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FLANK MARGIN CAVE DEVELOPMENT AND TECTONIC UPLIFT, CAPE RANGE, AUSTRALIA

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Abstract: Cape Range, Australia, on the northwest coast of the continent at 21° S, 113° E, is a north-northeast-striking anticlinal ridge 315 m high, 130 km long, and 32 km wide extending into the sea and consisting of Miocene carbonate rocks with a series of coastal terraces of Pliocene and Quaternary carbonates and siliciclastic dunes. Inland escarpments, representing former sea cliffs, and deep valleys cutting the limbs of the anticlinal ridge host many cave entrances at a variety of elevations. The lowest unit, the Mandu Formation, a chalky and marly limestone, contains many tafoni (pseudokarst) caves with simple, single-chamber plans and widths up to 15 m or more and height up to 10 m. The higher, purer Miocene limestones and the younger Pliocene and Pleistocene coastal terrace limestones host numerous flank margin caves from 300 m elevation in the Miocene rocks to sea level in the Quaternary rocks. These caves have entrances up to 30 m wide and heights of 6 m, with single-chamber caves being common, but complex caves are also present. Some caves are entered by small entrances that lead to large phreatic chambers, which eliminates both sea cave and tafoni as possible explanations. The close association of these caves with sea cliffs and incised valleys argues against a deep hypogene origin, which would leave a cave pattern unrelated to the surface configuration. Miocene uplift tapered off into the Pliocene. The flank margin caves in the paleo sea cliffs represent the outcome of the interplay of tectonic activity and glacioeustasy over a 300 m vertical range, with lowstands causing valley incision, while highstands raised the fresh-water lens and allowed cave development in the valley walls. Cave development began with the first tectonic-driven subaerial exposure in the Miocene and continued through to the last Pleistocene interglacial.

Introduction

A May 2014 expedition to Cape Range at North West Cape of Australia was conducted to look into what the flank margin caves of Cape Range could reveal about the timing of the uplift of the range and the interaction of that uplift with eustatic sea-level change in the Miocene. These results could be informative about the earliest time for cave generation and put an upper time limit on the colonization of Cape Range caves by troglobitic organisms. The research could also assist in other questions about karst development in an active tectonic setting on a continental margin. This expedition was a reconnaissance designed to provide an overview of cave configuration and setting at Cape Range, with a goal of determining what speleogenetic hypotheses can be constructed for later testing. The interpretations presented here are therefore preliminary and speculative. Much more field data are necessary to derive solid conclusions, and the ideas expressed here will help guide future work.

The Cape Range peninsula, or North West Cape, is located along the northwestern coast of Western Australia, from south latitude 21° 45′ southward to 22° 30′ and from east longitude 113° 30′ to 114° 15′, the largest inhabitation being the town of Exmouth (Fig. 1). Cape Range is bounded by Australia's longest fringing reef, the Ningaloo Reef. The range is constructed of Miocene to Quaternary sedimentary rocks, primarily limestones that have been compressed by tectonics into an anticlinal ridge that forms the axis of the peninsula, striking north-northeast. Cape Range was the location of the first producing oil well discovery, in 1953, in Western Australia, with a further 36 wells being drilled there up through 1995 (Collins et al., 2006). The interest of the petroleum industry in this region has helped produce a series of geological studies (e.g., Crostella, 1996), while more recently tourism has focused interest on biological and ecological studies (e.g., Humphreys, 1993).

Cape Range has a range of monthly average temperatures from 17 to 27 °C, with a maximum temperature of 45 °C frequently occurring in January (Collins et al., 2006). Rainfall is approximately 300 mm annually, and some of the rainfall occurs as single events from cyclones and mid-latitude depressions; but evaporation is 1700 to 3050 mm annually, creating a severe water deficit (Collins et al., 2006). Just prior to this expedition, a catastrophic rainfall event caused major flooding in the area, with destruction of roads, buildings, and bridges.

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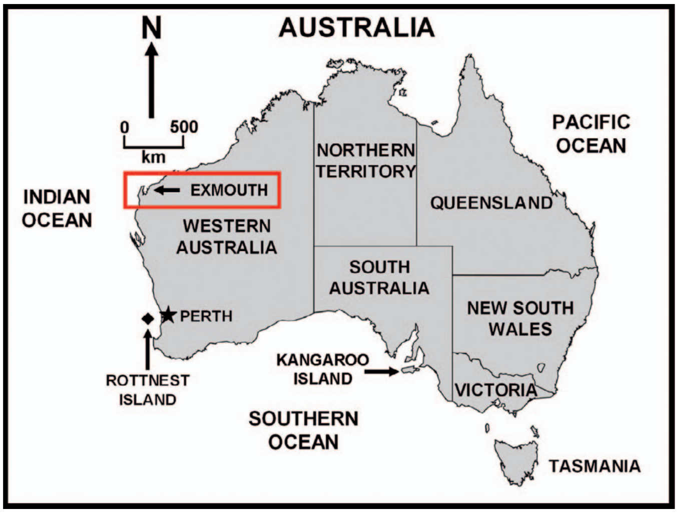

Figure 1. Map of Australia with the location of the Cape Range highlighted.

The Geology of Cape Range

Cape Range and Exmouth Gulf to the east are part of the larger Carnavon Basin, where post-Eocene faulting has resulted in compression and folding of basin sediments (Collins et al., 2006), forming anticlinal ridges and domes separated by synformal lowlands. The Cape Range anticline that forms North West Cape is 130 km long and 32 km wide, with a maximum elevation of 315 m (Whitney and Hengesh, 2015). The ridge is greatly dissected by stream valleys (Fig. 2), which creates significant local relief given the proximity of sea level. The Cape Range anticline is separated from the adjacent Rough Range anticline to the southeast by the Bundegi and Patterson-Learmouth faults (Van de Graaff et al., 1976).

The northward drift of the Australian continent since the Middle Eocene resulted in the deposition of carbonate units in the Cape Range area beginning in the Oligocene, with folding initiated in the Miocene as carbonate deposition continued (Allen, 1993). The geologic section of interest (Fig. 3) follows that of Allen (1993), with late Oligocene to early Miocene limestones resting unconformably on earlier units not exposed at Cape Range. In Cape Range, the lowest exposed unit is the Miocene Mandu Calcarenite (also known as the Mandu Limestone or the Mandu Formation), a chalky to marly calcarenite, calcisiltite, and calcilutite with moderate amounts of quartz and up to 25 % clays, 280 m thick, and deposited in water about 120 m deep (Chaproniere, 1975). The overlying Tulki Limestone is a coarse-grained calcarenitic, muddy foraminiferal packstone, and mud-free grainstone almost 100 m thick, deposited in shallow waters about 12 m in depth (Chaproniere, 1975). The Trealla Limestone overlies the Tulki Limestone, but the actual contact may be difficult to distinguish unless the faunal assemblages are examined; it is 20 m thick (Collins et al., 2006). The unit is most clearly expressed on the east side of Cape Range, whereas on the west side it interfingers with the Pilgramunna Formation, a quartz-rich bioclasitc grainstone 25 m thick (Chaproniere, 1975) that may have formed as a lagoonal barrier to the west (Collins et al., 2006). The final Miocene unit is the Vlaming Sandstone, 65 m thick, a well-sorted calcarenite with significant quartz content (Collins et al., 2006). The Vlaming is restricted to the west side of the range.

Marine-carbonate deposition on the axis of the Cape Range anticline had ceased by the Late Miocene, when uplift created subaerial exposure (Collins et al., 2006), and the subsequent Plio-Pleistocene depositional processes in this area were dominated by eolian sands, both calcitic and quartzose. The margins of the Cape Range anticline accumulated fringing lagoonal deposits, as continued uplift created terraces separated by escarpments (Fig. 4). These terraces are overlain by the Exmouth Sand, a fine- to medium-grained calcarenite with a basal coarse-grained to pebbly quartzose calcarenite and with local coral boundstones unconformable on the terrace below (Collins, et al., 2006). This sequence is interpreted to be a transition from sublittoral to eolian depositional environments, with the Muiron Member and Milyering Member of the Exmouth Sandstone occupying the top and penultimate terraces, respectively (Van de Graaff et al., 1976). The lower two terraces are occupied by the Jurabi (higher) and Tantabiddi (lower) Members of the Bundera Calcarenite and contain extensive coralgal reef deposits (Collins et al., 2006). The Jurabi Member is dominated by coralgal boundstone considered late Pliocene based on the occasional shark's tooth (Wyroll, et al., 1993); the Tantabiddi Member contains lagoonal carbonate gravels and sands and is late Pleistocene (MIS 5e) based on a U/Th age of 132–127 ka (Collins et al, 2006). Whitney and Hengesh (2015) provide a compilation of Western Australia U/Th dates from late Pleistocene fossil reefs and provide an age range of 130–117 ka with a mean age of 123.5 ± 6.5 ka. The Bundera Calcarenite underlies most of the coastal plain that fringes Cape Range. It consists primarily of calcarenite to calcirudite with coralgal reef deposits. The Mowbowra Conglomerate Member of the Bundera Calcarenite is a limestone pebble conglomerate (locally a fanglomerate) that contains minor coralgal reef deposits and well-sorted calcarenite. It forms an extensive veneer over the lower terraces and hosts unusual karren (Fig. 5), indicating that surficial denudation by karst processes has lowered the land surface. Whitney and Hengesh (2015) indicate that tectonic movement is still active at Cape Range, with both uplift and subsidence occurring, with respective ranges of 0.049 ± 0.030 mm yr^{-1} for uplift locations and –0.013 ± 0.034 mm yr^{-1} for subsidence locations. As they assumed no karst denudation, which would place the dated corals at a higher elevation than measured today when first emergent, these estimates are therefore a minimum value. While denudation rates for uplifted MIS 5e coral terraces on Guam have been measured at 0.064 mm yr^{-1} (Miklavič et al., 2012), Guam is a moist tropical island. Cape

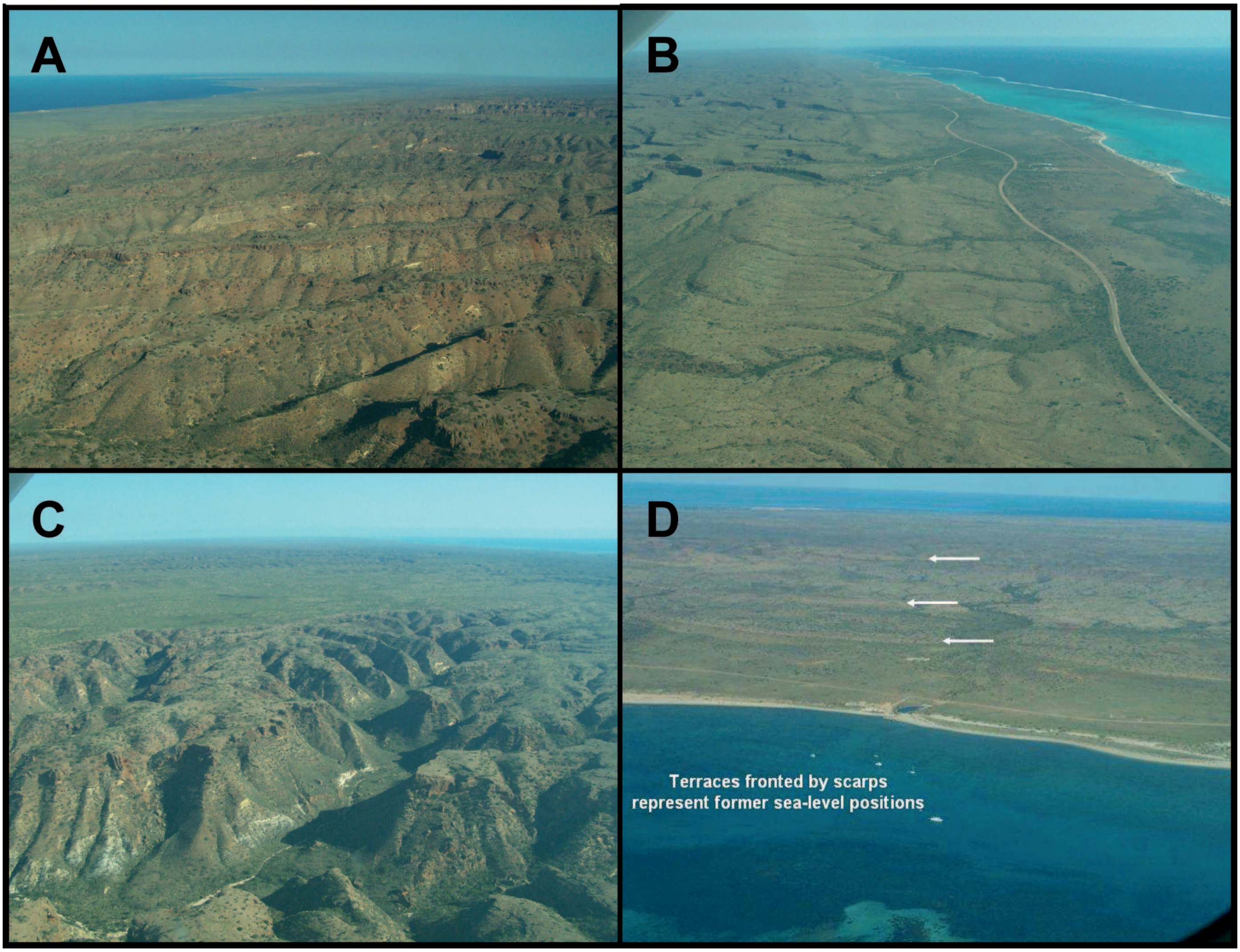

Figure 2. Low-altitude aerial photographs of the Cape-Range peninsula. A. Looking south along the east coast of the range, with the gentle anticline rising to the crest at the right side of the image. B. Looking south along the west coast of the range, with the gentle anticline rising to the crest at the left side of the image; note also the terraces. C. Closer image of the deep stream-valley incisions into the anticline. D. View eastward across the peninsula, with terraces and their associated scarps indicated by white arrows.

Range is an arid environment with a negative water budget, so denudation rates would be expected to be much less.

The Cave Question

The existence of epigenic stream caves in Cape Range is well established, and caves with lengths of multiple kilometers and depths over 100 m exist (e.g., Brooks, 2009; Fig. 6). However, these caves are quite cryptic, with vertical entrances commonly not in agreement with current landscape topography. Most obvious to the casual observer are the many cave entrances in the cliffs fronting the sea on the east and west sides of the peninsula and within the walls of valleys and gorges that drain the anticlinal ridge that forms Cape Range (Fig. 7). These caves appear to be of two types (Fig. 8), tafoni, pseudokarst caves formed by wind and subaerial weathering (Owen, 2013), and flank margin caves, formed in a discharging fresh-water lens (Mylroie, 2013). Superficially, both cave types look similar, having entrances that are usually wider than they are high and being a single, open chamber. However, tafoni usually have a maximum interior width that is little more than the entrance width and rarely have more than a single, simple chamber (Waterstrat et al., 2010; Owen 2013). Their configuration reflects their origin from the outside in by surficial processes. The existing caves could also be sea or littoral caves, formed by wave action against a rocky shore. Sea caves are also formed by an outside in mechanism similar to that forming tafoni. As a result, the entrance width and maximum width tend to be similar, and the interior

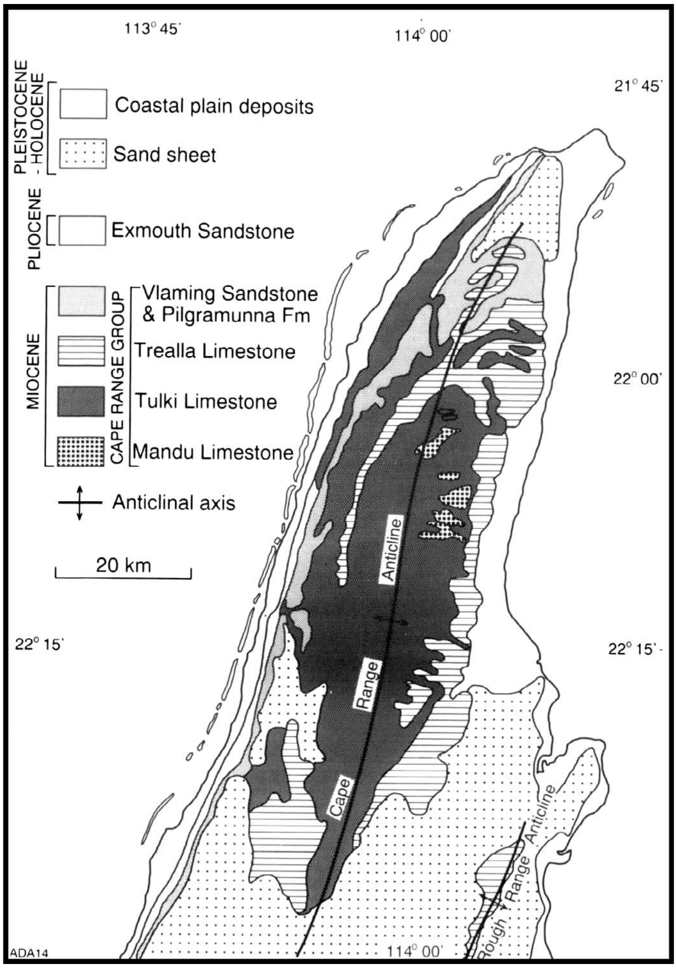

Figure 3. Geologic map of the Cape Range, showing the Miocene carbonate units and the anticline that forms the range. From Allen (1993).

morphology is simple compared to true karst caves, lacking dissolutional cusps, thin bedrock pillars and partitions, and complex passage connections. Waterstrat et al., (2010) discuss in detail the criteria for separating sea caves and tafoni from flank margin caves. Sea caves are tied to the exterior of the rock mass they form in, derived from the interplay of wave dynamics, tidal activity, and the rock's mechanical characteristics. As a result, once uplifted, sea caves are more vulnerable to removal by surface erosion than are flank margin caves, which are initially not exposed. It is unlikely that the caves of the narrow interior gorges are sea caves, as wave energy dynamics in such an enclosed water body most likely would not produce the necessary mechanical erosion forces required for sea-cave development.

Flank margin caves commonly have more elaborate chamber patterns and can be a series of chambers, only one of which may connect to the outside (Fig. 9). Entrances can be very small, leading to chambers with elaborate phreatic sculpturing, including wall pockets and cusps, bedrock pendants and arches, and oval side passages called *rimouts* (Fig. 10). Because flank margin caves form in the discharging margin of the fresh-water lens, under the flank of the enclosing landmass (hence the name), they are very vulnerable to breaching by surficial erosion processes. This mechanism also means that the caves form from the inside out. As scarp or slope retreat occurs, the caves are first tangentially intersected to form a small entrance. As scarp and slope retreat continue, the entire outer wall of the cave may be removed, creating a chamber with an entrance width close to that of the maximum chamber width. Such a large entrance allows external weathering processes to influence the cave interior. In this manner, flank margin caves can decay into apparent tafoni by this overprinting action, confusing the observer as to the true origin of the cave. In active coastal regions, breaching of flank margin caves by marine processes can also lead to overprinting to produce a hybrid cave (*sensu* Kambesis and Machel, 2013). A fractal analysis of cave types (Kambesis et al., 2015a) has demonstrated that caves of epigene, hypogene, flank margin, tafoni, and littoral origin can be separated from each other by analysis of their fractal dimension and lacunarity as provided by cave maps.

In the Cape Range, the tafoni appear to be lithologically biased, being formed mostly in the Miocene Mandu Formation, a marl that underlies purer limestones higher in the section. Those upper limestones, primarily the Tulki Limestone across the range and, above it, the Pilmagrunna Limestone on the west side and the Trealla Limestone on the east side, host what appear to be primarily flank margin caves and only a few tafoni. The Mandu Formation also appears to host a few flank margin caves (e.g., Fig. 7D); its marly characteristics make it an aquitard, and springs are perched on its upper contact with the Tulki Limestone. Dissolution caves of indeterminate origin also underlie the coastal plain on both sides of the Cape Range, some developed in Quaternary limestones.

Flank margin caves are found on the cliffs of the incised valleys and in the cliffs that front each of the coastal terraces (Fig. 2). From top to bottom, the caves are found fronting the Muiron Terrace, the Milyering Terrace, the Jurabi Terrace, and the Tantabiddi Terrace (Fig. 4).

Flank Margin Cave Origin in Cape Range

The morphology of the dissolution caves in the paleo sea cliffs and gorge walls of Cape Range indicates that most are undoubtedly phreatic in origin. They are almost certainly not epigene caves, having no conduit-flow pattern, wall scallops, or fluvial sediments and lacking a clear higher-elevation input to lower-elevation output plan. This exclusion of an epigene origin leaves two possibilities. First, the caves could be classic hypogene caves formed at depth by aggressive fluids in a laminar-flow system and now uplifted and breached by surface processes. Or they could be flank margin caves, and a fresh-water lens laminar-flow discharge produced the caves, formed when sea level was at the elevations where the caves are now

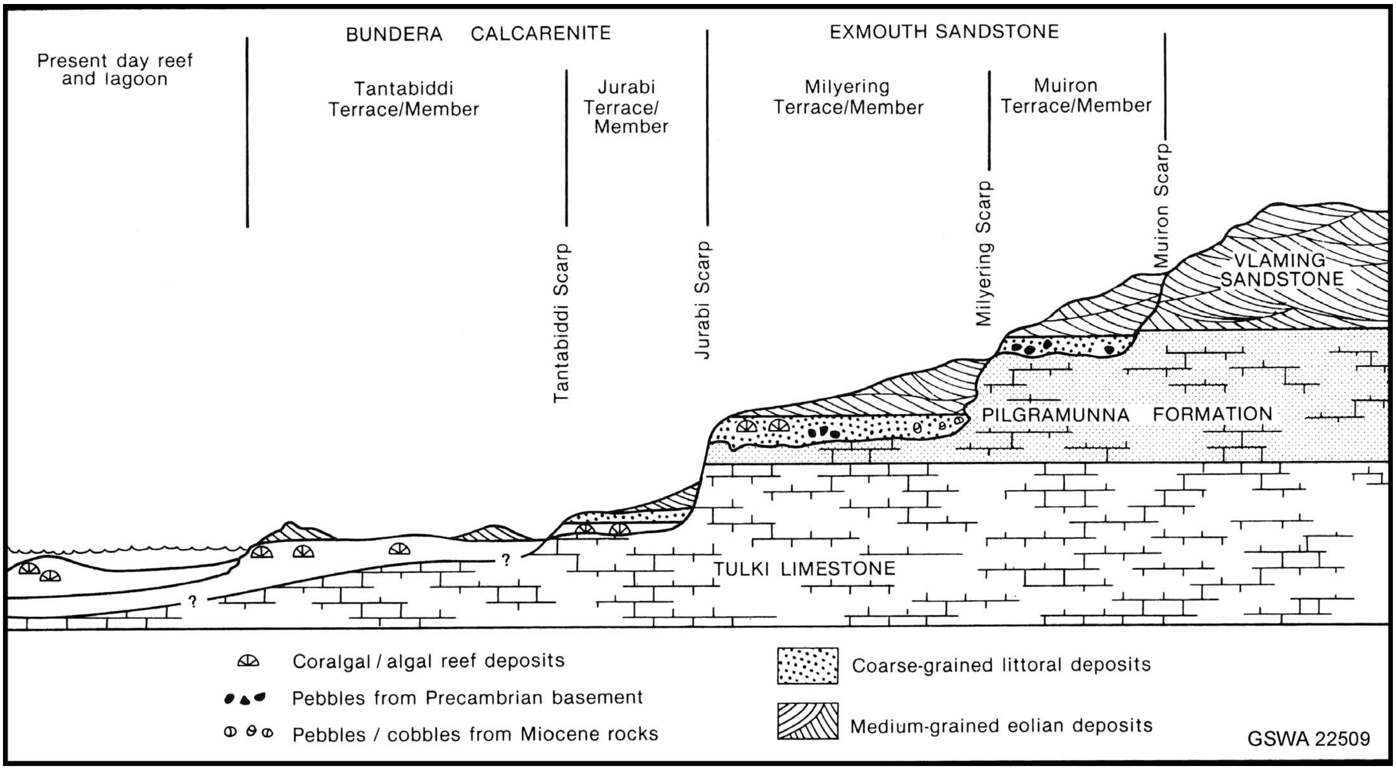

Figure 4. Depiction of the terraces and scarps on the west side of Cape Range, with Quaternary units stacked on terraces cut into the Miocene limestones. Vertical range displayed is approximately 110 m. From Van de Graaff et al. (1976).

found or perhaps at lower elevations from which they have been uplifted to their present position.

If the caves are hypogene in origin, their current expression on the cliffs and gorge walls is an accident of random intersection by surficial processes. If they are flank margin in origin, tied to the flank of the land, then the cave distribution should be controlled by the orientation of that flank, be it a paleo sea cliff fronting a coastal terrace or a gorge wall. The field work of the expedition indicates that the caves exist in a pattern that reflects the cliffed environment in which they are found. The long axis of the cave is almost always parallel to the cliff in which they are located (a few exceptions do exist, such as Adit Cave). Hypogene caves should follow a regional joint trend and be independent of the sea-cliff and gorge-axis directions, except to the degree to which jointing controls those features. Hypogene caves should have their long axis either at random or along the regional joint set. The caves in the cliffs do not show any secondary indicators of hypogene development, such as residual native sulfur, gypsum, or calcite spar wall coatings.

If one eliminates pseudokarst tafoni and sea caves and also eliminates epigene and hypogene caves, only flank margin caves remain. The observed caves contain all the features associated with flank margin caves. The Cape Range flank margin caves are not as individually extensive as those found in other well-known flank margin cave settings, such as the Bahamas (Mylroie and Mylroie, 2009a) or Isla de Mona (Frank et al., 1996). Cave chambers in the Cape Range can be large, 30 m or more long in the cliff-parallel axis and 15 m or more deep into the cliff, with ceiling heights up to 6 m, but the caves are usually not complex chamber associations with numerous passage interconnections. Large but simple flank margin cave patterns are associated with limited lens stability time, meaning that as the caves were forming, sea level changed and the cave is either abandoned if sea level dropped or flooded by non-speleogenetic marine water if sea level rose. This type of flank margin cave development is observed in the Mariana Islands (Jenson, et al., 2006), Barbados (Kambesis and Machel, 2013), Curaçao (Kambesis et al., 2015b), Kangaroo Island, Australia (Mylroie and Mylroie, 2009b), and in Mallorca island (Mylroie, et al., 2015), areas with active tectonics. Flank margin cave development as a result of tectonic influence on a passive continental coast has been presented for the Naracoorte karst area in Southeastern Australia (White and Webb, 2015).

The flank margin caves in Cape Range with the greatest degree of passage complexity are found at lower elevations, in what appear to be paleo coastal positions. There are two explanations. One is that the sea level was stable for longer periods of time at the lower elevations and the increase in lens-stability time allowed a longer duration for flank margin caves to mature. This longer stability time would be consistent with a decreasing tectonic uplift rate, given that uplift is believed to have been completed by the Pliocene (Wyrwoll, et

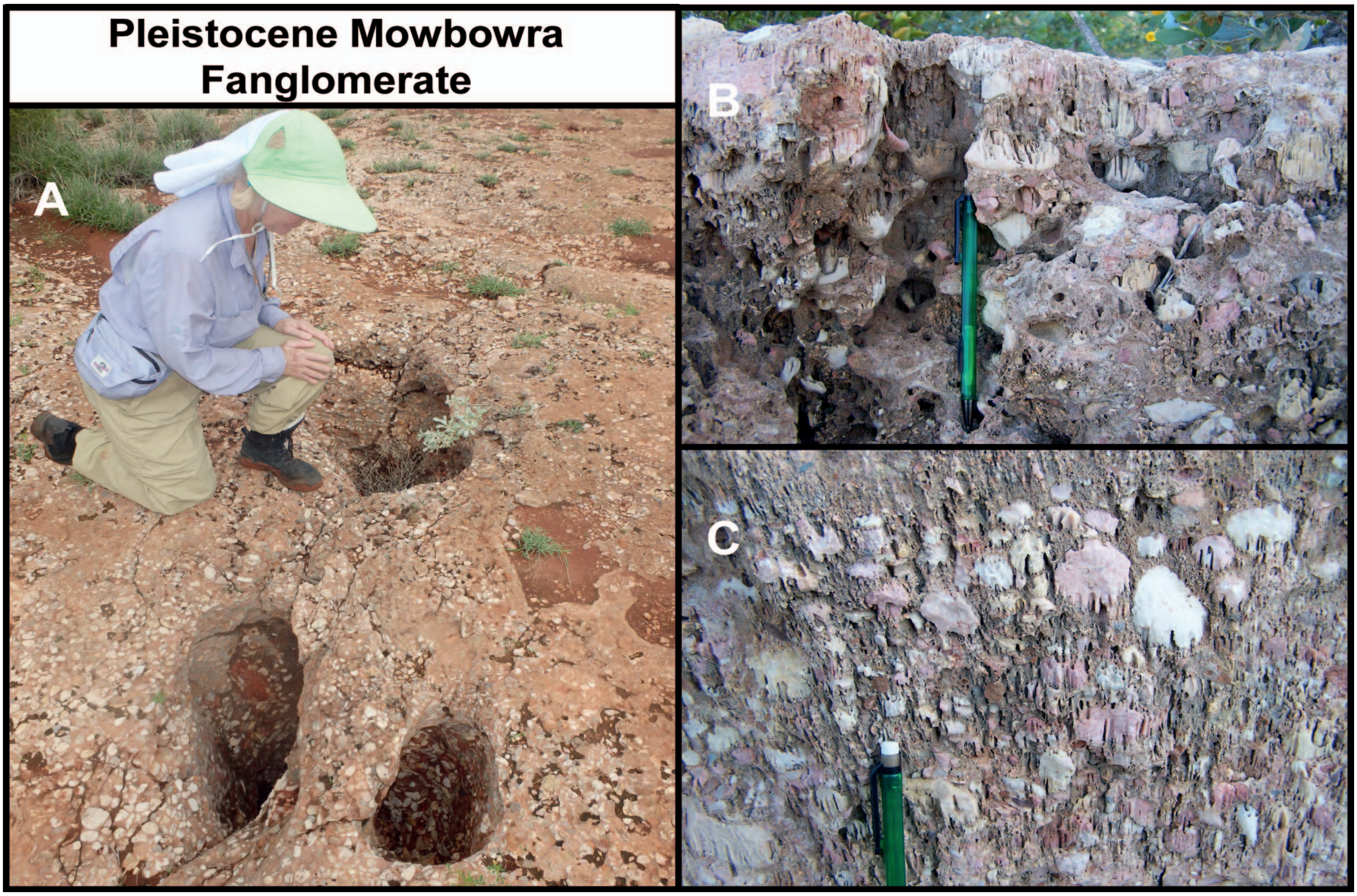

Figure 5. Karren in the Pleistocene Mowbowra Fanglomerate, east side of the Cape Range. Both the clasts and matrix are dominated by carbonates. A. Dissolution holes that cut through both clasts and matrix. B. Vertical ledge showing the variety of clasts (pencil 14 cm long for scale). C. Close-up of the unusual dissolution pattern produced in the carbonate clasts (pencil as in B for scale). The amount of dissolution shown is an indication that karst denudation has been significant, even in relatively young Pleistocene deposits.

al., 1993), or if it has continued (Whitney and Hengesh, 2015) it has done so at a slow rate. The second explanation is that the high-level caves in the gorges are older, more degraded by surficial erosion, and have lost some of their original length and complexity; in their original state they would have been similar to the lower elevation paleo sea cliff caves. The observed configuration of the higher-elevation caves would, however, indicate that the main chambers observed today are the original chambers and that there has been little loss of cave complexity. If correct, this observation indicates that lens-stability time varied, being shorter for older, high-elevation caves and longer for younger, low-elevation caves, consistent with a declining tectonic uplift rate.

Flank Margin Cave Genesis and Cape Range Geologic History

Accepting for the moment that the observed caves in the purer limestones (i.e., excluding the Mandu Formation) are flank margin caves, then what is the scenario that would allow their development on both the paleo sea cliffs and gorge walls? The paleo sea-cliff position is easy to explain. As the limestones of Cape Range were exposed subaerially, meteoric catchment and establishment of a fresh-water lens could occur. Once the lens was established, it discharged to the sea, and flank margin caves could form. As uplift continued or sea level fell eustatically, the initial suite of flank margin caves would be abandoned, and new ones would form at a lower level within the limestones. This model works well to explain flank margin caves on tectonically uplifted islands around the world, such as Barbados, Curaçao, Guam, and Mallorca, as noted earlier.

The situation for flank margin caves found in the gorge walls deep into the interior of Cape Range is more problematic. Recently, a model to explain gullies on Barbados, *bokas* on Curaçao, and *calas* on Mallorca, all cliffed rectilinear re-entrants in coastal limestones, has been developed (Mylroie, 2013). The basic model argues that if

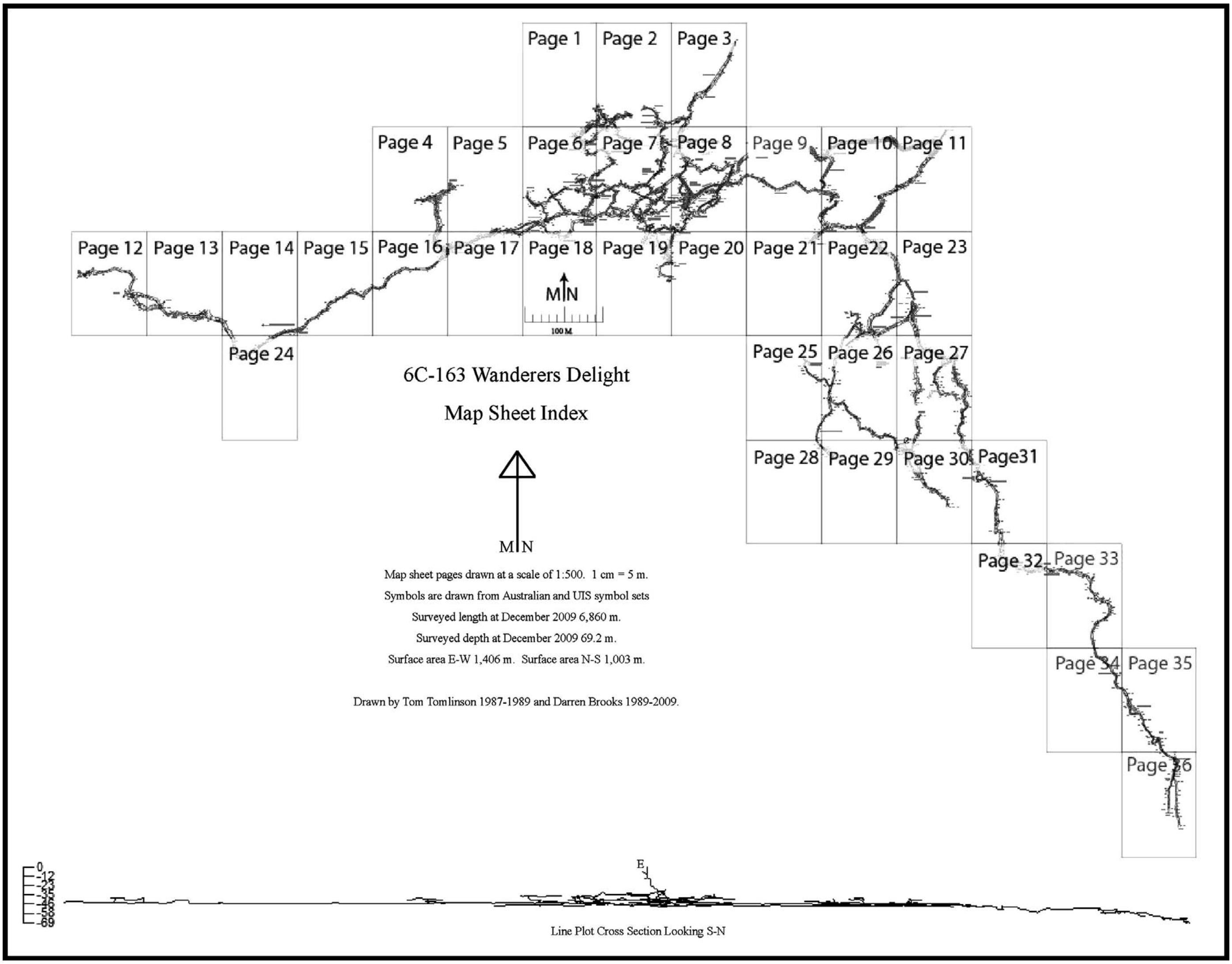

Figure 6. Map of Wanderers Delight, an epigenic stream cave 6.86 km long and 69 m deep. From Brooks (2009).

there is a sea-level fall on a carbonate coast, inland overland flow will cut valleys into the coastal limestones. If sea level rises, these valleys become invaded by marine water, and the valley walls become sites for flank margin cave development. The islands listed above all share a history of tectonic uplift associated with glacioeustasy. This condition guarantees that coastal valleys will be cut and later invaded by marine water. Applying this model to the Cape Range indicates that initial uplift would produce a subaerial landmass, allowing development of a fresh-water lens, but also allowing for surface flow and valley incision. Continued uplift would allow deeper valley incision. A subsequent eustatic sea-level rise would flood those valleys and create the fresh-water lens discharge necessary for flank margin cave development in those valley walls. Because uplift is episodic but continuous over the long term and Miocene glacioeustasy (Fig. 11) was an overprint on that uplift, the stability period of the fresh-water lens could be expected to be short, so that caves of high complexity did not have time to develop. On Barbados, the presence of dense calcite vadose speleothems such as stalactites, stalagmites, and flowstone on the walls of gullies was initially interpreted to indicate that the gullies themselves were collapsed epigenic stream caves (Kambesis and Machel, 2013). However, the width of some of those gullies was too great to have supported such a cave passage. The speleothems have since been interpreted as having grown in the caves after the marine invasion and been exposed in the gully walls by relatively minor wall retreat. (Kambesis and Machel, 2013). The deep, wide gorges of the Cape Range are far too large to have been a single cave-stream passage, and speleothems present are commonly associated with flank margin caves in the gorge walls. Figure 12 presents a model of valley invasion by marine waters, subsequent flank margin cave formation, and cave degradation.

One of the hallmarks of flank margin cave development is the presence of a series of chambers, all at a single elevation.

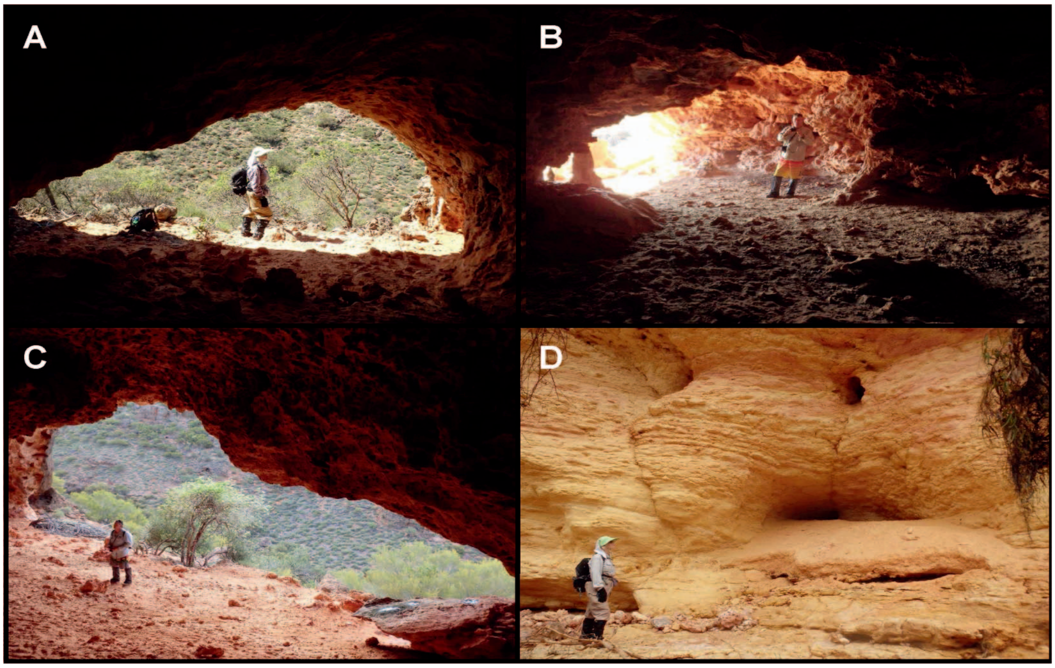

Figure 7. Flank margin caves of the Cape Range. A–C. Typical flank margin caves with entrances high on the valley wall in the Tulki Limestone. D. Small dissolution caves, much modified by tafoni processes, Mandu Formation. Note that the dissolution passages occupy joints, consistent with the Mandu Formation's aquitard character.

This line of caves has been called beads-on-a-string, and it reflects the sea level, and hence lens position, at the time of cave development (Mylroie, 2013). Such lines of flank margin caves are commonly found as multiple horizons on tectonically active islands, each line representing a sea-level position. At Cape Range, the caves are commonly a series of chambers along a common line, but in many places that line appears to be tilted. This tilt may follow the dip of the beds at 3 to 8 degrees on the west side of Cape Range, and 3 to 6 degrees on the east side (Whitney and Hengesh, 2015). This situation could indicate cave development prior to continued folding of the anticline, and an original straight line of caves could now be bent as a result of the subsequent folding and uplift. Alternatively, cave development could be favored at a specific stratigraphic horizon, perhaps a bed of higher rock solubility, and as dropping sea level "slid" down the limb of the anticline, caves were developed in the same bed at progressively lower elevations. Finally, valley incision could have progressed into the distal portions of the anticlinal limbs as uplift continued, and when the valley was invaded to a

Figure 8. Flank margin cave, at X, in the Tulki Limestone. Shallower, broader openings below the flank margin cave are tafoni developed in the Mandu Formation.

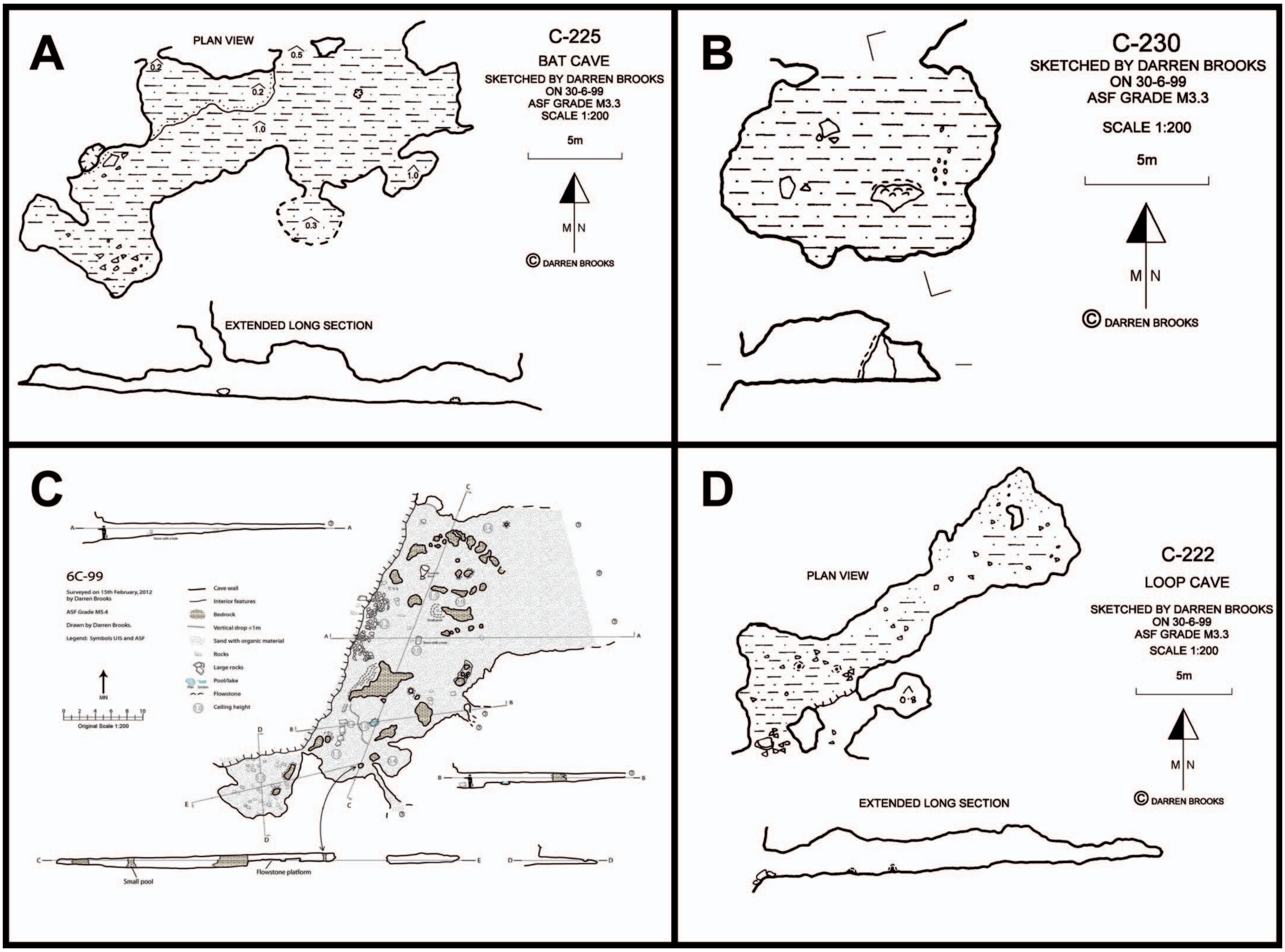

Figure 9. Maps of four flank margin caves in the Cape Range. A. Flank margin cave with multiple entrances and some chamber complexity. B. Simple flank margin cave with one entrance. C. Complex flank margin cave with numerous bedrock pillars subdividing the chambers. D. Flank margin cave with two small entrances leading into large chambers.

small degree during each sea level rise, it did so progressively farther away from the anticlinal axis, displacing cave development to only that portion of the valley that was flooded.

An important question regarding the model of marine water invading incised valleys during a transgression is: Where are the marine deposits that should be associated with that transgression? While one could expect to see fossil corals attached to valley walls, the amount of cliff and slope retreat necessary to expose the existing flank margin caves to the degree seen today would have removed any coastal or bioerosion notches, sea caves or fossil deposits, and similar features associated with a cliffed rocky coast (Waterstrat et al., 2010). It is possible that some of the fossil corals found in the Mowbowra Conglomerate are material representing corals deposited on, and then erosionally removed from, the paleo-cliff line after a drop in sea level.

Testing Flank Margin Cave Development

The determination of how, and perhaps more importantly when, the flank margin caves of the Cape Range formed requires detailed data collection and analysis. A representative sample of the caves need to be mapped. That mapping has to establish cave elevation, long-axis orientation, and long-axis inclination. The cave map subsequently needs to be analyzed to create entrance width to maximum width ratios (EW/MW), and area to perimeter (A/P) ratios. From these results the data set can be compared to those from tafoni to demonstrate that both cave types exist; A versus P is especially good at this determination (see Waterstrat et al., 2010). The long axis orientation data can be analyzed to see if the long axis faithfully follows the valley wall's orientation and can also be compared to the regional joint sets' orientations to see if there is any correlation. As gorge-wall orientation will be influenced by preexisting joint sets, differentiating cave orientation

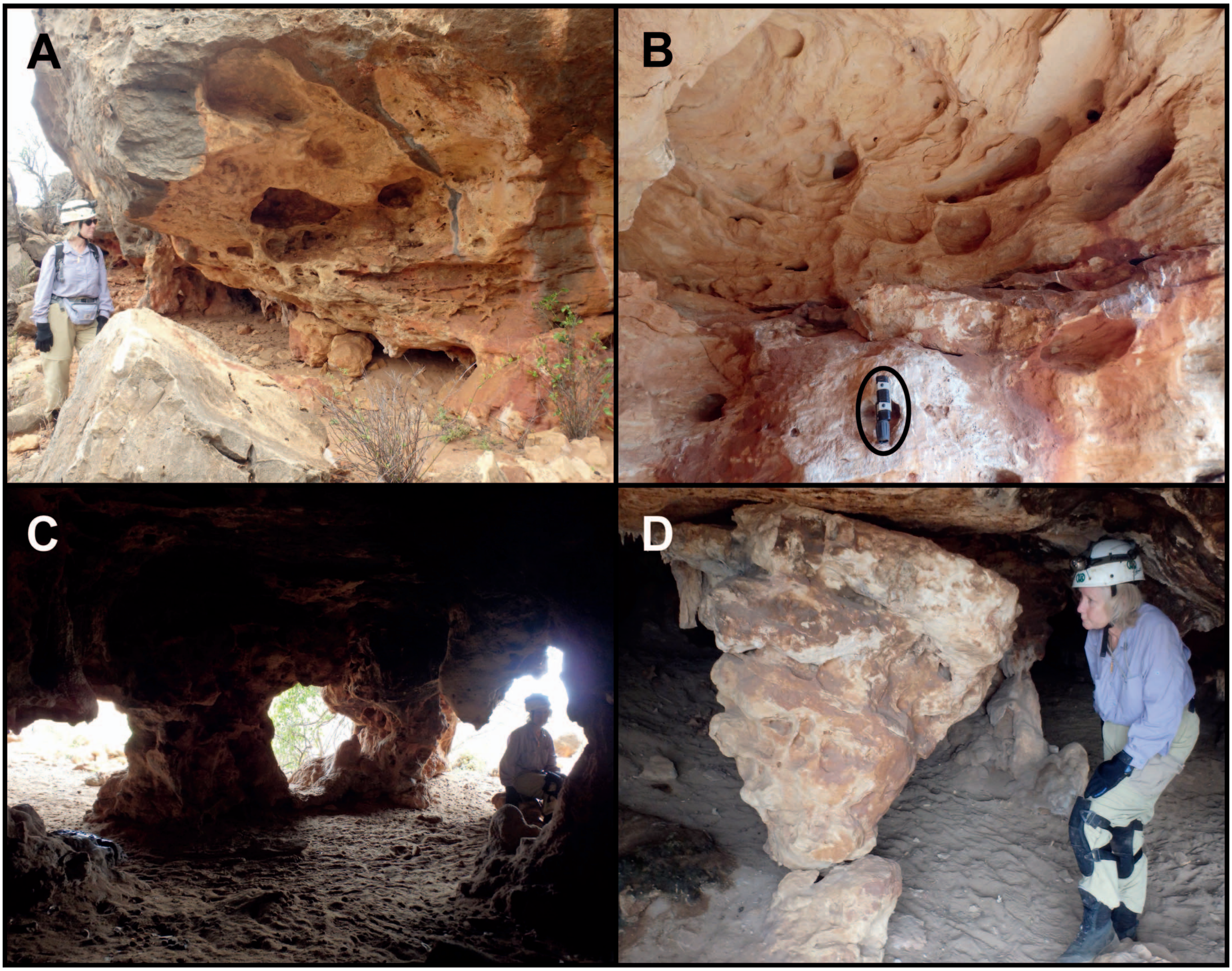

Figure 10. Speleogens in Cape Range flank margin caves. A and B. Dissolution pockets and rimouts (flashlight in circle in B 15 cm long for scale). C. Remnant bedrock pillars. D. Remnant bedrock pillar slowly disarticulating from the roof and floor. It is known as the Tornado.

produced by flow along joints in the hypogene condition from more recent flank margin caves produced by joint-controlled cliff orientation may be difficult. The cave elevation data will help determine if there is any correlation between true horizontality and position on the anticlinal limbs. The cave inclination data can detect whether the caves follow the bedding or cross it; if the caves cross bedding, it is an indicator of horizontal control independent of bedding, such as control by the fresh-water lens margin. In many places there are definite horizons of cave development on the walls of the gorges. The site-specific vertical separation of these horizons needs to be determined. If there is always a set difference in vertical separation between two cave horizons, then they probably formed as horizontal lines of caves. Any elevation disparities between widely spaced sites would then be due to later folding.

Summary

The caves on the paleo sea cliffs on the east and west sides of the Cape Range and the caves found in the deep gorges draining the range are flank margin caves when the caves are located in the Tulki or overlying limestones. The Mandu Formation contains primarily tafoni. The younger Pliocene and Pleistocene terrace limestones also host numerous flank margin caves. The flank margin caves at high elevations are very old, concurrent with the uplift and initial Miocene subaerial exposure of the Cape Range. As rapid uplift is thought to have ended in the Pliocene, even the lower-elevation flank margin caves in the gorges are likely Late Miocene in age, but those in the Jurabi Terrace are Pliocene in age, and those in the Tantabiddi Terrace are late Pleistocene in age. Cave development continued as the Quaternary carbon-

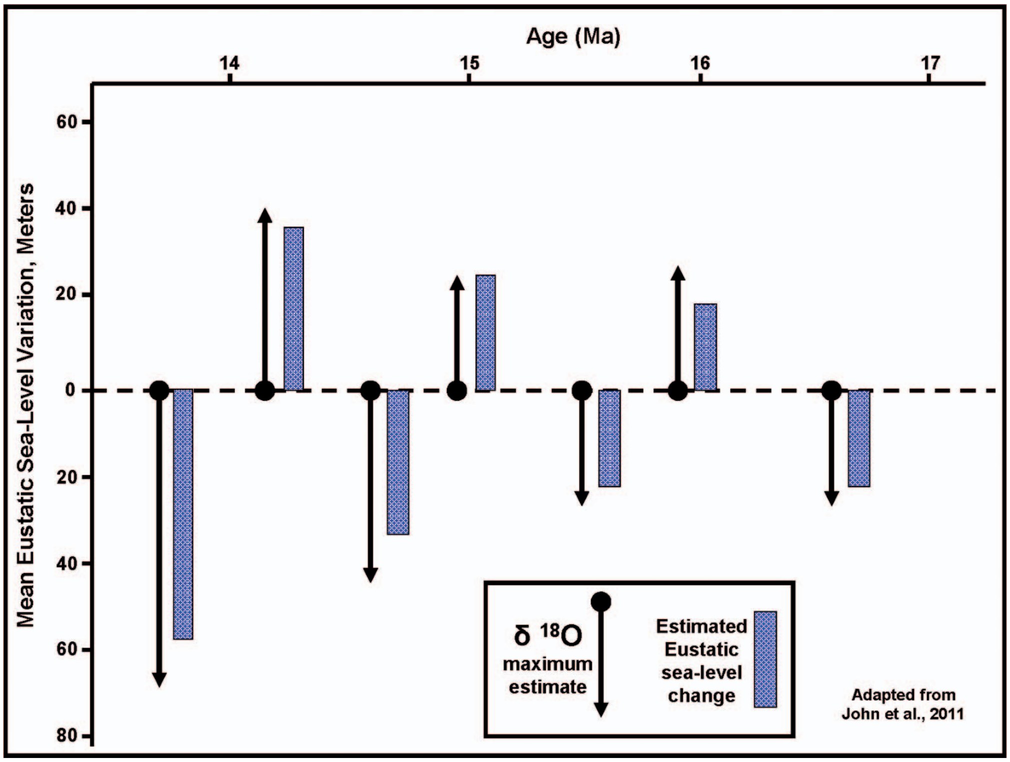

Figure 11. Australian Miocene eustatic sea-level curve adapted from John et al. (2011). The rising sea level was more than sufficient to flood valleys in the Cape Range during uplift in the Miocene.

ates were deposited and subjected to glacioeustasy and slower rates of tectonic movement.

The flank margin caves in the Cape Range gorges and valleys developed as a result of a complex interplay between tectonic uplift and Miocene glacioeustasy. Some of the caves may have developed while folding was still occurring, and their original speleogenetic position altered as a result. Following the Pliocene, cave development position was solely controlled by the high-amplitude, short-wavelength glacioeustasy of the Pleistocene with a minor tectonic overprint.

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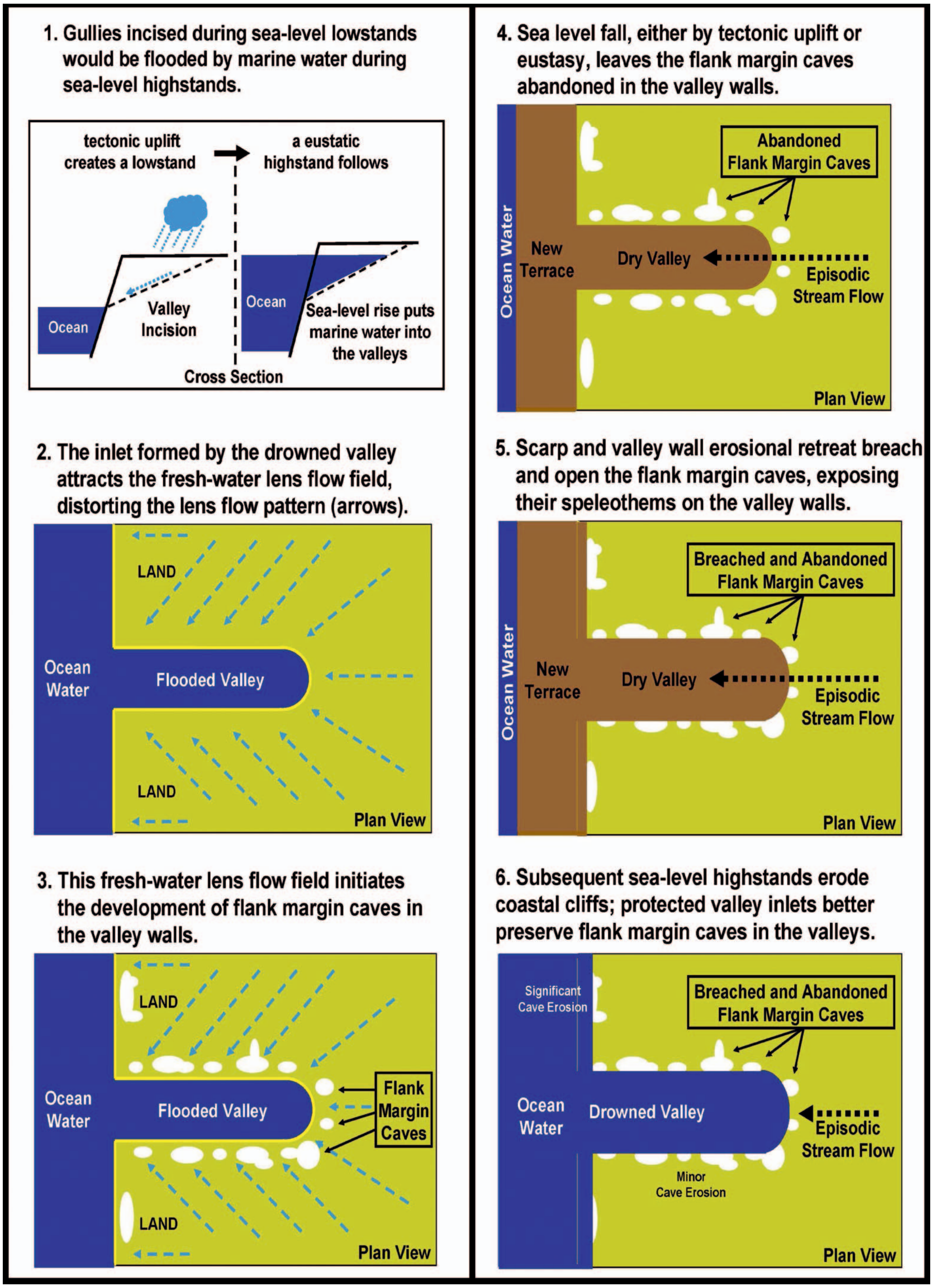

Figure 12. Six-panel cartoon demonstrating the valley-incision to valley-flooding model for developing flank margin caves in incised valleys of the Cape Range during the Miocene.

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