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CAVES AS SEA LEVEL AND UPLIFT INDICATORS, KANGAROO ISLAND, SOUTH AUSTRALIA

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Abstract: Flank margin caves have been observed in Quaternary Bridgewater Formation eolianites on Kangaroo Island, South Australia. Horizons of flank margin cave development at 25 m, 30 m, and 35 m elevation demonstrate tectonic uplift of tens of meters during the Quaternary, as the cave elevations are higher than any reported Quaternary glacioeustatic sea-level highstand. Distinct cave horizons indicate that episodic uplift was possible. Wave-cut notches at Hanson Bay, at 30 to 35 m elevation, also support the interpretation from caves that relative sea level was once at the ~30-m-elevation range. Admirals Arch, previously presented as forming solely by wave erosion, is a flank margin cave breached and modified by wave erosion. Point Ellen contains a Late Pliocene subtidal carbonate unit that formed within the reach of wave base, was uplifted and cliffed by wave processes, and then was karstified before being buried by Quaternary Bridgewater Formation eolianites. A possible flank margin cave developed at Point Ellen at 3 m above modern sea level is consistent with earlier interpretations of notching of the nearby coast at a similar elevation during the last interglacial sea-level highstand (MIS 5e); and therefore, no tectonic uplift in the last 120 ka. In contrast, the tafoni of Remarkable Rocks present a cautionary note on evidence of cave wall morphological characteristics as proof of dissolutional origin.

INTRODUCTION

Kangaroo Island is located 16 km southwest across the Backstairs Passage from Cape Jervis on the Fleurieu Peninsula, South Australia (Fig. 1). The island is a rectangle roughly 145 km east to west, and 60 km north to south with an area of 4,350 km^2 and a coastline length of 457 km (Short and Fotheringham, 1986). Kangaroo Island is a geologically diverse environment with rocks present from the Proterozoic through the Paleozoic, Mesozoic, and Cainozoic (Belperio and Flint, 1999). The island is a geologic extension of the Fleurieu Peninsula on the Australian mainland (Belperio and Flint, 1999; James and Clark, 2002). Although isolated Paleozoic outcrops of carbonate rock exist on Kangaroo Island, the dominant carbonate units are Cainozoic (James and Clark, 2002). Especially prevalent, primarily along the southern and western coasts, are eolian calcarenites of Late Pliocene through Holocene age (Ludbrook, 1983; Short and Fotheringham, 1986). The Cambrian Kanmantoo Group metasediments form the basement of the island (James and Clark, 2002), and commonly the eolianites rest directly upon them along the southern and western shore of Kangaroo Island. Cambro-Ordovician granites also outcrop at the southwest end of Kangaroo Island (James and Clark, 2002) and eolianites occasionally overlie those exposures.

The eolian calcarenites are assigned by most authors to the Bridgewater Formation, the name given to eolian calcarenites across South Australia and Victoria (Drexel and Preiss, 1995). These eolian calcarenites represent depositional episodes associated with glacioeustatic Quaternary sea-level fluctuations and consist of at least 16 separate events on the Australian mainland (Drexel and Preiss, 1995). On Kangaroo Island, the eolian depositional events are thought by some authors to represent only four glacial events because those authors recognize only the traditional, continental-based four Pleistocene glaciations (Twidale and Bourne, 2002), while other authors indicate that more than 16 sea-level highstands occurred in the Quaternary on Kangaroo Island (Short and Fotheringham, 1986). Most authors (e.g., Drexel and Preiss, 1995) consider the Bridgewater Formation to be Pleistocene in age. However, Ludbrook (1983) reports that eolian calcarenites of the Bridgewater Formation interfinger with Late Pliocene Point Ellen Formation subtidal facies at Point Reynolds, east of Point Ellen. This observation raises the possibility that the initial deposition of the Bridgewater Formation eolian calcarenites predates the Pliocene-Pleistocene boundary on Kangaroo Island. The Bridgewater Formation eolian calcarenites and the caves and karst features developed in them are the focus of this reconnaissance study.

Kangaroo Island was visited in September 2006 for five days as a reconnaissance expedition with the purpose of comparing cave development in the coastal eolian calcarenites on that island with those found in similar environments in the Bahamian Archipelago, half the world away. The observations reported here are necessarily brief and lack detail such as cave surveys. However, these brief observations establish important information regarding the nature of cave development on Kangaroo Island and

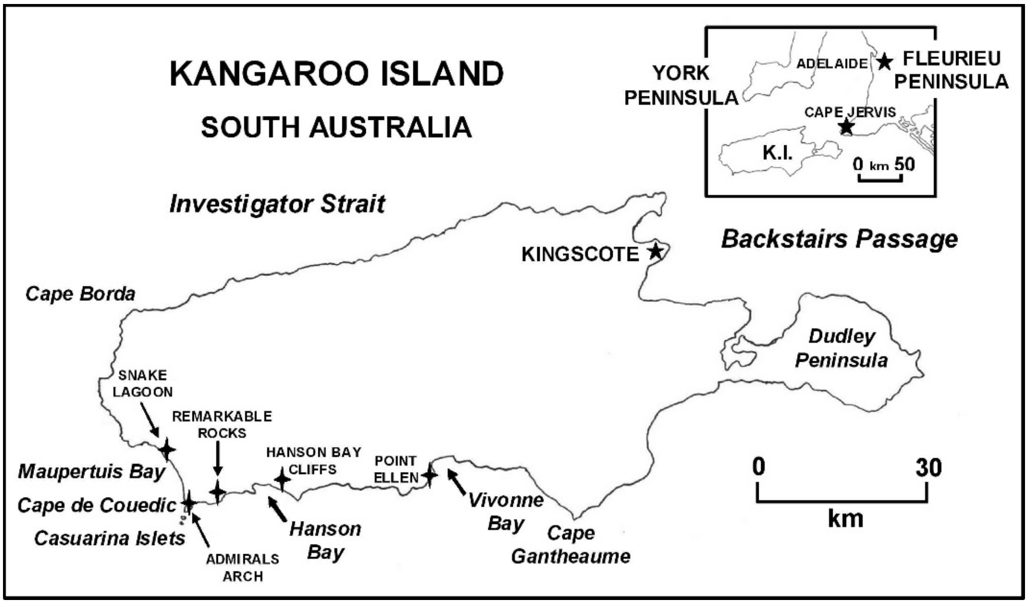

Figure 1. Map of Kangaroo Island showing its position off the Australian coast, and locations discussed in the text.

important sea level and tectonic interpretations that can be generalized from those observations.

Decades of work in the Bahamas (Mylroie, 1980; Vogel et al., 1990; Mylroie et al., 1995; Roth et al., 2006; Mylroie and Mylroie, 2007) developed an extensive database on cave development in eolian calcarenites. Those investigations led to the development of the flank margin cave model to explain rapid cave development in Bahamian eolianites as a result of mixing-zone dissolution. These caves develop in the distal margin of the fresh-water lens, under the flank of the enclosing landmass. At this location, the favorable dissolutional horizons at the top of the lens (vadose and phreatic fresh-water mixing) and at the base of the lens (sea-water and fresh-water mixing) are superimposed (Mylroie and Carew, 1990, 1995). These lens boundaries are also density interfaces, which collect organic material. Oxidation of these organics creates CO_2 to drive further dissolution, and with extreme organic loading, anoxic conditions develop and H_2S-mediated dissolution can occur (Bottrell et al., 1993). The decrease in lens cross-sectional area at the lens margin increases water-flow velocity, such that reactants and products move swiftly through the system (Raeisi and Mylroie, 1995). The model was expanded to non-eolianite carbonate islands of increasing complexity, such as Isla de Mona, Puerto Rico (Frank et al., 1998) and Guam in the Marianas (Mylroie et al., 2001). One of the prominent aspects of flank margin cave development is that the caves cut across carbonate facies without regard to grain size, porosity, or primary structures in the rock (Mylroie and Carew, 1995); fresh-water lens position, and hence sea level, is the primary factor in cave position. The flank margin cave model has evolved into the Carbonate Island Karst Model, or CIKM, which takes into account mixing dissolution, glacioeustasy, tectonics, carbonate/noncarbonate island relationships, and diagenetic maturity (Jenson et al., 2006; Mylroie and Mylroie, 2007). Flank margin caves form as isolated chambers or groups of chambers (i.e., they develop as mixing chambers without entrances). A similar rapid reconnaissance in August of 2006 at Rottnest Island, Australia, resulted in a number of new and important observations in the Quaternary eolianites and the flank margin caves there (Mylroie and Mylroie, 2009).

Flank margin cave development is controlled by the position of the fresh-water lens, which in turn, is tied to sea-level position. Other classic sea-level indicators on carbonate coasts, such as intertidal and subtidal deposits, and coastal notching, remain on the land surface after local uplift and/or eustatic sea-level fall. Flank margin caves also occur in a coastal setting, but inside the landmass. This difference in placement means that as surficial erosion strips away surface deposits and landforms, flank margin caves are still present. As surface erosion continues, the flank margin caves are breached and become visible to the surface observer. As a result, flank margin caves are not only sea-level indicators, but also indicators of rates of surface denudation (Figs. 2 and 3).

In the Bahamas, breached flank margin caves were once identified as fossil bioerosion notches before being recognized as erosionally-exposed subsurface features (Mylroie and Carew, 1991). The Bahamas are tectonically stable, subsiding at 1 to 2 m per 100 ka (Carew and Mylroie, 1995; McNeill, 2005), therefore, any sea-level indicators found in the subaerial environment today are the result of eustasy. As the surficial rocks of the Bahamas are less than 800,000 years old (Carew and Mylroie, 1997), this eustatic sea-level change is a result of glacial-deglacial cycles. The Bahamian situation is somewhat simplified, as

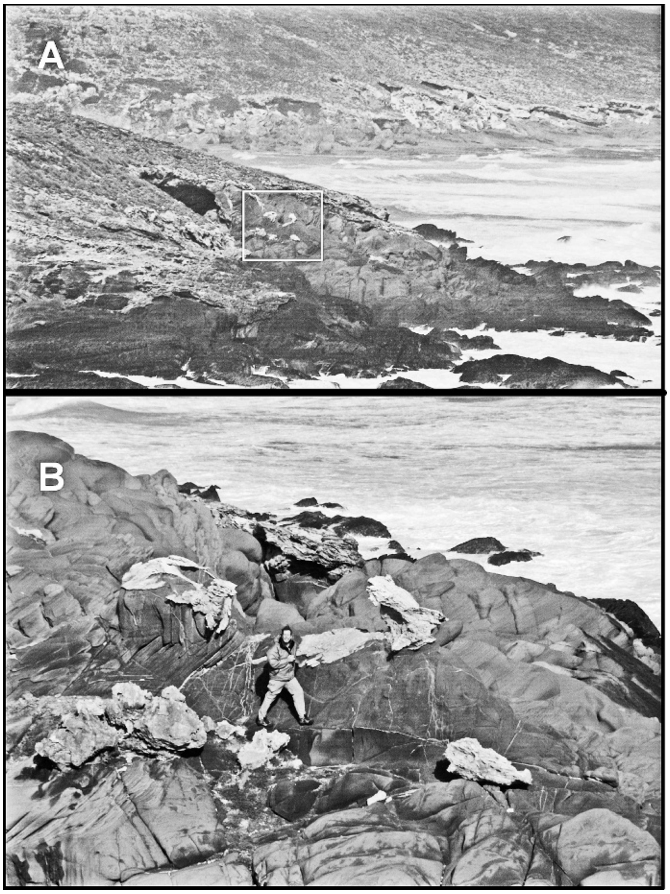

Figure 2. West coast of Kangaroo Island, north of Snake Lagoon and Rocky River. A – Overall scene, with light-coloured Bridgewater Formation eolianites overlying darker Kanmantoo Group rocks. The white box denotes the area presented in (B). B – Isolated Bridgewater Formation eolian calcarenite outcrops (light-coloured patches) on Kanmantoo Group rocks, demonstrating that a once-continuous eolian calcarenite unit has been stripped away by Holocene coastal erosion.

sea level or subtidal indicators above modern sea level today, such as fossil reefs, abandoned coastal notches, breached flank margin caves, or herringbone crossbedding, must be the result of a glacioeustatic sea-level highstand above modern levels. That highstand must also have been recent enough that its deposits have remained above modern sea level despite the isostatic subsidence rate of 1 to 2 m per 100 ka. Based on these constraints, the only sea-level highstand believed to be pervasively recorded in the Bahamas is that of the last interglacial, marine isotope substage 5e, or MIS 5e (Carew and Mylroie, 1997). In the Atlantic Basin, that highstand reached +6 m and lasted from 131 ka to 119 ka (Chen et al., 1991), a 12,000 year time window in which to create all the pre-modern sea-level indicators currently observed above sea level in the Bahamas, including the flank margin caves.

Kangaroo Island is in an environment that has been uplifted during the Quaternary (Short and Fotheringham, 1986; James and Clark, 2002; Twidale and Bourne, 2002); the debate has been over the amount of uplift. In high-relief coastal settings, such as on Kangaroo Island, cliff retreat under current sea-level conditions has removed many of the typical surface indicators of past, higher sea levels (Fig. 2), and uplift has displaced them from the elevation of their initial formation (Fig. 3). Numerous caves are found in the eolianite cliffs of the southern and western coasts of Kangaroo Island, and their location is potentially a representation of a past fresh-water lens position, and hence, a past sea-level position. This paper reports on how use of caves, especially flank margin caves, can help refine our understanding of Quaternary processes on Kangaroo Island.

METHODOLOGY

Conceptually, the methodology is simple; walk the eolianite outcrops and record the location and elevation of flank margin caves. Ideally, all caves identified are representative of a paleo sea-level position, but care is needed because the caves can be of two main types: dissolutional caves; and pseudokarst caves produced by processes other than dissolution. A distinction must be made between the two main cave types. If the cave is determined to be a dissolutional cave, then the nature of that dissolution must be determined to establish whether the cave formed in the distal margin of a fresh-water lens as a flank margin cave.

Cliffed coastal settings in eolian calcarenites commonly have two main types of pseudokarst caves: sea caves, and tafoni caves. Sea caves are the result of wave energy and wave transported debris mechanically eroding a hollow or cave into a bedrock outcrop (Waterstrat, 2007 and references therein). Such caves form from the outside inward as the waves continue their work. Sea caves are a sea-level indicator, but because they are produced from the surface inward, they remain near the active erosive face of the land surface and are vulnerable to later removal by scarp retreat. Tafoni caves are voids and hollows produced by subaerial weathering processes that selectively remove rock grains from a specific area in an outcrop. The processes involve wind, crystal wedging of evaporite minerals, wetting and drying, and a variety of other activities (Owen, 2007 and references therein). Similar to sea caves, tafoni caves form from the outside inward and are vulnerable to removal by scarp retreat. Unlike sea caves, however, their position on a cliff face is random and not related to a specific past sea-level position. Recent work in Bahamian eolian calcarenites has resulted in the development of criteria to allow the differentiation of breached flank margin caves and sea caves (Waterstrat, 2007; Mylroie et al., 2008a), as well as the differentiation of sea caves and tafoni caves from each other and from

Figure 3. Views of flank margin cave entrances in the lower Rocky River and Snake Lagoon area, developed in Bridgewater Formation eolianites. A – Valley north wall, showing a well-developed band of caves at ~30-m-elevation, and other caves at ~25-m-elevation. B – Valley south wall, showing three horizons of flank margin cave development, at ~25-, ~30- and ~35-m-elevation. As with the valley north wall, the best development is at ~30 m.

breached flank margin caves (Owen, 2007; Mylroie et al., 2008a).

One of the primary criteria to differentiate the cave types is inspection of the interior rock surfaces for the unique curvilinear shapes associated with carbonate dissolutional surfaces. Such inspection can be problematic if a flank margin cave has been breached while still in the surf zone because wave-dominated mechanical processes may have scoured, obscured, and overprinted the original dissolutional surfaces. The use of metrics, such as the ratio of cave area over cave wall perimeter, and the ratio of cave entrance width over maximum cave width reliably differentiate flank margin caves, sea caves, and tafoni caves from each other in the Bahamas (Waterstrat, 2007, Owen, 2007, Mylroie et al., 2008a). These metrics have been demonstrated to work for sea caves and flank margin caves in coastal Puerto Rico (Lace, 2008). The dissolutional origin of the flank margin cave creates a very complex perimeter, whereas the sea cave and tafoni cave tend to have smooth perimeters. This difference creates distinct area to perimeter ratios for the cave types. Because the sea caves and tafoni caves are created by erosive forces working from the outside inward, they commonly have a cave entrance width over maximum cave width ratio of near one (the entrance is the widest part of the cave). Flank margin caves initiate as dissolutional chambers that are later breached by surface erosion. The entrances are commonly small or medium sized, and the cave entrance width to maximum cave width ratio is much less than one. When a flank margin cave displays a ratio near one, that result is an indication that the cave has been breached and denuded to the extent that it is approximately half or more destroyed (Stafford et al., 2005, their Fig. 11). Finally, sealed cave chambers with humidity near 100% precipitate dense, crystalline calcite speleothems such as stalactites, stalagmites, flowstone, and other forms as a result of CO_2 diffusion from drip water into the cave atmosphere. In open air environments, such calcite precipitation is not possible, as evaporation competes with CO_2 diffusion to control the $CaCO_3$ chemistry, and crumbly tuffaceous deposits form. Taboroši et al. (2006) provide examples and criteria to determine which calcite precipitates found in open cave chambers formed inside a sealed cave and which are the result of open-air precipitation. Sea caves and tafoni caves originate as open voids and do not commonly contain dense calcite speleothems. Cave speleothems are commonly modified by surficial exposure, degrading into a more tuffaceous character, which can complicate interpretations (Taboroši et al., 2006)

Once it has been established that a given cave is the result of dissolution, that it is a karst cave, then the type of karst cave must be determined. Karst caves fall into two main groups (Palmer, 1991): epigenic caves that usually develop as conduit systems with rapid turbulent flow, that are directly coupled to the surface hydrology and hypogenic caves that develop in a laminar or slow flow system, decoupled from the surface hydrology. Flank margin caves, by this description, are similar to hypogenic caves because they are mixing chambers and do not have rapid turbulent conduit flow. Epigenic caves formed by conduit flow commonly contain wall markings that reveal the flow to be fast and turbulent. Dissolutional features called scallops are especially effective indicators of turbulent flow direction and velocity (Curl, 1966, 1974). Turbulent conduit flow commonly leaves behind diagnostic sedimentary deposits, and distinct passage shapes, such as vadose canyons. Other cave features, such as solution pipes and vadose shafts, can also be present. These other features represent part of the coupling system that connects the epikarst to the water table, and for epigenic caves, they couple the cave directly to the surface hydrology, but for hypogenic and flank margin caves, they represent random intersections. The Kelly Hill Caves on Kangaroo Island (Hill, 1984) are an example of conduit flow of water through an eolianite ridge, perched on underlying insoluble rocks. Subsequent collapse has created a maze of chambers and passageways within and above the collapse material, and the true nature of the original dissolutional passages is obscured in most of this epigenic cave.

Flank margin caves form entirely as phreatic features under laminar or slow flow conditions. Their wall sculpture consists of cuspate pockets, bedrock columns and spans commonly of delicate configuration, and curvilinear forms that cut across primary and secondary bedrock features (Mylroie and Carew, 1990, 1995). Flank margin caves contain no evidence of rapid turbulent flow, either as wall sculpture or as sedimentary deposits. Their development in the thin, distal margin of the fresh-water lens results in low, wide chambers that intersect randomly because each chamber was an initiation point for mixing dissolution (Roth, 2004; Labourdette, et al., 2007). This passage pattern is especially true of flank margin caves developed in diagenetically immature, or eogenetic, carbonate rocks such as Quaternary eolian calcarenites, where primary porosity can be as much as 30% and the waters are able to mix across a broad volume of the rock mass (Vacher and Mylroie, 2002). Flank margin cave size is controlled primarily by the duration of time that the fresh-water lens, and hence sea level, was in a stable position (Mylroie and Mylroie, 2007; Mylroie et al., 2008b).

The southern and western coasts of Kangaroo Island are areas of high wind and ocean energy (Short and Fotheringham, 1986). The coastal outcrops of eolianite are cliffed and have retreated landward. An idea of how much retreat has occurred can be seen on the west coast of the island where the eolian calcarenites rest unconformably on the Kanmantoo Group basement rocks. Remnants of eolian calcarenite can be seen that are tens of meters away from the current eolian calcarenite scarp, indicating significant Holocene erosional removal of eolian calcarenite material (Fig. 2). Such large-scale erosion not only strips off surface features such as intertidal deposits, but also removes sea caves, tafoni, and even flank margin caves, leaving no past sea-level record. To obtain a preserved eolian calacarenite section requires investigating embayments and stream valleys that are protected from direct marine assault, but which would have held a fresh-water lens in contact with sea water at a past, higher sea-level position. For these reasons, Rocky River, reaching the coast from Snake Lagoon to Maupertius Bay (Figs. 1, 3, and 4), was selected as the prime field investigation locality to search for flank margin caves and evidence of past sea-level highstands. Cape du Couedic was also investigated because offshore islands provided some wave protection (Fig. 5).

Each location was examined by preliminary reconnaissance and revealed its own set of observations. Follow-up quantitative mapping and subsequent map interpretation, as described in the Methods section, was not done due to lack of time at the field localities. As a result, the interpretations made as to the origin of these caves were based on physical configuration and appearance only. Each of the localities below is presented as an observation set and each locality is then used to generate a set of preliminary interpretations. The overall outcome of the study is then reviewed in the Summary section.

Results and Discussion

Snake Lagoon

The Flinders Chase National Park trail along Rocky River from Snake Lagoon was used as the access route to the west coast (Fig. 1). At the location where the wooden footbridge crosses over Rocky River, Kanmantoo Group rocks are visible in the streambed, and cave openings can be seen back to the east, on the north bank, high up on the eolianite valley wall. These caves were not directly visited, but have the appearance of similar features in the Bahamas that are flank margin caves. Continuing west downstream, more cave openings are visible high on the north bank. While they have the appearance from a distance of flank margin caves, they were not visited and their origin cannot be confirmed. As Rocky River and the trail approach the coast, numerous cave openings appear in the cliffs on both

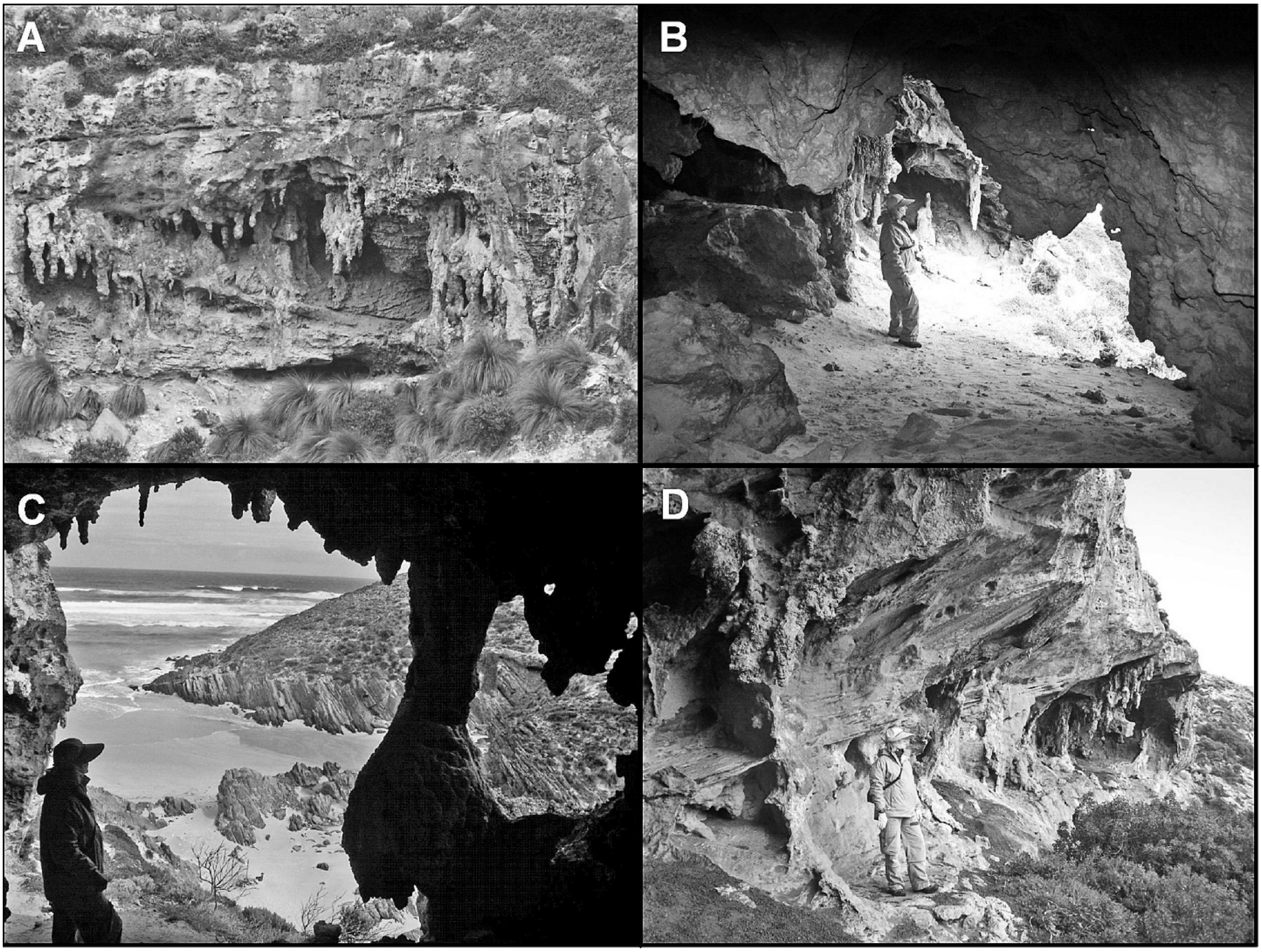

Figure 4. Flank margin caves at Snake Lagoon. A – Cave entrance at ~25-m-elevation in the valley north wall, showing abundant flowstone, stalactite and stalagmite development. B – Cave at ~25-m-elevation in the valley south wall, showing interconnecting chambers and stalactites. C – Looking northwest from a flank margin cave in the valley south wall, showing the ocean and Kanmantoo Group basement rocks that underlie the Bridgewater Formation eolianites. D – Series of eroded flank margin cave chambers on the valley south wall, showing smooth phreatic dissolutional surfaces and secondary vadose stalactites.

sides of the stream (Figs. 3 and 4). Those caves to the north were not visited because they were in a vertical wall (Figs. 3A and 4A), but the openings on the south bank were accessible and were thoroughly investigated (Figs. 3B, 4B, 4C, and 4D).

The single most obvious aspect of the caves is their development as a series of chambers that commonly connect internally. This observation is known as beads on a string (Mylroie et al., 2001) and reflects the degree to which individual flank margin cave chambers did or did not intersect as they grew by mixing dissolution in the distal margin of the fresh-water lens. The flank margin dissolutional origin of the caves is demonstrated by passage shape and configuration, abundant cave speleothems, and dissolutional wall morphologies (Fig. 4). The caves on the north side of the stream channel are found at two primary horizons, at approximately 25 m and 30 m elevation (Fig. 3A). The hill on the south side is higher, and contains evidence of three cave horizons at approximately 25 m, 30 m, and 35 m (Fig. 3B). The two horizons on the north side appear to correlate with the two lower horizons (at 25 m and 30 m) on the south side. At each cave horizon, the caves extend laterally over a distance of up to 100 m. The caves are not very deep, penetrating into the hillside generally less than 10 m. Because the caves have been breached by scarp retreat, the original voids had dimensions, perpendicular to the hillside, of over 10 m. The largest and most continuous band of caves, on each side of

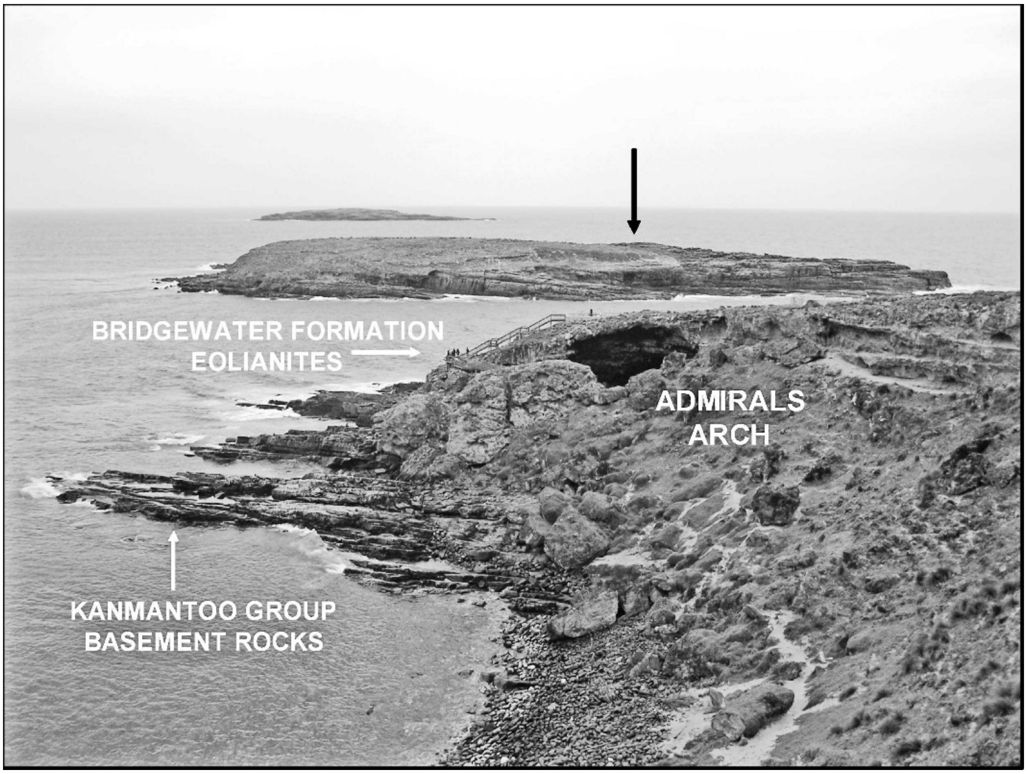

Figure 5. Overview of Cape de Couedic, the Casuarina Islets, and Admirals Arch, Kangaroo Island. The two islands in the distance are the Casuarina Islets, also known as The Brothers. The east opening of Admirals Arch is labeled in the foreground. The black vertical arrow in the background points to the cave shown in Figure 6A. Light colored Bridgewater Formation eolianites overlie dark Kanmantoo Group basement rocks.

the valley, is the one at 30 m, indicating perhaps a longer sea-level stillstand at that horizon than occurred at the 25 m or 35 m horizons.

The Snake Lagoon caves fit all the direct observational criteria that identify them as flank margin caves. As such, the caves represent past sea-level positions. All the caves described are above any past Quaternary glacioeustatic sea-level highstand. Therefore, uplift of Kangaroo Island is required to have occurred to place the caves at their current position with respect to modern sea level. Records of sea-level highstands on Kangaroo Island above 10 m are regarded as equivocal (Twidale and Bourne, 2002). However, Bauer (1961) indicated that a marine erosion terrace at 100 to 110 feet (30.5 to 33.5 m) was the most significant of the five terraces he recognized at 20 to 25 feet (6 to 7.6 m) and higher on Kangaroo Island. The cave observations presented here demonstrate a record of sea level well above 6 m, and at least three closely-spaced highstands are recorded. The duration of the highstands can be, in part, determined by how large the caves are. Cliff retreat since their formation has obviously decreased their size, but nonetheless, they are smaller than many flank margin caves in the Bahamas, which had 12,000 years to form. The development of the largest and most continuous caves at ~30-m-elevation agrees well with Bauer's (1961) best-developed terrace at that elevation. During glacioeustasy, the Bahamian record demonstrates that only when sea level is turning around from a lowstand or a highstand is it stable long enough to create large flank margin caves (Mylroie and Mylroie, 2007). If uplift is also involved, then the time of sea-level stability will be even less. The New Zealand flank margin cave record, in a tectonically active environment, provides time limits on lens stability (Mylroie et al., 2008b). The flank margin caves at Snake Lagoon indicate that uplift has definitely occurred, but it has been slow enough, and episodic enough, such that glacioeustatic stillstands can still leave a flank margin cave signature. Given that the last interglacial (oxygen isotope substage 5e) was 6 m higher than at present, such a eustatic sea-level elevation value should be considered when investigating the elevations of the caves found at Snake Lagoon today. In other words, the cave horizon at ~30-m-elevation could indicate an uplift of only 24 m, but that uplift would have had to occur in the last 120 ka, and other evidence at Point Ellen (below), suggests stability for the last 120 ka. The cluster of caves between ~25 m and ~35 m may represent two uplift events on a single glacioeustatic sea-level highstand, or no uplift episodes while three different glacioeustatic sea-level highstands occurred, or a combination of the two.

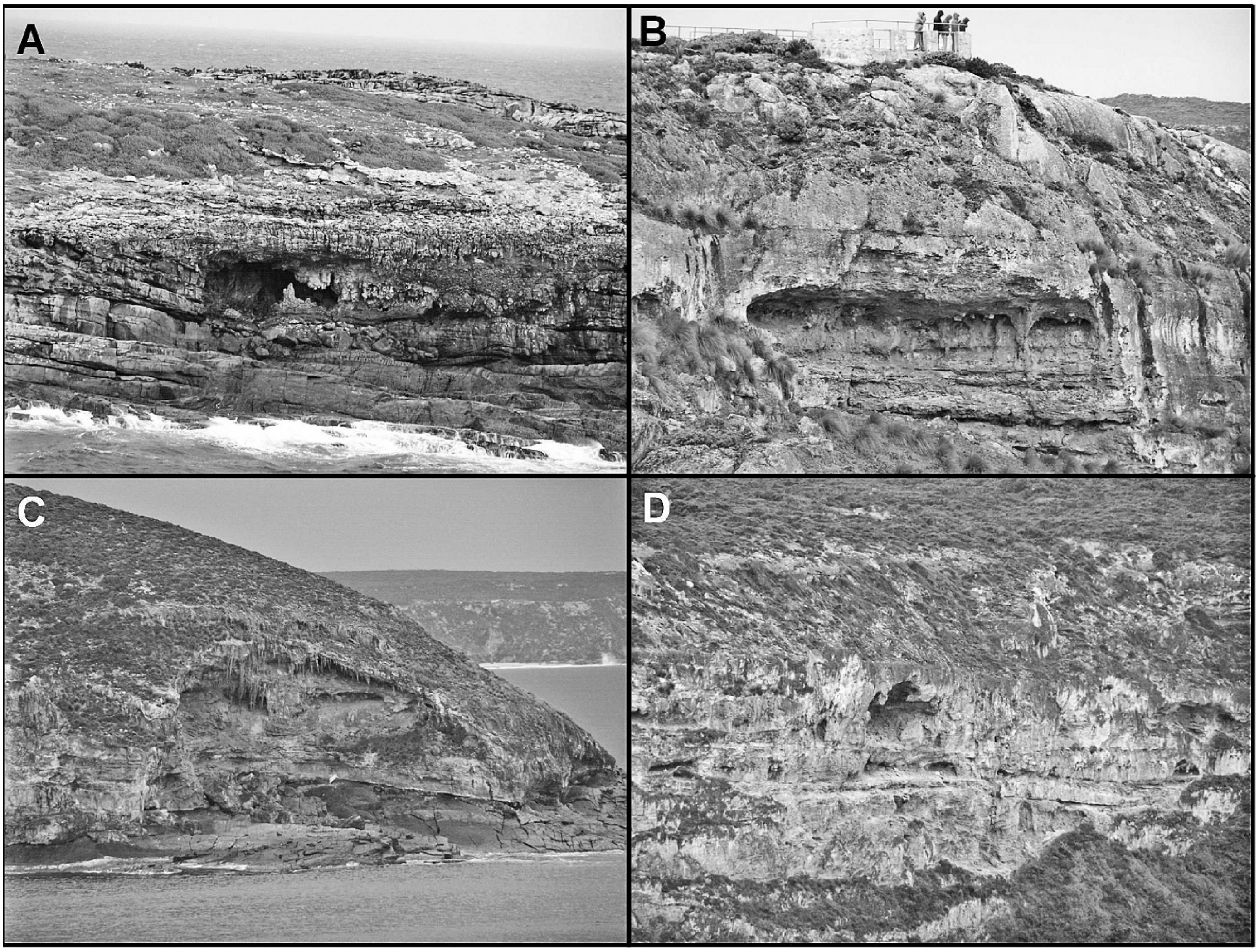

Figure 6. Eroded flank margin caves in the Cape de Couedic area. A – Cave entrance at the eolianite-basement contact, showing stalactites and stalagmites, on the landward of the two Casuarina Islets (Figure 5). The prominent stalagmite in the cave entrance is ~1-m-high. B - Back wall of a flank margin cave intersected by cliff retreat, in a small point just east of Admirals Arch. People at top for scale. Note the curvilinear shape of the cave wall, and the stalactites and flowstone. C - Large breached flank margin cave at the major headland between Admirals Arch and Remarkable Rocks. Note the Bridgewater Formation contact with the Kanmantoo Group basement rocks near sea level, and the many stalactites and stalagmites present. D – Small flank margin cave, and associated phreatic pockets in cliff wall, between Admirals Arch and the breached cave seen in Figure 6B. The cave entrance is ~3-m-high.

Cape du Couedic

This location (Fig. 1) is famous for Admirals Arch, a large void penetrating a rocky point composed of Bridgewater Formation eolian calcarenites overlying Kanmantoo Group basement rocks (Fig. 5). The steep eolianite cliffs to the east contain a number of breached flank margin caves (Fig. 6). Unfortunately, Flinders Chase National Park access regulations prevented direct investigation. Visual examination demonstrates that these features have dissolutional wall morphologies, calcite speleoethems, and align horizontally with other caves on the same cliff face.

Admirals Arch was also not available for independent direct investigation, but public access places the observer where clear views can be had of the cave interior (Fig. 7). The public display on the tour path presents Admirals Arch as a product solely of wave erosion. However, visual examination of the north wall of the arch reveals that it has a series of phreatic dissolution pockets (Fig. 7C) and that the original floor of the arch was horizontal and developed in limestone above the dipping contact with the underlying Kanmantoo Group basement (Figs. 7A and 7D). The cave has abundant calcite speleothems.

Admirals Arch appears to be a breached flank margin cave, which has been modified by wave action on the current (and perhaps last interglacial) sea-level high-stand(s). The phreatic dissolution surfaces and abundant

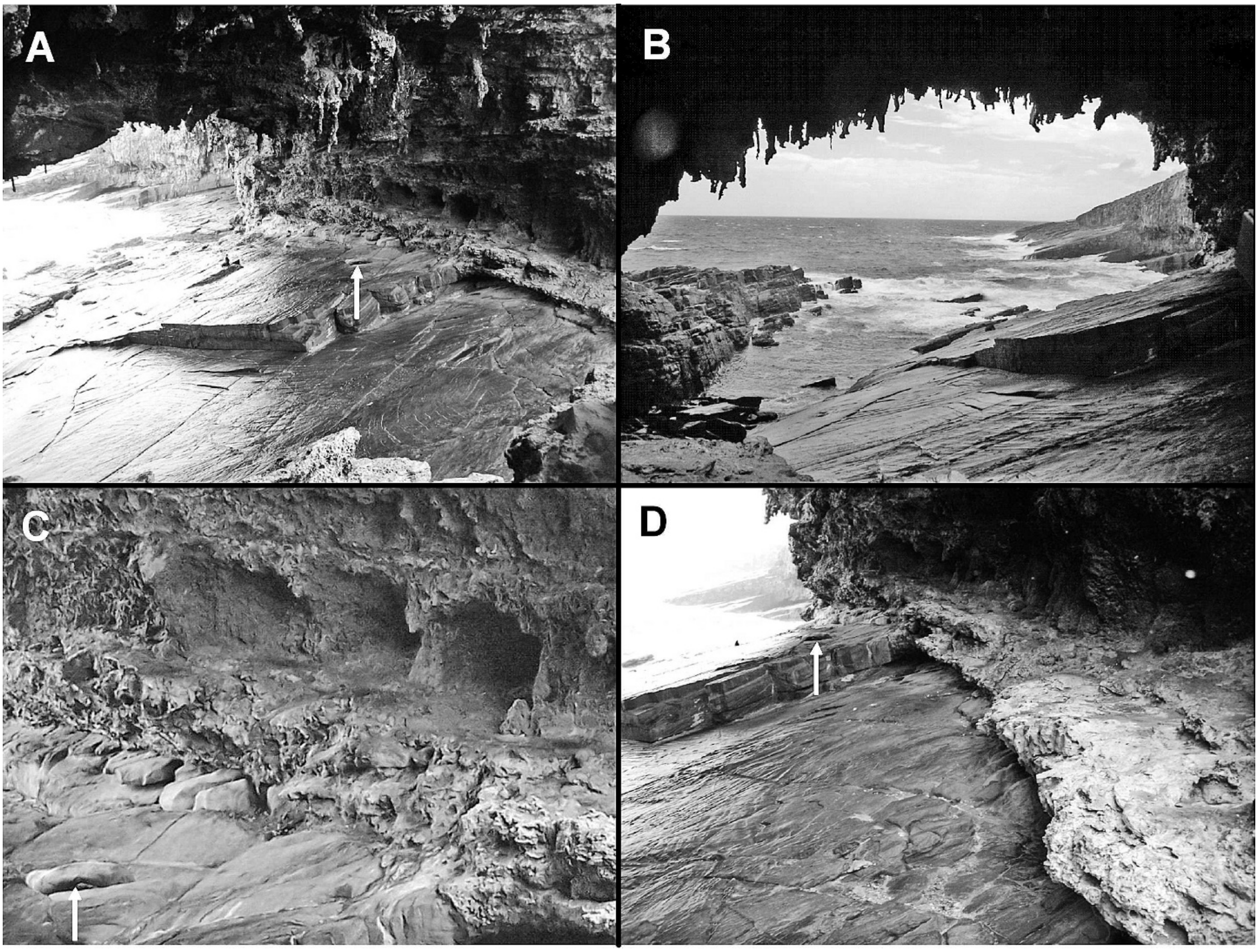

Figure 7. Images from Admirals Arch. A – Looking northwest through the Arch. Note the steep dip of the Kanmantoo Group basement rocks, and stalactites in upper foreground. Reclining seal, 1.5-m-long, in the center of the image for scale (white arrow; same seal as in C and D). B – Looking west through the Arch, showing numerous stalactites silhouetted by the western entrance. The twisted and gnarly appearance of the stalactites is an outcome of modification by both evaporation and algal growth. C – Phreatic pockets along the north wall of the Arch, formed in the Bridgewater Formation eolianites along a horizontal datum, just above the sloping Kanmantoo Group basement rocks. Seal, ~1.5-m-long, in lower left foreground for scale (white arrow). D – Surviving section of the original horizontal floor of the Arch. The phreatic pockets of Figure 7C are in shadow ahead and to the right in the image. Seal lying in background for scale (white arrow).

calcite speleothems indicate a cave that formed by phreatic, mixed-water dissolution, then was drained such that vadose speleothems could develop in a sealed cave chamber. The remnant flat limestone floor on the north side of the cave is another indication of flank margin cave development. That floor has been mostly stripped away by modern wave action ramping up the sloping Kanmantoo Group basement rocks.

Observation from a distance of the nearer of the two Casuarina Islets (The Brothers) revealed two caves in the eolian calcarenites on the cliff facing Admirals Arch (Figs. 5 and 6A). Remnant speleothems could be seen, but little of interior configuration was observable. The caves are quite close to the Kanmantoo Group basement contact. They appear to have phreatic morphologies, and as the islands are too small to support conduit flow, the most likely interpretation is that they are flank margin caves.

POINT ELLEN

At Point Ellen, on the western side of Vivonne Bay (Fig. 1), a sequence of carbonate and non-carbonate rocks is exposed. As described by Ludbrook (1983), eolian calcarenites of the Bridgewater Formation overlie subtidal carbonates of the Late Pliocene Point Ellen Formation, which in turn rest unconformably on the Kanmantoo

Figure 8. Point Ellen outcrop. A – Panorama photo of the major outcrop, looking north. The foreground is Kanmantoo Group basement rocks, the cave and laterally adjacent rocks are Point Ellen Formation marine carbonates, and the overlying rocks are Bridgewater Formation eolianites. Person in white oval for scale. B – Outcrop of the Point Ellen Formation, showing numerous mollusk shells. Pencil is 15-cm-long for scale (arrow). C – Closer view of the section in (A). Kanmantoo Group basement rocks in the foreground, grade upward into a Kanmantoo boulder and rubble facies interfingered with Point Ellen Formation, which forms the back wall of the cave. The Bridgewater Formation eolianites form the cave roof and top of the section. Person in black oval for scale.

Group basement rocks (Fig. 8). Our observations indicate that the eolian calcarenites drape over the Point Ellen Formation, and a fossil epikarst with a terra rossa paleosol separates the two units. The eolian calcarenites extend seaward of the Point Ellen Formation and sit directly in contact with Kanmantoo Group basement rocks (Fig. 9A). The outcrop is very complex and contains a wealth of information. The contact of the Point Ellen Formation with the underlying Kanmantoo Group basement rocks commonly contains rounded clasts of the basement rocks in the first 1 to 2 meters of the Point Ellen Formation (Figs. 9B and 9C). Such evidence is an indication of wave base actively eroding the basement rocks at the time of Point Ellen Formation deposition. This wave-base evidence places limits on the depth of deposition of the Point Ellen Formation. The transport of these eroded Kanmantoo Group rocks down a submarine slope cannot be discounted, however. The report by Ludbrook (1983) that eolian calcarenites of the Bridgewater Formation interfinger with Late Pliocene Point Ellen Formation subtidal facies at Point Reynolds, east of Point Ellen, is another indication that the Point Ellen Formation was deposited in relatively shallow water.

The contact of the Point Ellen Formation with the overlying Bridgewater Formation is a paleokarst, a fossilized epikarst with a terra rossa paleosol. A paleokarst requires that the Point Ellen Formation was subaerially exposed for a substantial time. Subsequently, the Bridgewater Formation was deposited. The area where the Bridgewater Formation eolian calcarenites extend over the Point Ellen Formation has a relief of several meters (Fig. 10), and at this point, the Point Ellen Formation is cliffed and a paleo-talus occupies the space between the Bridgewater Formation and the Point Ellen Formation. The setting is suggestive that the Point Ellen Formation was deposited in waters within reach of wave base, and then as uplift occurred, the Point Ellen material was cliffed by wave action as it transited into the supratidal environment. It remained exposed for a period of time long enough to develop a mature epikarst and terra rossa

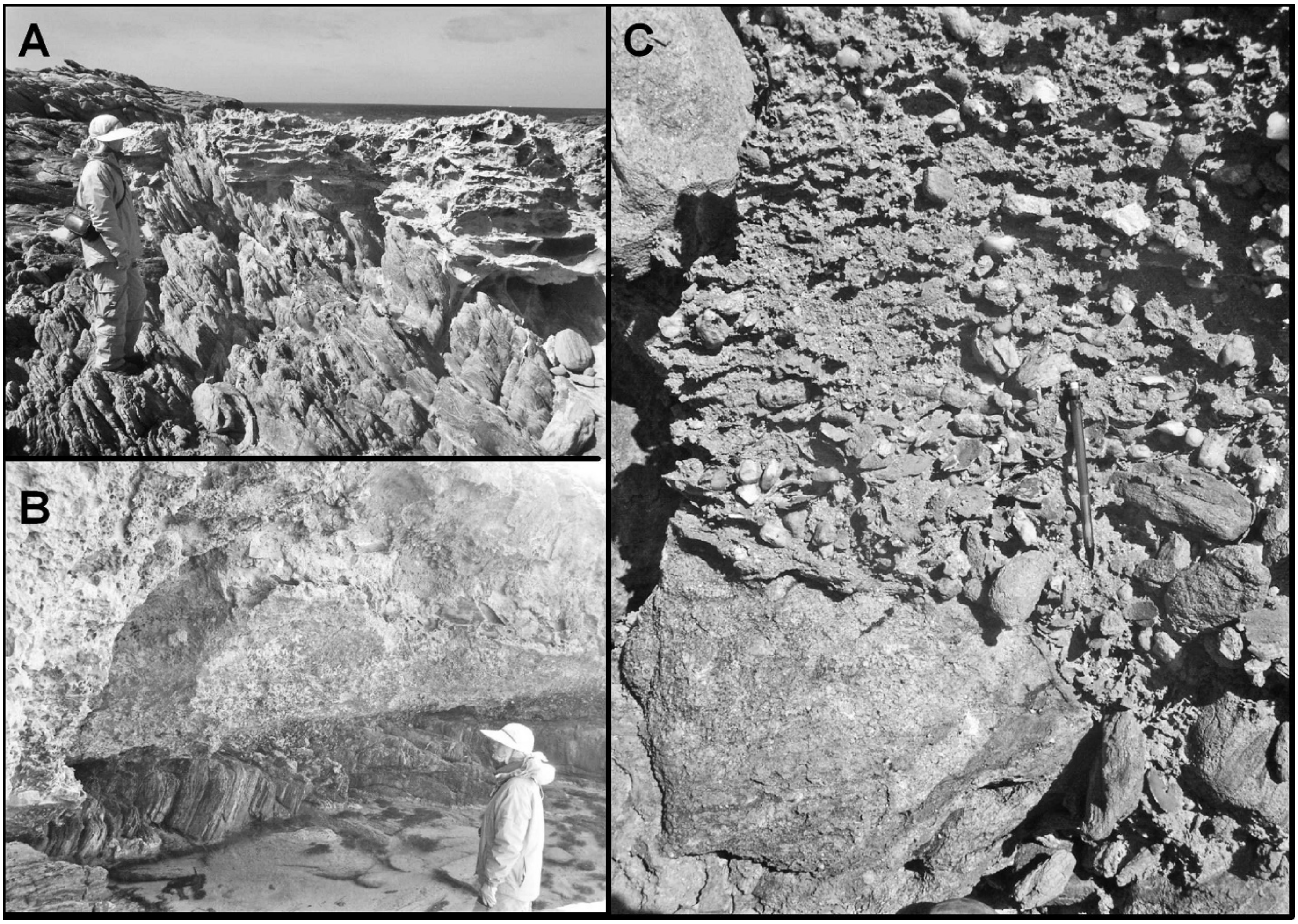

Figure 9. A – Bridgewater Formation eolianites lying directly on deformed Kanmantoo Group basement rocks. The Point Ellen Formation is missing. The location is where the photograph of Figure 8A was taken, seaward of the main outcrop by about 30 m. B. – West (left) around the point shown in the far left of Figure 8A, the Point Ellen Formation rests on a planated bench of Kanmantoo Group basement rocks. Weathered boulders and cobbles of Kanmantoo Group basement rocks are visible 1 to 2 m above the contact. C – Point Ellen Formation rocks, with abundant subtidal fossils, intermixed with, and overlying, Kanmantoo Group basement rocks present as boulders and cobbles. Pencil is 15-cm-long for scale.

soil. A talus formed along the former sea cliff. Based on Bahamian examples, the minimum time frame for terra-rossa palesol development would be in the 50 to 100 ka range (Carew and Mylroie, 1997). Subsequently, the Point Ellen Formation was entombed by Bridgewater Formation eolian calcarenites that overrode the unit, overrode the talus deposit, and extended on to the Kanmantoo Group basement rocks at a sea level lower than present.

The outcrop also has a cave in it (Figs. 8A and 8C). This cave is within reach of storm waves. It is difficult to determine if the cave is a breached flank margin cave or a sea cave. The cave contains floor to ceiling columns that are not speleothems, but rather remnant solution pipes (Milnes et al., 1983). Because the column walls became micritized when they were part of an active epikarst, they are now stronger than the host rock and weather out in relief (Fig. 11). Such features are common on coastal South Australia in Bridgewater Formation eolian calcarenites. The survival of these columns within a cave allows their connection to the original epikarst surface to be observed. The solution pipe columns to the east (right facing into the cave) are made up of paleosol material (Fig. 11C), but to the west (left facing into the cave) the material is strongly-indurated Point Ellen material that the solution pipe had drilled into (Fig. 11B). The correct interpretation of the cave is important. If it is a sea cave, produced as a result of storm activity on this coast, then it is a Holocene feature. If it is a flank margin cave, then it is at least 125 ka old and formed on the last interglacial sea-level highstand (MIS 5e). As benches at 3 m elevation from the last interglacial are reported on the southern shore of Kangaroo Island (Short and Fotheringham, 1986; Twideale and Bourne,

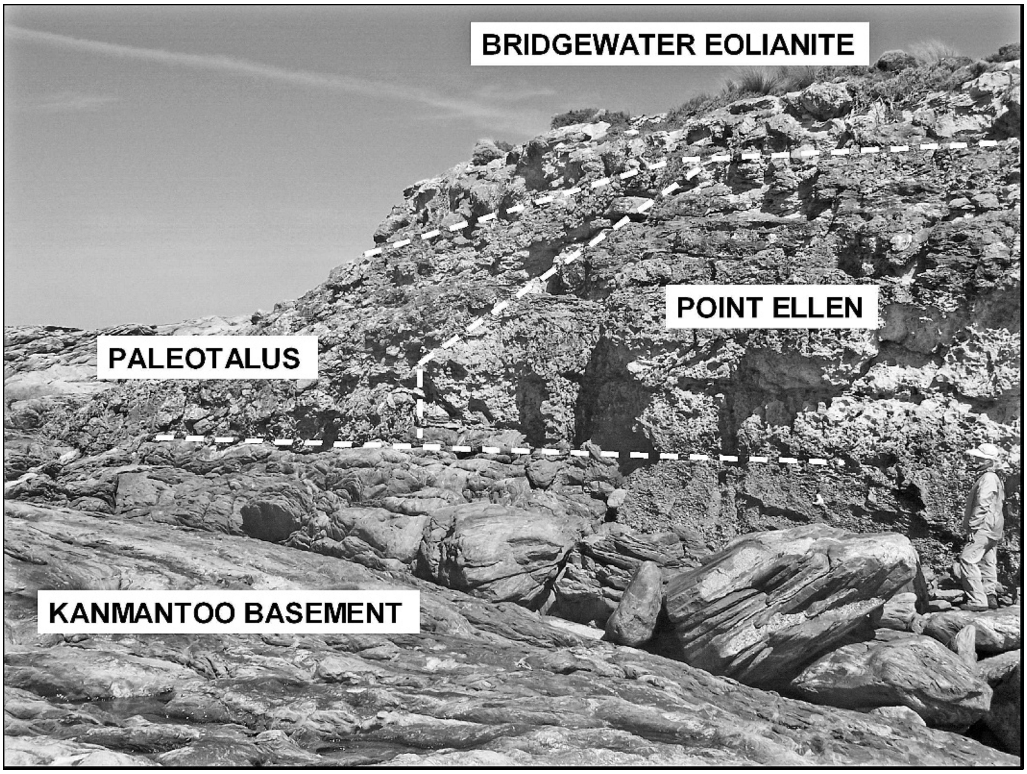

Figure 10. Outcrop section at Point Ellen, the left portion of Figure 8A. Kanmantoo Group basement rocks at the bottom, passing through a rubble facies into Point Ellen Formation marine carbonates. A paleo-cliff separates the Point Ellen Formation laterally from a paleo-talus to the left (south). Bridgewater Formation eolianites overlie the Point Ellen Formation and the paleo-talus unit. Seaward (left or south) of this location, the Bridgewater Formation eolianites overlie the Kanmantoo Group basement rocks directly, as shown in Figure 9A.

2002), a fresh-water lens could easily have existed in this outcrop during the last interglacial and a flank margin cave formed. If these benches, and the cave, are truly last interglacial, then uplift over the last 120 ka has been minimal and the uplift at Snake Creek was at least 30 m and occurred prior to MIS 5e.

Remarkable Rocks

The tafoni developed in Cambro-Ordovician granite at Remarkable Rocks (Figs. 1 and 12) provide a cautionary tale. The interior of several of the larger tafoni have wall sculpture that is especially cuspate and dimpled and bare a striking resemblance to dissolutional wall morphology as found in flank margin caves (Fig. 12C versus Fig. 12D). They also have been misidentified. Twidale and Bourne (2002, their Figure 14c) presented a photograph of the interior of a tafoni at Remarkable Rocks, calling the wall surface mammillated. This error is a result of printing the picture upside down, such that lighting and shadows invert the apparent relief in the picture. The features are clearly cuspate and not mammillary, as seen in Figures 12B and C. Because such cuspate features are part of the visual inventory used to define a cave in limestone as phreatic in origin, the Remarkable Rocks example indicates that multiple lines of evidence should be used to identify a cave's origin. A review of tafoni, their mechanisms of formation, and the techniques utilized to differentiate them from dissolutional caves can be found in Owen (2007).

Hanson Bay

The east side of Hanson Bay (Fig. 1) begins as a stretch of beach, and gradually trending southeastward, becomes a high eolian ridge with sea cliffs down to the ocean below. High up on these cliffs are a series of planated notches (Fig. 13A) that could easily represent small wave-eroded platforms. The platforms have a rubble deposit of rounded clasts in a grey matrix (Fig. 13B). These are clearly not a paleosol layer, in which the clasts would be more angular and the matrix would carry the red color of a terra rossa paleosol. Such deposits, when found in the Bahamas, indicate a back beach or rock platform rubble facies (Florea et al., 2001). It is therefore likely that these notches indicate a sea-level highstand approximately 30 m to 35 m above modern sea level, which would require tectonic uplift. Such a sea-level interpretation supports the observations of flank margin caves at similar elevations at Snake Lagoon to the west.

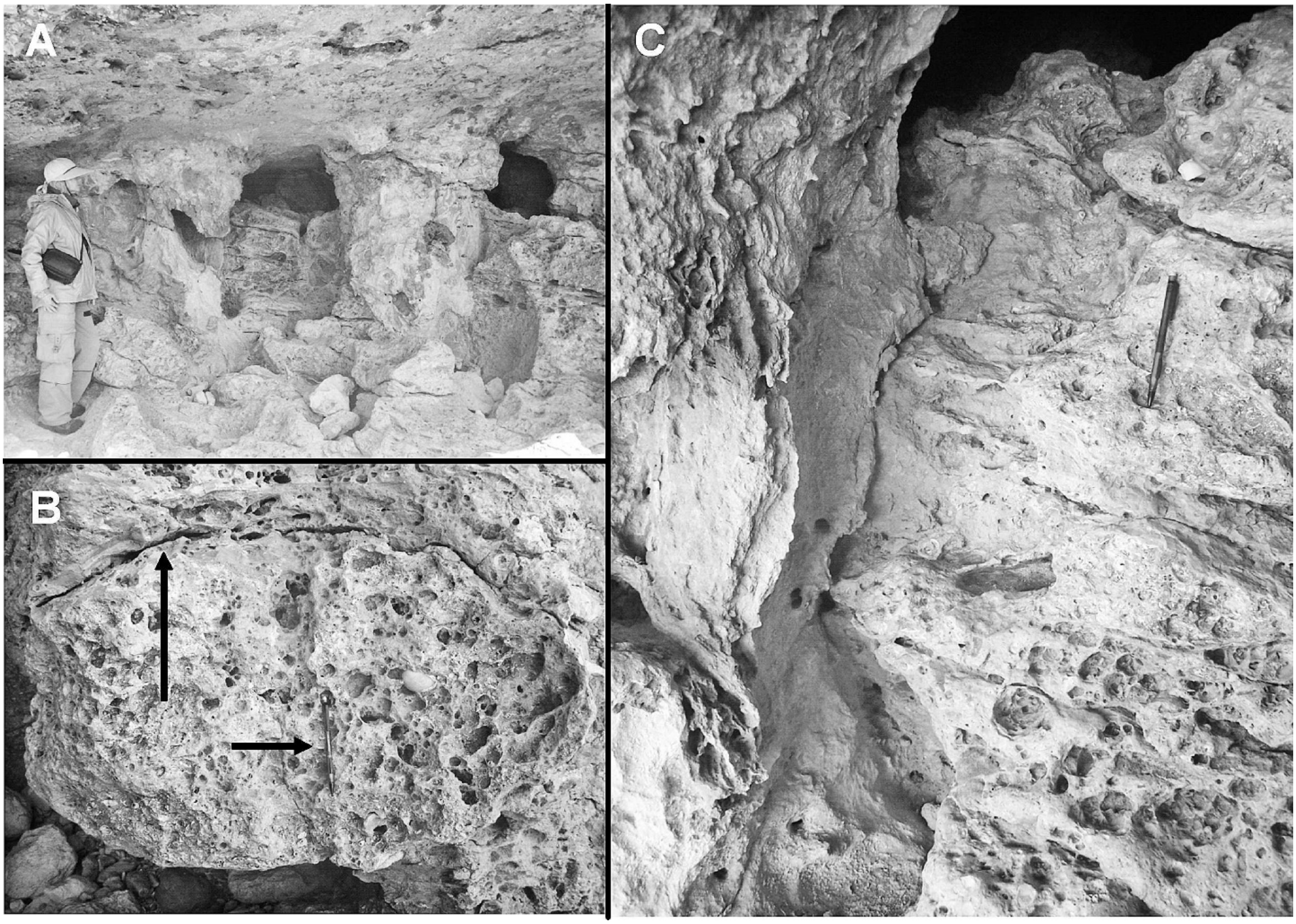

Figure 11. The cave at Point Ellen. A – Looking into the cave, with the Bridgewater Formation eolianites forming the cave roof, and infilled solution pits descending into the Point Ellen Formation. B – Close up of Bridgewater Formation eolianites on top of Point Ellen marine carbonates. The contact is the upward convex line arching through the top portion of the photograph (long vertical arrow). Pencil is 15-cm-long for scale (short horizontal arrow). C – Vertical contact of Bridgewater Formation eolianites and paleosol infilling a solution pit to the left, with Point Ellen Formation marine carbonates to the right. Pencil is 15-cm-long for scale.

Summary

The observations made on Kangaroo Island in September 2006 are admittedly cursory and superficial. They consist of simple visual descriptions at the macroscopic scale, without detailed site survey or rock-sample analysis. On the other hand, the simple observations allow new interpretations to be offered that may help illuminate geologic processes on the island. None of the previous workers who interpreted the Cainozoic geology of Kangaroo Island utilized the potential data stored in caves on the island.

It is clear that flank margin caves are present on Kangaroo Island, and this paper is the first report of their existence there. The positions of the flank margin caves at Snake Lagoon reveal sea-level highstands of at least three elevations: ~25 m, ~30 m, and ~35 m, substantiating early claims by Bauer (1961) that Twidale and Bourne (2002) later called into question. The absence of flank margin caves from many high-energy coasts underlain by Kanmantoo Group rocks verifies the vulnerability of flank margin caves to destruction by powerful wave-generated slope-retreat processes. In such locales, flank margin caves are preserved in embayments and surface water course incisions, as at Snake Lagoon, or by offshore barriers, as at Cape du Couedic. Observations from Hanson Bay show marine erosion features consistent with development during one or more sea-level highstands at approximately 30 m to 35 m, concurring with observations at Snake Lagoon, which would require tectonic uplift.

At Cape du Couedic, an arch in Bridgewater Formation eolianites resting on Kanmantoo Group rocks is presented to the public as being the result of wave erosion with wave energy being focused on the point by the presence of the

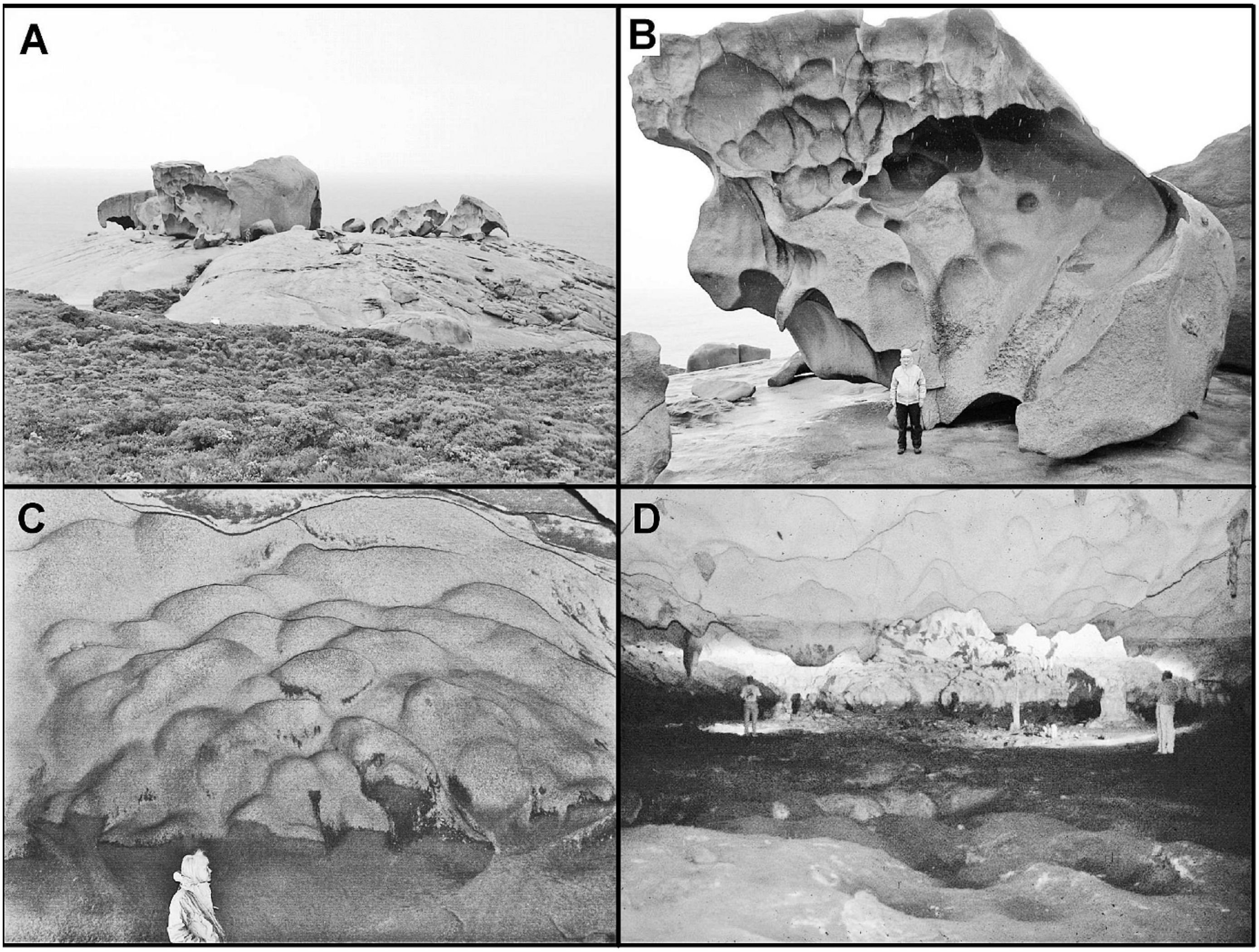

Figure 12. Remarkable Rocks. A – The Remarkable Rocks, where tafoni have developed in granitic rocks. B – Classic cavernous weathering to produce a complicated tafoni. C – Inside one of the larger tafoni, with pockets or cusps eroded into the ceiling. D – Chamber in Salt Pond Cave, Long Island, Bahamas, in eolian calcarenites, showing the pockets and cusps considered as one of the diagnostic indicators of cave formation by phreatic dissolution. Compare with Figure 12C. Two people in background, left and right, for scale.

islands offshore. The evidence from the eolianite portion of the arch suggests that the original void formed as a flank margin cave and was subsequently breached by wave erosion. The offshore islands not only acted as a focusing mechanism for wave energy, but also provided a barrier function that has prevented the entire eolianite section at Admirals Arch from being removed by wave erosion.

At Point Ellen, a cave has been useful in interpreting the stratigraphic section of eolian, marine, and basement rock relationships. The preserved fossil epikarst and paleosol at this location place boundary conditions on the timing of the carbonate-depositional events. A paleo-talus is described here for the first time. The cave itself is indeterminate in origin, but if it is a flank margin cave, it would provide a second line of evidence to suggest that uplift on Kangaroo Island has been minimal for the last 120 ka. Remarkable Rocks demonstrate how non-dissolutional erosive forces can produce surfaces in tafoni that mimic one of the classic indicators of flank margin cave development, and as such, are a warning about using single lines of evidence to make important cave origin interpretations.

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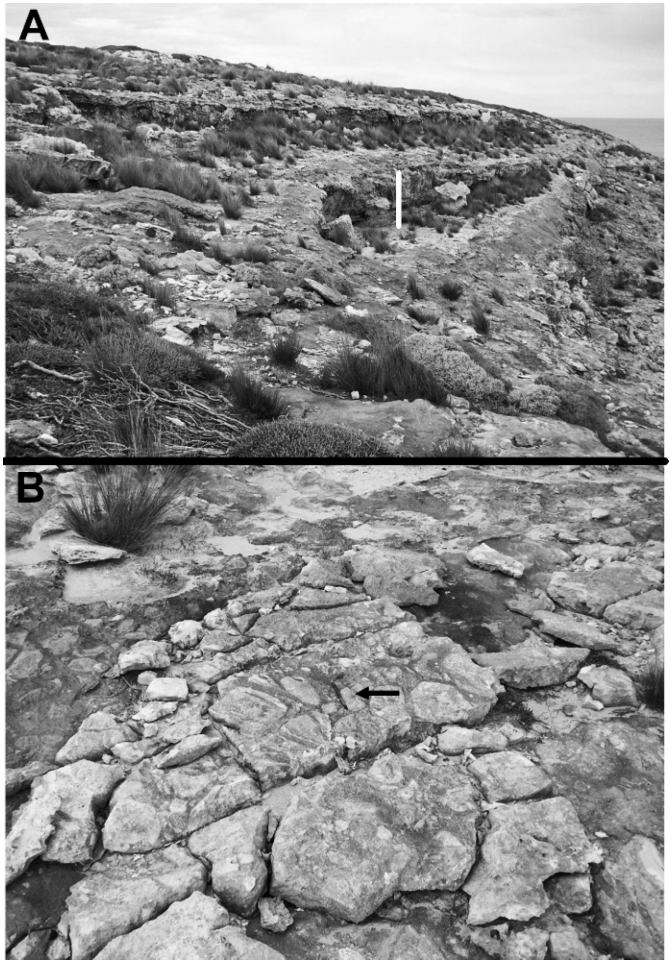

Figure 13. Hanson Bay. A – Long, linear and level notches cut into the eolianites of the Bridgewater Formation. Vertical white bar 1-m-long for scale. B – Rubble facies found on the floor of the notches shown in Figure 13A. The matrix is sandy and white or gray, not red, and the clasts are more rounded than normally seen in a paleosol, and are interpreted as a back-beach rubble facies. Pencil 15-cm-long for scale (black arrow, same length as the pencil).

provided significant logistical support and important scientific insight.

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