure 9). Note that (b) and (f) are different views of the same very large rock shelter, emphasising respectively the upper and lower beds in the shelter back wall.

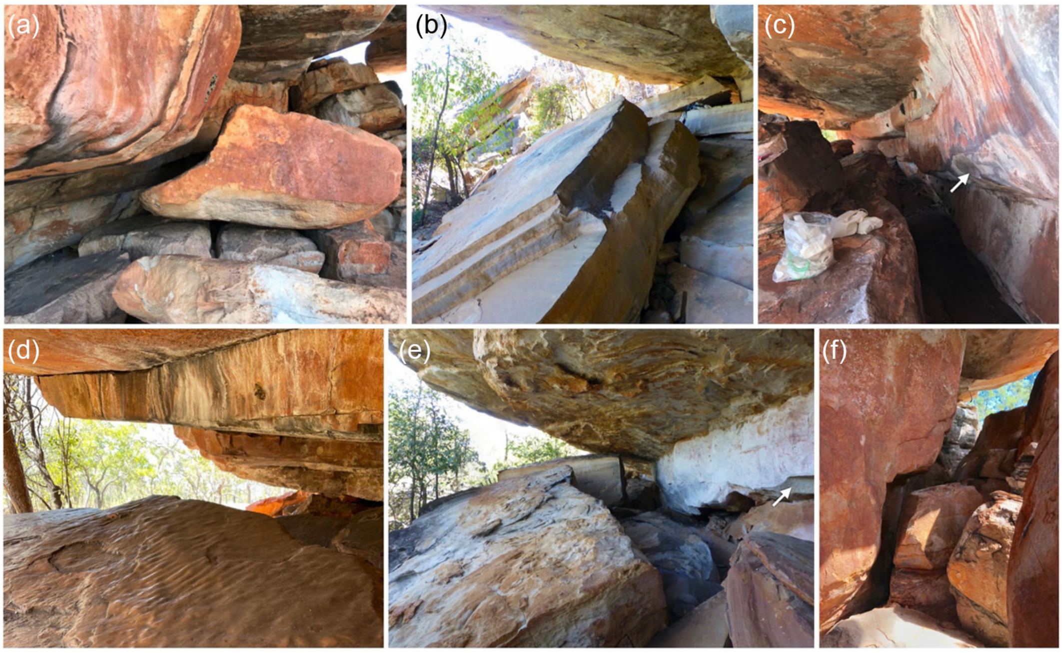

FIGURE 5 Fallen sandstone slabs accumulating on the floors of rock shelters in the Warton Sandstone. The different ages of the slab falls are indicated by the sharpness of the edges, the degree of rock surface discolouration and the presence of post-fall surface mineral accretions, shown most clearly by the glossy coating of the ripple-marked bedding surface in (d). These coatings typically consist of calcium sulphate and oxalate minerals with lesser amounts of magnesium phosphates and traces of other minerals (Green et al., 2017). During their fall, the intact rock slabs tend to slide outwards from the shelter to varying degrees, often leaving a narrow 'corridor' cave between them and the new back wall e.g. (c, d, e, f). These corridor caves often serve to provide access for producing rock paintings on the new rear walls. Arrows in (c) and (e) show further examples of post-formation spallation scars (section 5.2 and Figure 9).

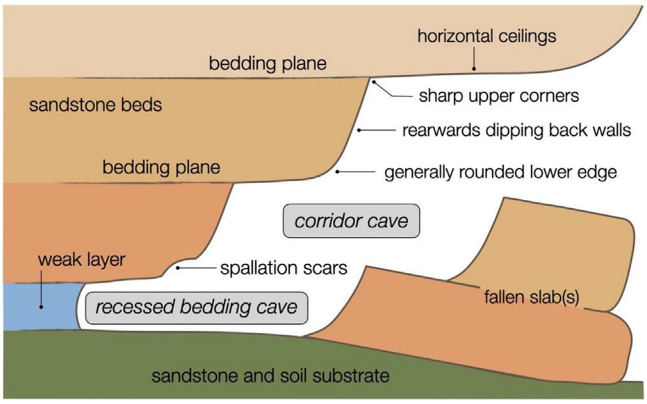

FIGURE 6 Major primary features of a typical rock shelter in the Warton Sandstone. In addition to some primary rounding, the lower edges of a sandstone bed are also often secondarily modified by spallation of their lower edges.

escarpment above, as described by Delannoy et al. (2020). Most of these transported blocks are found around the emergence of the river from a deeply incised gorge where it cuts through the escarpment of the Warton Sandstone.

Rock shelters in the Wunaamin Miliwundi Sandstone show many similarities to those in the Warton except for the strong association with environments along the Carson Escarpment. Sandstones in the Wumaamin Miliwundi tend to be coarser grained than in the Warton and often have somewhat thicker and more massive bedding, although the two overlap substantially in their properties. In places, the joints also tend to be more closely spaced in the Wunaamin Miliwundi giving rise to somewhat taller and narrower towers around which rock shelters develop.

4 | PRIMARY FEATURES OF THE SANDSTONE ROCK SHELTERS

Rock shelters developed in the Warton Sandstone exhibit a very consistent set of characteristics throughout the region. These can be divided into primary characteristics that reflect the formation of the rock shelter itself and secondary characteristics that appear due to subsequent modifications of the shelter as it evolves.

Figures 4 and 5 illustrate the major primary characteristics of the rock shelters. The only significant structural control related to the sandstones themselves is that exerted by near-horizontal bedding planes. By comparison, vertical joints exert relatively little control at the scale of an individual rock shelter, other than occasionally to provide a lateral side wall to the shelter or a partition separating different segments.

The primary features seen in the profile of a typical rock shelter in the Warton Sandstone are summarized diagrammatically in Figure 6. Most rock shelters display all, or most, of these features to some degree. They are therefore interpreted as reflecting the fundamental mechanism whereby the rock shelters develop and evolve. These primary features are now discussed individually in the following sections.

4.1 | Lower parts of the rock shelters

One of the most strikingly consistent characteristics of the rock shelters is that the deepest (most recessed) parts of the rock shelters are invariably at or near the base, as shown in the examples in Figure 4. These deeply recessed zones are usually made up of much weaker rock types such as shales, siltstones, or fine-grained laminated sandstones. In some cases, the recessed bed consists of a shattered sandstone that is heavily degraded by sub-horizontal fractures. Mostly the recession occurs where the weaker bed is found near to ground level, but occasionally it may be found some meters up a local cliff face.

Most of the shelters have rock floors and only rarely show any significant sedimentary accumulations. The overall form of the shelters is one of a series of back walls stepping out vertically towards the ultimate cantilevered overhang. These overhangs may be less than 1 m deep in the smaller shelters but can reach up to 4–5 m in larger shelters (e.g. Figure 1). These large overhangs, a primary feature of all major rock shelters, offer both a relatively habitable area and sufficient protection for the long-term survival of rock art.

4.2 | Ceilings and bedding slab falls

The ceilings of rock shelters are exposed sandstone bedding planes, and back walls are typically a stepped series of simple fracture surfaces resulting from the failure and collapse of successive bedding slab falls. Both surfaces provide protected environments in which rock paintings are typically produced and preserved across the region. Figure 5 shows the accumulation of fallen bedding slabs on the floors of rock shelters. The physical strength and coherence of the Warton Sandstone beds mean that many of these slab falls remain largely intact even after impact and movement outwards. On rare occasions, rock art that was originally painted on a shelter ceiling can still be observed on the underside of a fallen bedding slab.

The fallen bedding slabs show a range of ages indicated by their morphological variation from sharply angular blocks with a complete absence of mineral coatings (e.g. Figure 5b) to more rounded forms and well-developed surface coatings (e.g. Figure 5d). Some fallen slabs constitute a single sandstone bed (Figure 5a,d,e), but others show two beds with a stepped edge marking the bedding plane between them (Figure 5b,c,f). Other examples give evidence that successive slab falls have occurred at quite different times. Because there is often a sloping surface leading to the entrance of a rock shelter due to the accumulation of smaller blocks and previous slab falls, the slabs tend to slide outwards from the shelter to some degree. This opens up a narrow passageway behind the slab pile, which we here call a 'corridor' cave, as shown in Figure 5c–f. Such corridor caves have often been exploited to provide access for artists to paint on the exposed back wall.

4.3 | Back walls

The back walls are occasionally vertical, but much more typically they slope backwards towards the base of the shelter with dips of ~70–80°. It appears that each segment of the back wall consists of a single fracture surface penetrating through a single sandstone bed. On wide horizontal segments, reaching several meters or more, these fracture surfaces are commonly curved, forming a lateral concave arc along the bed as may be seen in Figures 4a,c,d and 5c,d. Where a fracture has penetrated a particularly thick (~ 3 m) sandstone bed, a similar curvature can also be seen in the vertical plane, with the surface changing dip down the wall to slope outwards towards the base. In such cases, the fracture surface has the form of a spherical shell, somewhat resembling a very large conchoidal fracture.

Contacts between relatively horizontal ceilings and the tops of the back walls are mostly quite sharp. In contrast, the lower unconstrained edges of the fractured sandstone beds are often curved inwards along a convex edge rolling under toward the recessed base of the shelter. In some cases, this curvature is also reflected in the edge of the fallen slab, as in Figure 5(a), but in many others, the rounding of the edge appears to be a progressive secondary modification due to spallation of the edge, as discussed below.

4.4 | Side walls and lateral form of the rock shelters

Most of the rock shelters display a similar vertical section profile as shown schematically in Figure 6 along their entire length, hence producing a shelter that is laterally continuous and often traversing the entire width of the host rock outcrop. The form of this profile, therefore, is also representative of their 3D structure. The lack of side walls in the majority of rock shelters strongly suggests that the typical 2D profile (Figure 6) is representative of their lateral extent and also representative of the underlying 3D stress distribution.

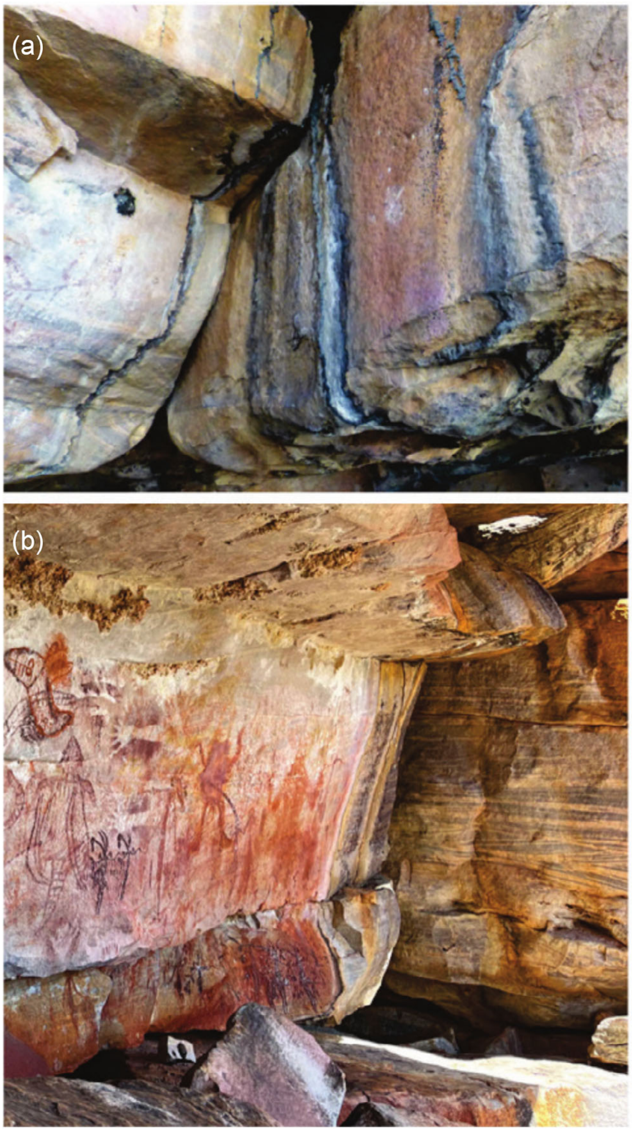

FIGURE 7 Two examples of side walls, on the right, that abruptly terminate the continuity of rock shelter back walls on the left. Such side walls are not common but are mostly defined by a vertical joint plane oriented approximately normal to the back wall, which divides the rock shelter into two sections. Because the joint plane separates the two sides of the shelter, little mechanical stress or load is transferred across the side wall.

This lateral continuity is an important difference, in both lateral and vertical dimensions, between the rock shelters described here and more arch-like forms commonly observed in more homogeneous sandstone caves elsewhere (e.g. Bruthans et al., 2014; Filippi et al., 2024; Young, Wray, & Young, 2018). In addition to the lack of side walls, another significant factor in this difference is the existence of weak bedding planes at intervals of 1–3 m in the Warton Sandstone and also the regional joint pattern. The step-like profiles observed in the Warton Sandstone shelters are strongly influenced by the discontinuities defined by these weak bedding planes.

Although side walls to the rock shelters are uncommon, where they do occur, they are nearly always defined by a major joint plane approximately normal to the back wall. These side walls form a sharp, near-right-angle corner with the back wall, as shown in two examples in Figure 7. The separation of the back wall from the side walls by an open sub-vertical and continuous joint plane, often a few centimetres or more wide, means that there is very little, if any, transfer of mechanical load or support across the side wall.

Where the backwall of a shelter shows curvature laterally, the amount is quite limited and the depth of the fracture segment relative to its ends is only ever about 5–10% of the radius. These curved segments, therefore, do not continue forward to provide supporting side walls to the shelter. In smaller shelters, a single mildly curved segment may make up the whole of the back wall. In larger shelters, individual curved segments appear more like an undulation along a near-continuous back wall, with each segment associated with a single slab fall.

5 | SECONDARY FEATURES OF ROCK SHELTERS

The accumulation of surface deposits and ongoing structural changes to the rock surfaces may be considered as secondary characteristics of the rock shelters, serving to modify the shelter once it has formed. These deposits and structural changes reflect a variety of inorganic, organic, physical and chemical processes that operate over the lifetime of the shelter. Importantly, the presence of these deposits shows that the protected interiors of rock shelters are net depositional environments.

5.1 | Internal accretionary systems within rock shelters

The internal accumulation of mineral and biological accretions on rock surfaces within a shelter has been considered in detail by Green et al. (2017); Green et al. (2021b); Green et al. (2021a) and Finch et al. (2019). These surface accretions have proved to be of great importance in constraining the ages of rock art (e.g. Finch et al., 2020, 2021; Roberts et al., 1997) but also appear to provide a new record of paleoclimate change over tens of thousands of years (Green et al., 2021b). Figure 8a-d shows examples of the different systems of mineral accretions identified by Green et al. (2017) in different interior contexts within the rock shelters, which are considered to originate by a combination of inorganic and microbiological mechanisms (Green et al., 2017; Green et al., 2021a).

The resulting mineral accretions can form pervasive coatings across the rock surfaces and build up to ~5 mm in thickness, which can obscure or react with rock art pigments, and in some cases bleach them entirely. Figure 8e,f shows fossilized mud wasp nests that, in addition to their importance for dating rock art, can also be so dense as to obscure and damage the paintings. These mineral accretions are only found on the interior sides of drip lines on rock shelter ceilings and lines of external water flow around their side walls. However, within that protected zone, their existence provides strong evidence that the rock surfaces have been almost entirely protected from erosion and have remained in a depositional state over thousands to tens of thousands of years.

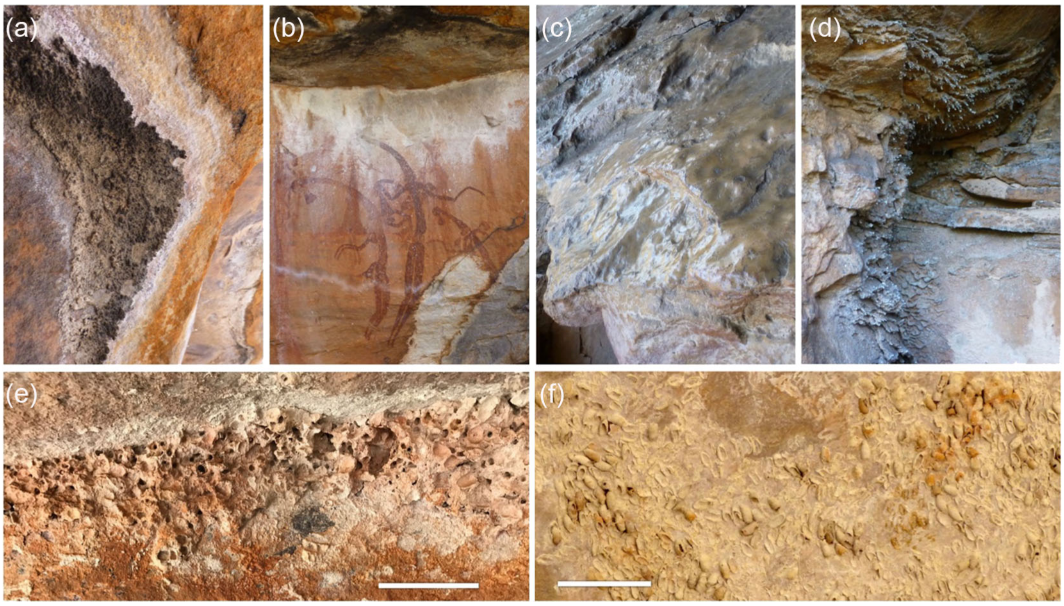

FIGURE 8 Examples of secondary accumulations observed within rock shelters in the Warton Sandstone. The upper panels show four distinct mineral accretion systems: (a) lateral polychrome fringes, (b) dispersed wall coatings, (c) floor glazes and (d) silica stalagmites and skins - see Green et al. (2017) for more information. These mineral accretions consist mostly of varying proportions of hydrated calcium sulphates, calcium oxalates, magnesium phosphates and amorphous silica. The lower panels show fossilized mud-wasp nests that have accumulated as (e) large compound aggregates forming a cornice along the sharp concave boundary between fractured back walls and bedding plane ceilings, and (f) individual nest cells that occur dispersed across the rock surface. Scale bars are ~10 cm and individual cells are approximately 2–3 cm in length.

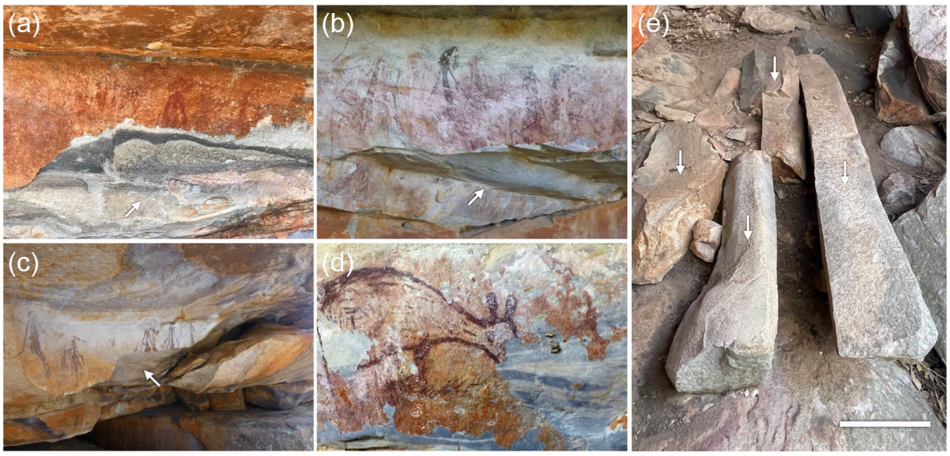

FIGURE 9 Secondary structural modifications of rock shelters. Arrows in (a-c) identify a series of large (∼1 m long) lower edge spallation scars, all of which expose fresh grey sandstone. In all three cases, spallation has caused significant truncation and partial loss of the rock art preserved above them, showing that spallation must postdate the paintings. Spallation in (b) shows some structural control from cross bedding. A large spallation flake cutting right through the bed can be seen still partially attached to the rock surface in (c). (d) Shows dispersed surface exfoliation on a shelter back wall that has damaged a painted kangaroo from the earliest irregular infill animal style. (e) Shows a group of four spallation prisms, marked by vertical arrows, that have accumulated on the floor of a rock shelter from the progressive modification of the lower edges of overhanging sandstone beds through ongoing edge spallation. The scale bar in (e) is 20 cm, and the longest of these prisms reach more than 1 m in length.

5.2 | Spallation and rounding of lower bed edges

Structural modification of the rock shelters following their initial formation occurs in three ways: first by spallation of large flakes from the lower convex edges of fractured sandstone beds left by major slab falls (Figure 9a-c). Second, modifications occur by dispersed exfoliation of back wall surfaces (Figure 9d), and third, by ongoing fracturing, evidenced by crushing below bedding planes and pervasive scaly flaking of sandstone surfaces in the lower parts of some large rock shelters (see section 5.5).

Although some rounding of the lower edges of sandstone beds may in part be inherited at the time of a shelter-forming rock fall (e.g. Figure 5a), it is clear that many of the spallation scars shown in Figure 9a-c have formed much later. Evidence for this is seen from the relatively fresh grey to white surfaces exposed in many of the spallation scars compared to the generally discoloured and coated older rock surfaces. Moreover, many spallation scars are more recent than the rock art painted on the primary fractured surfaces, leading to significant destruction of the lower parts of many paintings as seen in Figure 9a-c.

Further examples of these common spallation scars are marked by diagonal arrows in Figures 4 and 5. Their association with convex lower edges may in part be due to a similar mechanism that produces rounding of granite boulders and tors from original, joint-defined cuboid forms. Alternatively, it may also be a response to the internal stress distribution around the sandstone edge, as suggested by the large flake still hanging almost in place in Figure 9c. Similar spallation is almost never seen on the top edges of a fractured sandstone bed, where it comes into sharp contact with the overlying ceiling. Spallation prisms of the edges removed by this process are sometimes found preserved on the floors of rock shelters, such as those shown in Figure 9e, although often these are quite thin and break up into smaller pieces during the fall.

The dimensions of both the scars and the fallen prisms are up to about 1 m in length and mostly about 20–30 cm wide in the middle, but some may be up to 50 cm. The scale of these spallation features differentiates them from very much smaller scars (mostly less than a few cm) from anthropogenic working of edges for stone tool flakes seen in a few shelters.

5.3 | Exfoliation on back walls

Partly overlapping with the lower edge spallation scars are areas of patchy veneer-like exfoliation, which are dispersed over many of the rock shelter back walls. The resulting exfoliation flakes range in size from ∼ 2 cm up to 30 cm or more across and are typically only 1–3 mm thick. An example is shown in Figure 9d, exposing fresh grey sandstone with a strong contrast in colour to the discoloured surfaces that has been removed. Like the edge spallation, exfoliation may lead to significant damage to the older painted rock art styles.

The pattern of exfoliation is similar to that widely observed on exposed rock surfaces in many different surface environments. The common explanation due to differential thermal expansion of the surface layer under changing diurnal and seasonal temperatures is probably applicable, although they are common even in the most protected environments in the Warton Sandstone. Case hardening of the surface layer from accumulation of weathering products and silica deposition may also be a contributing factor, although judging from the surface discolouration seen in Figure 9d, for example, the underlying quartzites are already pervasively silicified.

5.4 | Rock crushing

Figure 10 shows examples of secondary modification of the rock shelters by crushing and the formation of pervasive scaly fracturing of lower sandstone back walls in some localities. Figure 10a, e, f shows examples of crushing of underlying sandstone beds in supporting walls beneath a continuous ceiling bedding plane. The thickness of overlying sandstone in such cases is often 5 m or more. Similar examples may also be seen on rock pedestals beneath large, transported sandstone blocks. Figure 10a shows a joint-defined side wall of the very large rock shelter shown in Figure 4b, f where the overlying sandstone pile is 5–10 m thick, but similar crushing may be observed even under an overlying thickness of only 2–3 m where there is a local concentration of stress, such as at an irregularity on a bedding plane. In such cases, a set of sub-vertical, often open fractures e.g. Figure 10a, e may be oriented approximately normal or parallel to the surface of the supporting wall,

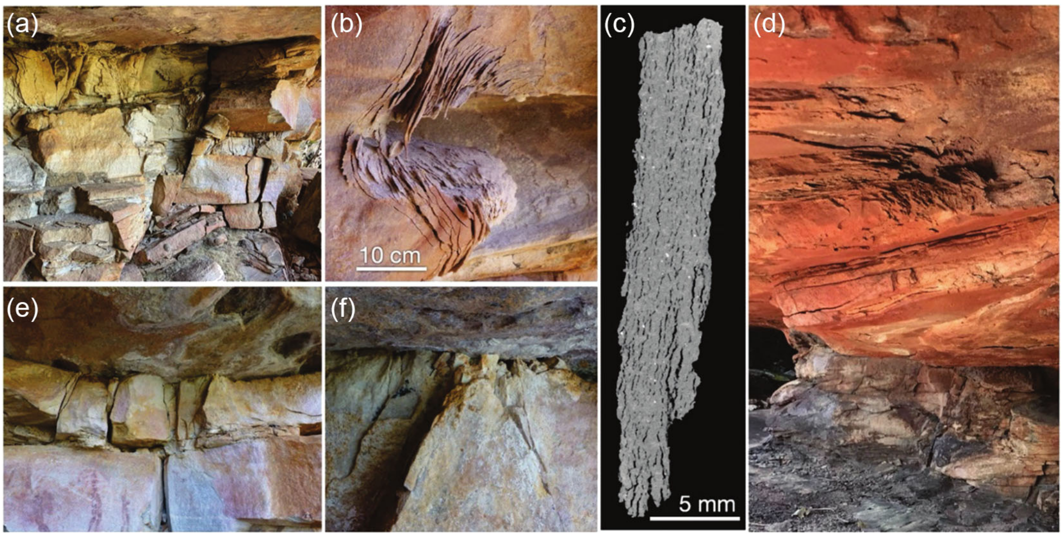

FIGURE 10 Secondary structural modifications of rock shelter interiors from fracturing in response to the internal stress distribution in the host rocks. (a) Shows intense fracturing in an approximately 3 m high side wall of the large rock shelter shown in Figure 4(b, f) as well as scaly fracturing parallel to the surfaces of the sandstone blocks. (b) and (d) shows examples of intense scaly fracturing. A micro-CT scan (c) of a flake from the surface in (b) shows that the fracturing is pervasive down to the grain scale. The flake dimensions in (c) are ~5 × 30 mm. (e) and (f) show localized crushing of supporting sandstone walls beneath unbroken bedding plane ceilings, suggesting a point concentration of compression from above. Note also the accumulated debris on the floor of the rock shelter in (d), mainly resulting from spallation from the incompetent bed at the bottom of the shelter.

suggesting tensile failure under compressional load. The fracturing observed in these cases (Figure 10a, e, f) exists only in the lower bed, and there is no visible continuity of the fractures across the bedding plane ceiling into the overlying sandstone. The pattern of dipping and fractures, such as in Figure 10f suggests failure on shear planes, radiating from an almost point-like concentration of stress from the sandstone overburden. It is suggested that similar fracture mechanisms may be involved in the initiation of failure, leading to the larger slab falls.

5.5 | Scaly fracturing

The heavily fractured surface seen in Figure 10a also shows, in addition to the set of penetrative sub-vertical tensile fractures, a different style of scaly fracturing parallel to the rock surfaces of the back and side walls. Further examples of this phenomenon are shown in Figure 10b,d. Such scaly fracturing is relatively uncommon, being found only in the lowermost sandstone backwalls of some rock shelters, all of which are characterized by relatively thick sandstone overburden, suggesting a higher-than-average compressive load. In a small number of rock shelters, this kind of approximately surface-parallel scaly flaking has completely destroyed the original back wall of the shelter and left a broad concave surface above a pile of fallen flakes. In their thin plate-like form, the flakes produced are superficially similar to those resulting from exfoliation, but those exfoliated flakes are of relatively uniform mm-scale thickness and have only a single fracture along their back surface. In contrast, the flakes resulting from the scaly fracturing are defined front and back by fractures, are much more variable in thickness, and have many persistent parallel fractures on multiple scales within the rock. These pervasive scaly fractures occur in completely fresh rock, and there is no evidence of any chemical alteration or buildup of salts or other weathering products. Rather, they appear to be caused by an entirely physical process related to the internal stress field in the rock.

Figure 10c shows a Micro-CT cross section of one of the flakes from (b), which reveals that the set of parallel fractures persists down to the level of individual sand grains. Indeed, seen at that scale, the apparently parallel fractures appear to be made up of a fine zigzag pattern defined by failure along the grain boundaries, perhaps reflecting an intersecting set of conjugate micro shear planes. Modelling of microfracture development in granular materials under uniaxial compressive stress produced an almost identical pattern of small shear and tensile deviations on grain boundary surfaces (e.g. Hoek & Martin, 2014; Napier et al., 1997). These microfractures can coalesce under uniaxial stress in their digital models to produce an overall dilatancy normal to the loading, as observed here. It is therefore inferred that the secondary scaly fractures represent dilation normal to the principal loading direction, which is concentrated around the lower back walls of rock shelters.

The pattern of this pervasive surface-parallel micro-fracturing appears identical to that resulting from shear stress and associated extensional failure in brittle rocks on the unconfined side walls of road tunnels, mine shafts and other underground excavations under conditions of high compressional load (e.g. Hoek & Martin, 2014; Lan, Martin, & Andersson, 2013; Li et al., 2024). Bruthans et al. (2014) and Filippi et al. (2018) showed by both physical and numerical modelling that a similar stress concentration is found around the unconfined edges of cavities developed in rock masses under near-surface conditions.

Figure 11 shows schematic diagrams of the inferred stress distribution, (a) at the time of a primary shelter-forming slab fall, and (b) during later secondary modification. Also shown are rock surfaces with (c) a fracture pattern in a fallen block which may represent shear planes formed whilst the sandstone bed was in situ prior to the slab fall event, and (d) a further example of a sandstone back wall that is heavily modified by scaly fracturing due to tensile failure on a retreating convex back wall.

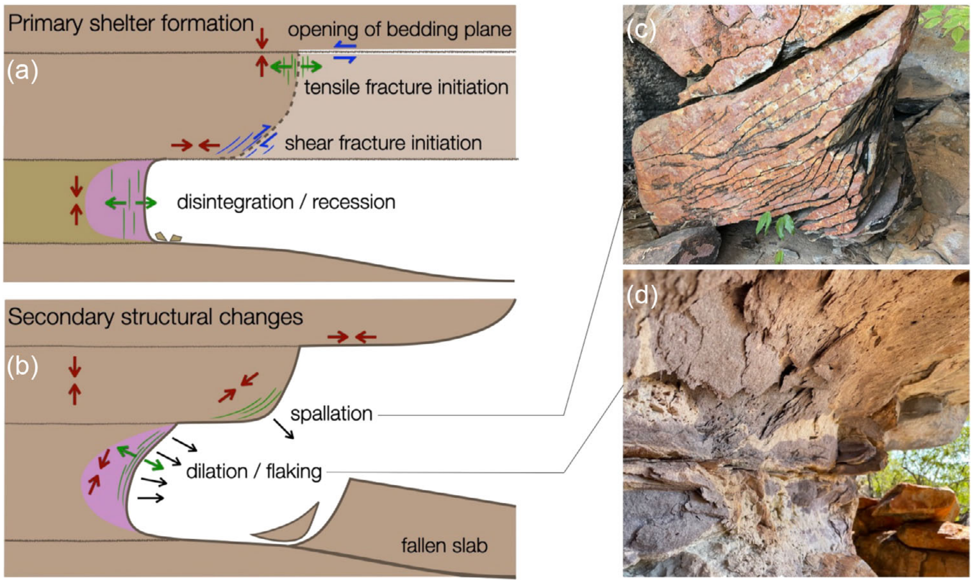

FIGURE 11 Inferred distribution of compressional (red arrows) and tensile (green arrows) stresses, with the resulting failure mechanisms in a rock shelter (a) at the time of a primary shelter-forming slab collapse and (b) afterwards during secondary structural modification. A concentration of compressional stress (purple area) is inferred around the deepest part of the void in both cases causing leading to crumbling, fracturing and recession of incompetent beds such as shales in (a), and flaking of sandstone surfaces on some concave back walls in (b). (b) Also shows spallation of prismatic blocks from the convex lower edges of overhanging sandstones which may reflect dilation acting on inherited shear planes from the time of the slab fall. (c) Shows a regular conjugate fracture pattern in a fallen sandstone block that may represent in situ shear fractures in a lower sandstone edge. (d) Shows a further example of scaly fracturing on a rounded and concave sandstone back wall in a lower shelter wall beneath a massive overlying sandstone roof.

6 | EVOLUTION OF THE ROCK SHELTERS

6.1 | Rock shelter initiation

Rock shelters begin to form when the external face of a less competent bed retreats differentially from the original side of a joint-bounded sandstone block to form a low, recessed bedding cave. Examples of such slot-like bedding caves are shown in Figure 12a-c and are often only ~0.2–0.5 m high. These three examples are as much as 5 m deep and represent cases where the overlying sandstone remains intact. The recessed cave becomes a highly protected, dry and dusty environment where there is no obvious influence of any external erosional agency. This then poses the question of how the incompetent beds can be excavated to such a depth despite the complete absence of active erosion. Here, we suggest that the incompetent materials undergo disintegration under the compressional load of the sandstone overburden.

It is possible that part of the recession occurred during subsurface weathering prior to sub-aerial exposure of the etched landscape. However, remnant pieces of the incompetent bed found scattered across the floors of most of these recessed bedding caves attest to their ongoing development in the current surface environment. The fact that recession of such thin, often clay-rich beds occurs frequently near ground level might suggest some involvement of groundwater seepage as an agent of the weakening process. However, the pattern of recession on a rough, crumbling surface with at least some of the debris remaining is not consistent with erosion by flowing water. Supporting this inference, pools of water or evidence of their intermittent existence are not commonly found on their floors in the wet season, although some seepage on bedding planes may occur. However, the rock types making up the recessed beds often have almost no porosity or permeability, and some of these bedding caves form at elevations several meters above ground level, suggesting that groundwater seepage is not a significant factor in their formation.

Another feature of the three deep bedding caves shown in Figure 12a-c is that the depth to the back of the recess is variable, and all these larger examples exhibit remnant pillars of shale, 1–2 m across. This indicates that support for the overlying sandstone is somewhat more distributed than the maximum depth might suggest. Being more accessible, the remnant pillars can be observed more closely than the deep back surfaces, although their surfaces appear identical.

Many of the pillars show active crumbling around their edges, often on a near-vertical or roughly concave surface. Similar crumbling can be seen along the irregular back walls, also associated with an accumulation of debris on the shelter floors. Some pillars (e.g. Figure 12c) are visibly broken up by sub-vertical tensile fractures and are clearly disintegrating under the overlying compressional load. The pillar in Figure 12a also shows a fresh shale surface on its right side where material has spalled away. These pillars are reminiscent of those left behind for support in underground mining, which can be vulnerable to failure and collapse under the overlying load, often demonstrating concave outer surfaces due to spallation (Esterhuizen, Dolinar, & Ellenberger, 2011).

These characteristics of the bedding caves suggest that recession is ongoing, so that the overlying sandstones are being supported by an ever-decreasing area of incompetent material, probably through ongoing tensile failure of these weak materials under load. Once the remnant pillars have completely disintegrated the entire load will be concentrated on the retreating back wall in the deepest part of the cave.

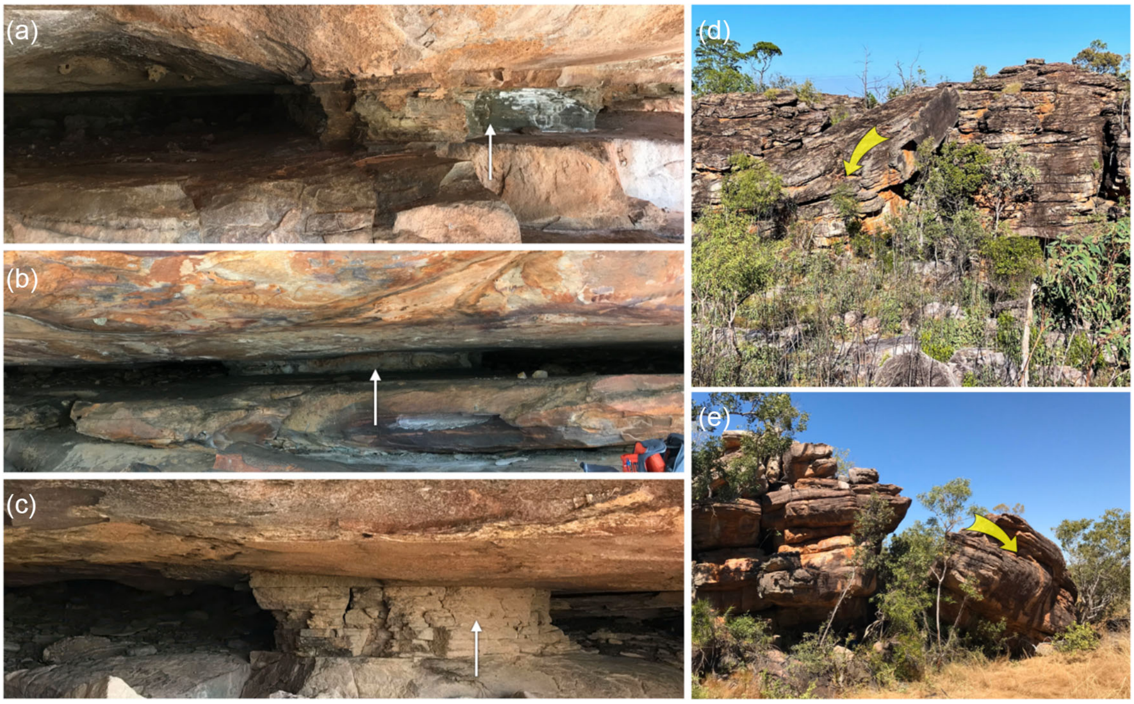

FIGURE 12 Images on the left (a-c) show examples of bedding caves caused by early recession of weaker shale or siltstone beds that undermine overlying massive sandstone beds. These are inferred to represent the earliest stage in the evolution of rock shelters in the Warton Sandstone. Undermining initiates a cycle of shelter-forming sandstone slab falls. All three examples of recessed bedding caves are only ~ 30–50 cm in height but up to 4–5 m deep. Vertical arrows in (a-c) highlight remnant shale pillars with rough concave vertical faces, with a freshly spalled face exposed in (a) and a series of sub-vertical fractures in (c). These features suggest ongoing tensile failure of the weak material in response to vertical compression. Images on the right (d-e) show the final stage of shelter evolution, where former rock shelters have collapsed with motions indicated by the yellow arrows. The roof block has toppled forwards and to the left in (d) and rotated to the right in (e). Collapse has been caused by continued undermining that has reached a critical point of failure on pre-existing vertical joint planes, exhibited most clearly by the right-hand face of the block in (d) and the cleft which has opened behind the small tree in the centre of (e).

6.2 | Formation and enlargement by successive ceiling slab falls

Ongoing recession of the weak layer progressively undermines the overlying sandstone bed, which eventually fractures and falls, often as an intact bedding slab. However, the fallen slabs never break at the very back of the recess beneath them, but usually about 0.5-2 m outwards from that point, which shifts the point of support for the next overlying bed progressively outwards towards the front of the shelter. Once a slab has fallen, the remaining recess in the underlying bedding cave is typically only 1–1.5 m deep.

Because of the typically meter-scale bedding thickness, an accessible rock shelter for human utilization is established after the first slab fall. In some cases, two sandstone beds may fall as an intact block, leaving a stepped backwall with a matching inverse profile on the fallen slab. In turn, the next overlying sandstone bed will now become unsupported and subsequent ceiling slab falls may lead to progressive enlargement of the rock shelter. Each fall acts to minimise the amount of unsupported rock (or ballast, Bruthans et al., 2014) above the shelter.

Initiation of failure in the brittle sandstone probably includes tensile failure (ie crack surfaces are pulled apart normal to the crack plane) on the upper bedding surface of the unsupported cantilever. However, the sloping to sub-spherical, shell-like, form of the primary back walls suggests that shear failure (ie crack surfaces slide apart laterally by shear forces parallel to the crack plane) is also involved and may be dominant. Some of the numerous cases of tensile and shear fractures beneath an intact bedding plane suggest that failure may originate at some point of irregularity on the bedding plane, as discussed in 5.4. The regular pattern of the slab falls and the generally clean ceiling surfaces exposed suggest that there is relatively little adhesion or support across the bedding plane. Any weathering or separation along the overlying bedding plane will only increase the gravitational instability of the ceiling slab.

The gravitational load acting on the cantilever of an unsupported sandstone bed will place the upper surface under tension and the lower part under compression. A combination of tensile and shear fractures might explain the often rounded or faceted primary form of the new back wall resulting from a slab fall, such as seen on the fallen block in Figure 5a. Experimental and modelling studies (e.g. Diederichs, 2003; Napier et al., 1997) indicate that these fractures often coalesce from a field of smaller tensile microcracks under uniaxial compression during failure. It is possible that a set of oblique shear planes is formed in the lower part of the sandstone bed due to horizontal compression during failure, which might pre-dispose the convex lower edges of the back walls to subsequent spallation.

The secondary structural modifications due to edge spallation and dilational scaly fracturing, although not universally present, provide clear evidence that continued stress remains around the lower part of the sandstone back walls long after initial rock shelter formation. The shelters that exhibit this behaviour tend to be those with a thick and massive overburden of multiple overlying sandstone beds, indicative of substantial load from above. The edge spallation and scaly fracturing are therefore the strongest direct evidence for the role of extensional dilation in response to this ongoing compressional load.

6.3 | Late stages of rock shelter enlargement

Successive rock falls will eventually leave a stepped back wall with only a relatively thin ceiling. Stepped back-walls result for two reasons. First, the successive rearward slope from top to bottom of each fracture surface means that the upper surface provides more forward support for the overlying bed. Second, and more importantly, the strength of the sandstone means that failure always seems to occur somewhat further forward, often by a tens to hundreds of cm, from where the overhanging layer meets the edge of the supporting bed beneath. Hence, each successive fracture is likely to step further out towards the front of the cave, leading to the stepped cross section of the shelters seen in larger examples as shown in Figure 4.

Perhaps non-intuitively, the final configuration reached, where only a relatively thin (1–2 m) roof remains, appears to be one that is comparatively more stable, presumably because the overburden, which determines the gravitational load, becomes greatly reduced as the roof becomes thinner. Figure 1 is a good example of a very large rock shelter where the roof is only 1–2 m thick but must be of great antiquity because it protects paintings spanning the entire time range of painted art (~20 ka, Finch et al., 2021).

The roof above this shelter, and most others, is covered by disconnected remnant blocks of formerly overlying sandstone beds that have largely been eroded away by extensive sub-aerial weathering in that very exposed setting. In this way, weathering and erosion of the exposed upper surface further reduce the gravitational load on the remaining roof. Such exposed upper roof surfaces are often highly silicified, being occasionally quarried for stone tool production on a local scale. They are always highly irregular and often contain hollows that become ponds during the wet season.

6.4 | Terminal stage of rock shelter evolution

The final stage in this evolutionary sequence is the collapse of the rock shelter and with it the partial or complete loss of rock art often contained within it. In principle, there are two ways this can occur, the first being the final collapse of the remaining roof so that the interior becomes fully exposed and the art within is no longer protected from weathering. Despite such roof collapse being the logical conclusion of the sequence of enlargements described above, no clear examples of this having occurred were observed in the hundreds of rock shelters examined in this study, so it remains a purely theoretical possibility. The reason for this is almost certainly the apparent increase in stability as the remaining roof becomes thinner, as described in 6.3 above.

The second way for a rock shelter to be destroyed, and by observation the most common, is by rotational toppling of the entire sandstone edifice due to continued undermining at its base. Numerous examples of this process were observed, either where rock shelters are found on both sides, or all around a sandstone block forming a 'mushroom' rock, which will eventually become unstable and topple over. Given the location of the north Kimberley, only about 500 km from the subduction zone of a major convergent plate boundary in Indonesia, it is possible that at least some of these toppling events might be triggered seismically by regional tremors or great earthquakes on the plate boundary.

Two examples of the toppling of the entire superstructure of a rock shelter are shown in Figure 12d,e. Continued recession of the weak bedding layer at the base of the rock shelters has undermined the whole edifice to a point where tensional failure on a nearby joint plane has allowed the entire mass to rotate forward, thereby destroying the rock shelter beneath it on that side. Although not visible in the photographs 12(d) and (e), in both these cases, a small gap (~0.5–1 m) remains beneath the fallen mass, allowing sufficient access to see remnant rock art on the former ceiling, indicating that a much larger shelter existed there before the collapse. Rotational collapse of the block in Figure 12e is further illustrated by a series of normally vertical anthropomorphic figures on the far side of this collapsed shelter that are rotated to exactly the same degree (~35°).

6.5 | Mechanism of rock shelter evolution

The repetitive structural features of rock shelters in the Warton Sandstone reflect both the brittle character of the massive orthoquartzite beds and the occurrence of occasional incompetent beds between them. As argued above, the primary structural features strongly suggest shelter initiation begins with undermining by recession of an incompetent bed due to its progressive disintegration under compressional load. This is followed by a series of mass wasting events by tensile and shear failure arising from gravitational stresses on the cantilevered sandstone beds. A series of slab falls resulting from the failure of the overlying sandstone beds gradually enlarge the rock shelter. This model suggests that the brittle behaviour of the Warton and Wunaamin Miliwundi Sandstones might be the major explanation of why they alone are hosts to almost all the rock art shelters in the Kimberley Basin.

Continued recession of the incompetent bed leads to a progressive concentration of compressive stress around the back of the deepest part of the cave, leading to further failure and retreat. Eventually, this process makes the entire overlying sandstone block unstable, even more so when a major vertical joint plane is approached, leading to catastrophic failure and forward collapse. The influence of this stress concentration may also be seen in the lowermost fractured sandstone walls of some shelters, where scaly flaking develops, reflecting a dilational response to the stress concentration. Notably, such flaking is not observed in higher parts of the shelters, where compressional stresses should be much lower.

The different response between the lower sandstone bed and the underlying incompetent shale or siltstone bed probably reflects the greater strength and more brittle character of the sandstone. In this model, the various structural features observed in the different beds reflect their mechanical response to a fundamentally similar stress regime in the lower rock shelter after its formation by a series of slab falls.

This mechanism is different to those that rely purely on differential erosion or undercutting of the lower part of a rock face due to fluvial erosion. Despite the very high monsoonal rainfall in the north Kimberley, it is clear from the accumulation of mineral accretions and the preservation of rock art that the interiors of at least the larger rock shelters have remained protected to a remarkable degree from the action of common erosional agencies, especially running water.

Various authors (Bruthans et al., 2014; Filippi et al., 2018; Filippi et al., 2024; Young, Wray, & Young, 2018) have previously pointed to the significance of shear and tensile stress distributions and the importance of applying rock mechanical principles for understanding the formation of sandstone caves. This study, based on examination of hundreds of rock shelters, has provided strong confirmation of the importance of that view, but with the important difference that in the Kimberley sandstones the evolution is dominated by physical failure of extremely competent and brittle orthoquartzite slabs, rather than surface erosion of relatively porous sandstones in pressure shadows.

7 | CONCLUSIONS – THE LIFE CYCLE OF ROCK SHELTERS

The four stages in the evolution of rock shelters in the Warton Sandstone inferred in the previous section are summarized diagrammatically in Figure 13. Together, these stages constitute a distinct life cycle, the different stages of which can be observed in many field examples. This life cycle, and some of the events occurring within it, provide an ultimate limit on the survival of rock art within the rock shelters. This sequence of events also provides opportunities for the dating of individual slab falls using cosmogenic radionuclides, which will be detailed elsewhere in a separate major study.

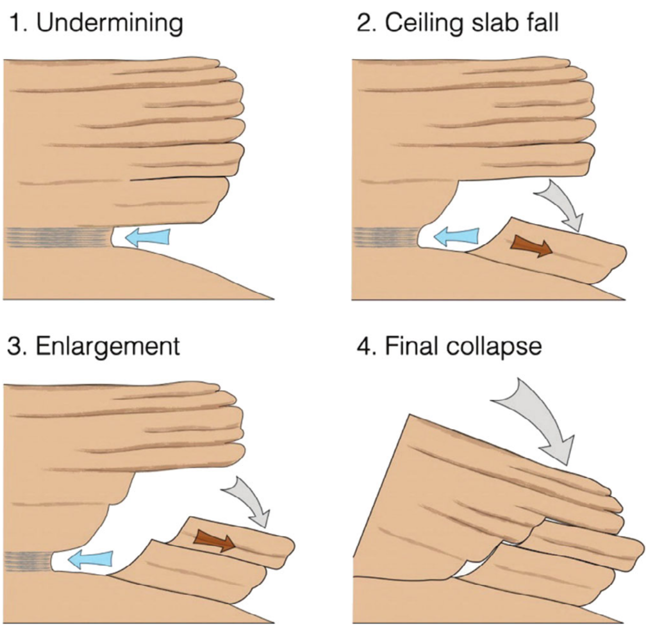

FIGURE 13 Four stages in the life cycle of a rock shelter in the Warton Sandstone. 1. Shows the initial stage of undermining (blue arrows) by recession of a weak bed beneath a series of overlying sandstone layers to form a bedding cave. 2. Shows the emergence of the first rock shelter through the collapse of an unsupported sandstone slab from the shelter ceiling. 3. Shows enlargement of the shelter by additional sandstone slab falls, and 4. Represents the terminal stage where the entire sandstone edifice collapses by toppling forwards.

Despite significant variability in the particular circumstances of each rock shelter, it is clear that the process rates in most shelters are such that rock art can survive within them for tens of thousands of years. Nevertheless, many examples have also been found where sandstone slabs falls and even the complete collapse of shelters have buried or destroyed paintings that once existed on former ceilings. Paradoxically, it is these same destructive falls that create fresh back walls and ceiling surfaces for a new generation of rock paintings. Recognition of the different stages of this cycle, and the mechanisms responsible for it, also give an opportunity to identify rock shelters that may be in imminent danger of major structural change or catastrophic collapse. Some of these 'at risk' shelters may contain rock art of great significance, and it is not out of the question that appropriate structural interventions might be considered to preserve them for the benefit of future generations.

One of the most significant conclusions of this study is that understanding the rock mechanics of shelter formation is vital to comprehending their evolution. We have argued that many of the rock shelter features documented in this study point to the role of tensile and shear failure associated with compressional stress from the overlying rock mass, leading to rock fracturing and ultimate failure.

A second significant conclusion from our proposed rock shelter formation mechanism is that initiation of a receding cavity in one of the less competent beds creates a positive feedback loop leading to further recession, by concentration of the load on a decreasing area of support in the deepest part of the shelter. This leads inexorably to further undermining of the cavity, ultimately driving the collapse of the overlying sandstone edifice. Once established, the rock shelter will be progressively enlarged by failure of overlying sandstone beds and successive bedding slab falls due to failure on a combination of tensile and shear fractures. The distribution of stress has an important role in the evolution of these rock shelters, as noted previously for other sandstone caves by Bruthans et al. (2014) and Young, Wray, & Young (2018).

We consider that such physical rock deformation processes are the principal driving mechanism for the initiation and subsequent evolution of the sandstone rock shelters as summarized above. This is an area that will require more intensive study, not only in the north Kimberley environment, but perhaps in similar non-limestone terranes globally. Numerical modelling of the underlying rock mechanics should also lead to additional insights into the life cycle of these rock shelters. The work presented here has important implications for understanding the long-term survival of rock art and for identifying archaeological sites that are at risk of collapse.

AUTHOR CONTRIBUTIONS

Andrew Gleadow: Conceptualization; funding acquisition; methodology; investigation; resources; supervision; writing—initial draft; writing—reviewing and editing. **Helen Green:** Investigation; writing—reviewing and editing. **Damien Finch:** Investigation; writing—reviewing and editing. **Samuel Boone:** Investigation; writing—reviewing and editing. **David Fink:** Investigation; resources; supervision; writing—reviewing and editing. **Réka-Hajnalka Fülöp:** Investigation; resources; writing—reviewing and editing. **Alexandru Codilean:** Investigation; writing—reviewing and editing. **Augustine Unghango:** Resources; investigation; supervision.

ACKNOWLEDGEMENTS

We acknowledge and thank Traditional Owners, the Kalumburu Community and Balanggarra Aboriginal Corporation for permission to work on their Country, for their support during fieldwork and their generous engagement with the project over many years. In particular, we thank senior elders Augustine Unghango and Ambrose Chalarimeri for their support, and many others we have worked with, especially from the Unghango and Waina families. We are very grateful to Cecilia Myers, Pauline Heaney, Peter Veth, Sven Ouzman, Sam Harper, Paul Hartley, Robyn Maher, Chris Townsend, Pete Turnbull and Sue Ball for fieldwork support and assistance. Many thanks also to Dunkeld Pastoral Company and staff at Theda and Doongan Stations for their hospitality and logistical support, and especially Cecilia Myers, Maria Myers and Susan Bradley for their warm reception, generous hospitality and support. Special thanks to helicopter pilots William Maher, Nick Sundblom and Dan Horsford, without whose skill and experience none of our remote area fieldwork would have been possible. The assistance of Gordon Lister with the interpretation of the geomechanics is gratefully acknowledged. We thank the Western Australian Department of Aboriginal Affairs for the necessary S16 permit. Additional in-kind support was provided by the Western Australia Department of Biodiversity, Conservation and Attractions (DBCA). Ongoing laboratory infrastructure support at the University of Melbourne is provided by AuScope under the National Collaborative Research Infrastructure Strategy. Helen Green acknowledges the support of a Fellowship in Rock Art Dating provided by the Ian Potter Foundation and Rock Art Australia. The manuscript was substantially improved through the comments of an anonymous reviewer and the editor which are greatly appreciated.

DATA AVAILABILITY STATEMENT

The observations upon which this study is based, principally photographic records, are reported in the article. Representative examples comprise most of the Figures and enlarged versions of the individual photographs are included in the supplementary information.

ORCID

Andrew Gleadow https://orcid.org/0000-0003-0496-0028
Helen Green https://orcid.org/0000-0002-7842-6007
Damien Finch https://orcid.org/0000-0002-9447-5685
Samuel Boone https://orcid.org/0000-0003-2274-7933
David Fink https://orcid.org/0000-0001-7156-4602
Réka-Hajnalka Fülöp https://orcid.org/0000-0002-3237-0319
Alexandru Codilean https://orcid.org/0000-0003-1895-5633

REFERENCES

Bruthans, J., Soukup, J., Vaculikova, J., Filippi, M., Schweigstillova, J., Mayo, A.L., et al. (2014) Sandstone landforms shaped by negative feedback between stress and erosion. *Nature Geoscience*, 7, 598–602. Available from: https://doi.org/10.1038/ngeo2209

Cazes, G., Fink, D., Codilean, A.T., Fülöp, R.H., Fujioka, T. & Wilcken, K.M. (2020) 26Al/10Be ratios reveal the source of river sediments in the Kimberley, NW Australia. *Earth Surface Processes and Landforms*, 45(2), 424–439. Available from: https://doi.org/10.1002/esp.4744

Delannoy, J.J., David, B., Genuite, K., Gunn, R., Finch, D., Ouzman, S., et al. (2020) Investigating the anthropic construction of rock art sites through archaeomorphology: the case of Borologa, Kimberley, Australia. *Journal of Archaeological Method and Theory*, 27, 631–669. Available from: https://doi.org/10.1007/s10816-020-09477-4

Department of Water and Environmental Regulation. (2023) Hydrology of the Fitzroy River, Kimberley, Western Australia. Surface water hydrology series, Report HY38, 75p.

Diederichs, M.S. (2003) Manuel Rocha Medal Recipient Rock Fracture and Collapse Under Low Confinement Conditions. *Rock Mechanics and Rock Engineering*, 36(5), 339–381. Available from: https://doi.org/10.1007/s00603-003-0015-y

Donaldson, M. (2012a) *Kimberley rock art, volume one: Mitchell plateau area*. Mount Lawley WA: Wildrocks Publications. 528p.

Donaldson, M. (2012b) *Kimberley rock art, volume two: North Kimberley*. Mount Lawley WA: Wildrocks Publications. 396p.

Ebert, K. (2009) Terminology of long-term geomorphology: a Scandinavian perspective. *Progress in Physical Geography*, 33, 163–182.

Esterhuizen, G., Dolinar, D.R. & Ellenberger, J.L. (2011) Pillar strength in underground stone mines in the United States. *International Journal of Rock Mechanics and Mining Sciences*, 48(1), 42–50. Available from: https://doi.org/10.1016/j.ijrmms.2010.06.003

Filippi, M., Bruthans, J., Mares, J., Adamovic, J. & Fitz, T. (2024) Factors influencing the evolution of sandstone sea caves: a case study from the Apostle Islands National Lakeshore (Lake Superior, USA). *Journal of Great Lakes Research*, 50, 102251. Available from: https://doi.org/10.1016/j.jglr.2023.102251

Filippi, M., Bruthans, J., Rihosek, J., Slavík, M., Adamovic, J. & Masín, D. (2018) Arcades: products of stress-controlled and discontinuity-related weathering. *Earth-Science Reviews*, 180, 159–184. Available from: https://doi.org/10.1016/j.earscirev.2018.03.012

Finch, D., Gleadow, A., Hergt, J., Heaney, P., Green, H., Myers, C., et al. (2021) Ages for Australia's oldest rock paintings. *Nature Human Behaviour*, 5(3), 310–318. Available from: https://doi.org/10.1038/s41562-020-01041-0

Finch, D., Gleadow, A., Hergt, J., Levchenko, V.A. & Fink, D. (2019) New developments in the radiocarbon dating of mud wasp nests. *Quaternary Geochronology*, 51, 140–154. Available from: https://doi.org/10.1016/j.quageo.2019.02.007

Finch, D., Gleadow, A., Hergt, J., Levchenko, V.A., Heaney, P., Veth, P., et al. (2020) 12,000-year-old Aboriginal rock art from the Kimberley region, Western Australia. *Science Advances*, 6(6), eaay3922. Available from: https://doi.org/10.1126/sciadv.aay3922

Fujioka, T., Fink, D., Nanson, G., Mifsud, C. & Wende, R. (2015) Flood-flipped boulders: in-situ cosmogenic nuclide modeling of flood deposits in the monsoon tropics of Australia. *Geology*, 43(1), 43–46. Available from: https://doi.org/10.1130/g35856.1

Gellatly, D. C. & Sofoulis, J. (1969) Drysdale-Londonderry, WA sheet SD52–9 and SD52–5, 1:250,000 geological map series explanatory notes 18.

Green, H., Gleadow, A., Finch, D., Hergt, J. & Ouzman, S. (2017) Mineral deposition systems at rock art sites, Kimberley, northern Australia - field observations. *Journal of Archaeological Science-Reports*, 14, 340–352. Available from: https://doi.org/10.1016/j.jasrep.2017.06.009

Green, H., Gleadow, A., Finch, D., Myers, C. & McGovern, J. (2021a) Micro-stromatolitic laminations and the origins of engraved, oxalate-rich accretions from Australian rock art shelters. *Geoarchaeology*, 36(6), 964–977. Available from: https://doi.org/10.1002/gea.21882

Green, H., Gleadow, A., Levchenko, V.A., Finch, D., Myers, C., McGovern, J., et al. (2021b) Dating correlated microlayers in oxalate accretions from rock art shelters: new archives of paleoenvironments and human activity. *Science Advances*, 7(33), eabf3632. Available from: https://doi.org/10.1126/sciadv.abf3632

Gunn, R.G., David, B., Delannoy, J.-J., Smith, B., Unhango, A., Waina, I., et al. (2022) Superpositions and superimpositions in rock art studies: Reading the rock face at Pundawar Manbur, Kimberley, Northwest Australia. *Journal of Anthropological Archaeology*, 67, 101442. Available from: https://doi.org/10.1016/j.jaa.2022.101442

Harper, S., Veth, P. & Ouzman, S. (2020) Kimberley Rock Art. In: Smith, C. (Ed.) *Encyclopedia of global archaeology*. Switzerland: Springer Nature. https://doi.org/10.1007/978-3-030-30018-0_3449

Hoek, E. & Martin, C.D. (2014) Fracture initiation and propagation in intact rock - a review. *Journal of Rock Mechanics and Geotechnical Engineering*, 6(4), 287–300. Available from: https://doi.org/10.1016/j.jrmge.2014.06.001

Lan, H.X., Martin, C.D. & Andersson, J.C. (2013) Evolution of in situ rock mass damage induced by mechanical-thermal loading. *Rock Mechanics and Rock Engineering*, 46(1), 153–168. Available from: https://doi.org/10.1007/s00603-012-0248-8

Li, H., Song, Y., Wang, Y., Zhao, X., Dai, B. & Sun, L. (2024) Spalling criterion of hard brittle rock mass based on dilatation lateral strain. *ACS Omega*, 9, 2640–26408. Available from: https://doi.org/10.1021/acsomega.4c02572

Migoń, P. (2004) Etching, etchplin and etchplanation. In: Goudie, S.A. (Ed.) *Encyclopedia of geomorphology*. London, New York: Routledge, pp. 345–347.

Morwood, M.J., Walsh, G.L. & Watchman, A.L. (1994) The dating potential of rock art in the Kimberley. *Rock Art Research*, 11, 79–87.

Napier, J.A.L., Daehnke, A., Dede, T., Hildyard, M.W., Kuijpers, J.S., Malan, D.F., et al. (1997) Quantification of stope fracture zone behaviour in deep level gold mines. *Journal of the South African Institute of Mining and Metallurgy*, 97, 119–134.

Phillips, C. (2023) Sedimentology and revised stratigraphy of the Kimberley basin, Western Australia. *Geological Survey of Western Australia*, Report 241, 110p.

Roberts, R., Walsh, G.L., Murray, A., Olley, J., Jones, R., Morwood, M.J., et al. (1997) Luminescence dating of rock art and past environments using mud-wasp nests in northern Australia. *Nature*, 387(6634), 696–699. Available from: https://doi.org/10.1038/42690

Ross, J., Westaway, K., Travers, M., Morwood, M.J. & Hayward, J. (2016) Into the past: a step towards a robust Kimberley rock art chronology. *PLoS One*, 11(8), e0161726. Available from: https://doi.org/10.1371/journal.pone.0161726

Sheppard, S., Page, R.W., Griffin, T.J., Rasmussen, B., Fletcher, I.R., Tyler, I.M., et al. (2012) Geochronological and isotopic constraints on the tectonic setting of the c. 1800 ma hart dolerite and the Kimberley and Speewah basins, northern Western Australia. *Geological Survey of Western Australia*, Record 2012/7, 28p.

Twidale, C.R. (2002) The two-stage concept of landform and landscape development involving etching: origin, development and implications of an idea. *Earth-Science Reviews*, 57, 37–74.

Tyler, I.M., Hocking, R.M. & Haines, P.W. (2012) Geological evolution of the Kimberley region of Western Australia. *Episodes*, 35(1), 298–306. Available from: https://doi.org/10.18814/epiiugs/2012/v35i1/029

Veth, P., Myers, C., Heaney, P. & Ouzman, S. (2018) Plants before farming: the deep history of plant-use and representation in the rock art of Australia's Kimberley region. *Quaternary International*, 489, 26–45. Available from: https://doi.org/10.1016/j.quaint.2016.08.036

Walsh, G.L. (2000) Bradshaw art of the Kimberley. *Takarakka Nowan Kas Publications in association with the Australian Centre*. Toowong: University of Melbourne, 464p

Walsh, G.L. & Morwood, M.J. (1999) Spear and spearthrower evolution in the Kimberley region, N.W. Australia: evidence from rock art. *Archaeology in Oceania*, 34, 45–58.

Ward, I., Nanson, G.C., Head, L.M., Fullagar, R., Price, D.M. & Fink, D. (2005) Late Quaternary landscape evolution in the Keep River region, northwesternAustralia. *Quaternary Science Reviews*, 24, 1906–1922.

Welch, D. (1993) Stylistic change in the Kimberley rock art. In: Lorblanchet, M. & Bahn, P.G. (Eds.) *Australian rock art studies: the post-stylistic era or where do we go from here?* Oxbow Books, Oxford: Oxbow Monograph, pp. 99–113.

Welch, D.M. (2015) *Aboriginal paintings of Drysdale River National Park, Kimberley, Western Australia*. Coolalinga, Northern Territory: David M. Welch, 322p.

Wingate, M.T.D., Lu, Y., Kirkland, C.L. & Hollis, J.A. (2018) 206156: Dolerite sill, Idamere Yard. *Geological Survey of Western Australia*, Geochronology Record 1536, 5p.

Young, R. & Young, A. (1992) *Sandstone landforms*. Berlin, New York: Springer-Verlag, 163p.

Young, R.W., Wray, R.L. & Young, A.R.M. (2018) *Sandstone landforms*. Cambridge, New York: Cambridge University Press, 314p.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Gleadow, A., Green, H., Finch, D., Boone, S., Fink, D., Fülöp, R.-H. et al. (2025) The origin, evolution and life cycle of rock art shelters in the Kimberley Basin of NW Australia. *Earth Surface Processes and Landforms*, 50(9), e70124. Available from: https://doi.org/10.1002/esp.70124