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THE MOYJIL SITE, SOUTH-WEST VICTORIA, AUSTRALIA: STRATIGRAPHIC AND GEOMORPHIC CONTEXT

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ABSTRACT: Shelly deposits at Moyjil (Point Ritchie, Warrnambool), Victoria, together with ages determined from a variety of techniques, have long excited interest in the possibility of a preserved early human influence in far south-eastern Australia. This paper presents a detailed analysis of the stratigraphy of the host Bridgewater Formation (Pleistocene) at Moyjil and provides the context to the shelly deposits, evidence of fire and geochronological sampling. We have identified five superposed calcarenite–palaeosol units in the Bridgewater Formation, together with two prominent erosional surfaces that may have hosted intensive human activity. Part of the sequence is overlain by the Tower Hill Tuff, previously dated as 35 ka. Coastal marine erosion during the Last Interglacial highstand created a horizontal surface on which deposits of stones and shells subsequently accumulated. Parts of the erosional surface and some of the stones are blackened, perhaps by fire. The main shell deposit was formed by probable mass flow, and additional shelly remains are dispersed in the calcareous sand that buried the surface.

Keywords: Point Ritchie, Bridgewater Formation, Pleistocene, erosional surfaces, Last Interglacial, calcarenite, palaeosol

INTRODUCTION

Since the 1980s, the Moyjil/Point Ritchie site at Warrnambool, Victoria, has intrigued scientists due to the occurrence there of shell deposits and discoloured stones of apparent antiquity, and for its possible archaeological association. While the archaeological provenance of the features had not been demonstrated, geochronologically determined ages (>60 ka) suggested antiquity greater than the then accepted period of human occupation in Australia. Archaeological and geological documentation, together with additional geochronological investigation, were therefore essential to furthering our understanding of what is clearly an unusual site. In this, the second in a series of papers concerned with the possibly archaeological materials at Moyjil, we present the geological context of the features, in particular, descriptions and interpretations of the geomorphology and stratigraphy of the site. Other papers in the series provide an overview of the project (Sherwood 2018), examine the site's geochronology (Sherwood et al. 2018a), shell taphonomy (Sherwood et al. 2018b) and evidence for fire (Bowler et al. 2018), and present an archaeological investigation of a hearth-like feature (McNiven et al. 2018).

Location

Moyjil is on the coast at Warrnambool and lies at the edge of the Newer Volcanics Province, 16 km east of the Tower Hill explosive crater. The site is adjacent to the mouth of the Hopkins River and at the eastern limit of Lady Bay (Figure 1), and features a cliffed headland and adjacent sea stacks. The cliffs expose Quaternary calcarenite and palaeosols, and are cut into the toe of the stabilised and vegetated Dennington dune, named here after the Dennington Member, a component of the dune (see Reeckmann & Gill 1981).

Previous work

Following earlier studies of the coastal geology and geomorphology of south-western Victoria (Jutson 1927; Baker 1943; Boutakoff 1963), the late Edmund Gill devoted much time to the study of Quaternary volcanic and coastal features of the Warrnambool region (e.g. Gill 1967, 1976; Reeckmann & Gill 1981; Gill & Segnit 1982). At Moyjil, while working with one of us (JS) in 1981, Gill identified a shell midden (Figure 2A) with an unusual cemented assemblage of marine shells on top of a small sea stack (West Stack, Figure 3). Its resemblance to Holocene shell middens raised the question of its origin through human agency, while its degree of cementation suggested an age beyond the Holocene (Nair & Sherwood 2007).

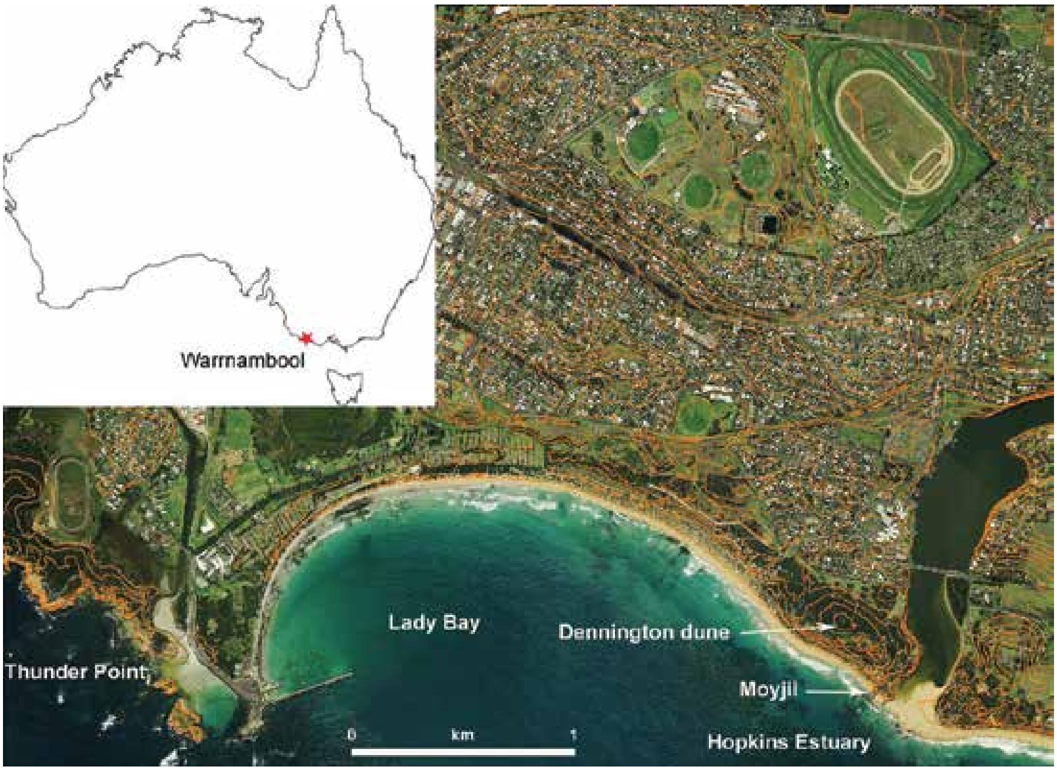

Figure 1: Locality map, Moyjil, Warrnambool, Australia. Contours at 5 m interval highlight dune morphology at Moyjil and Thunder Point. Photo map courtesy Warrnambool City Council; inset map of Australia courtesy Geoscience Australia.

Figure 2: **A**. Shell aggregation on top of West Stack, originally identified as a possible midden by Edmund Gill. **B**. Rhizomorph bridging a fracture on abrasion surface, Block B, together with blackening of surface on left side (scales for A and B in centimetres). **C**. Rotated block (Block F) showing pothole-like depressions on surface. Some depressions contain stones; block of calcrete on surface (arrow; horizontal and vertical scales = 50 cm). **D**. *Terra rossa* (palaeosol) of unit Q2 beneath weathered, stratified Tower Hill Tuff (unit P), Hopkins River section (scale = 100 cm).

Figure 3: Geomorphic features of Moyjil, Warrnambool, including: headland, estuary of Hopkins River, East Stack, West Stack and Dennington dune. The locations of two fallen blocks (B and F) referred to in the text are also shown. Photo map courtesy Aboriginal Victoria.

The problem of the shell assemblage's age was first addressed by Prescott and Sherwood (1988), Goede (1989) and Sherwood et al. (1994), and reviewed by Nair and Sherwood (2007). The unexpectedly old ages obtained (>60 ka) have prompted a new phase of geochronological study (Sherwood et al. 2018a). The earlier investigations employed conventional radiocarbon, thermoluminescence (TL), uranium/thorium radiometric dating (U/Th) and amino acid racemisation techniques (Sherwood et al. 1994) and electron spin resonance (Goede 1989). Radiocarbon analysis of charcoal and shell from the site indicated antiquity beyond the method's limit (>~40 ka). TL dating of quartz from the sandy matrix to the shells yielded an age of 67 ± 10 ka. Further, TL dating of discoloured (heated?) stones suggested that either the colouration had another cause or that the stones had not been heated sufficiently to reset their quartz grains, as the stone TL ages significantly exceeded the sand TL age (Prescott & Sherwood 1988; Sherwood et al. 1994). Oyston (1996) subsequently used TL to re-examine the age of the sands and found them to be late Last Interglacial (LIG) — 80 ± 10 ka and 93 ± 11 ka. Note that we use the term LIG to refer to the whole of MIS stage 5 (i.e. 80–130 ka), the last time sea levels were as high as or higher than present. It is not always possible to specify the age of particular events within this broad period. Where an event has been dated to the LIG sea-level maximum (MIS 5e, approximately 120–125 ka) either based on stratigraphy or chronological techniques, we have referred to the shorter interval.

Since 1986, many archaeologists and geologists familiar with Victorian coastal stratigraphy have visited the site and failed to agree on the origin of the shell deposit. One reason for scepticism derives from the unusual characteristics of the deposit. As stressed by Nair & Sherwood (2007, Table 1), shells are predominantly of one species (*Lunella undulata* syn. *Turbo undulatus*) and mostly fragmented with only one entire shell/valve for more than 10 fragments. Furthermore, recent observations have identified striking similarities between seabird and human middens in south-eastern Australia (Sherwood et al. 2016). Archaeological scepticism is heightened by the great antiquity of the shelly assemblage — beyond the accepted period of human occupation in Australia at 60–65 ka (Clarkson et al. 2017). Systematic evaluation is required to resolve the question of age and to investigate evidence for early human presence.

Current project

In 2007 JB and JS decided to undertake a major re-evaluation of the site. Because of the multidisciplinary nature of the research needed, the team was subsequently expanded to include archaeological (IMcN) and additional geological (SC, MK) expertise. If certain features of Moyjil are indeed archaeological, it is important to: (1) distinguish them from natural (geological) characteristics of the site, and (2) elucidate the geological history of the site to provide the environmental context of possible human activity. This paper reports on the field relations (stratigraphy) at Moyjil. Our focus is on the older parts (>60 ka) of the sequence and is restricted to exposures at Moyjil and surrounds.

GEOMORPHOLOGY

Coastal setting

Moyjil's putative archaeological materials occur in a system of beach ridges located just south of the Quaternary Newer Volcanics Province. Beach ridges have been developing along Warrnambool's high-energy coastline for much of the Quaternary (Gill 1976). Similar features occur intermittently along the southern and western coast of Australia where they form dune-and-barrier systems (Baker 1943; Boutakoff & Sprigg 1953; Playford et al. 1976; Brooke et al. 2014; James & Bone 2017; Lipar et al. 2017). Source-bordering dunes, preserved as aeolianite, derive from the deflation of littoral calcareous sands with a largely nearshore–intertidal provenance (Joury et al. 2018). Sensitive to Quaternary sea-level oscillation, the dunes mostly formed during interglacial high sea levels in response to eccentricity-dominated orbital forcing (Murray-Wallace & Woodroffe 2014), though some developed at low and intermediate sea levels (Brooke et al. 2014). Alternating deposition and pedogenesis are represented by successive aeolianite–palaeosol couplets, with several such couplets developing during prolonged highstands (James & Bone 2015). Highstand aeolianite, as at Warrnambool, formed with a periodicity near 100 ka in response to variation in global ice volume and the occurrence of high sea levels. At Warrnambool, the Dennington dune is one of several stabilised Pleistocene calcareous dune systems that underlie the city and environs (Figure 1). Rising to >30 m Australian Height Datum (AHD), it is eroded and exposed at Moyjil on the western margin of the Hopkins River estuary (Figure 1), on which it exercises a strong topographic and hydrological influence. A younger, more seaward dune system, referred to here as the Thunder Point dune, rises from below present sea level (Reeckmann & Gill 1981) and is exposed in cliffs at Thunder Point, 3 km west of Moyjil (Figure 1). Two thermoluminescence (TL) ages for the Thunder Point dune sand (72 and 82 ka; Oyston 1996) are in close agreement with six multigrain optically stimulated luminescence (OSL) measurements (77–91 ka) determined by Agar (2013) and indicate the Thunder Point barrier developed at MIS 5a, a time of lower sea level than existed when dune formation was active at Moyjil (which we show to be post-MIS 5e, Sherwood et al. 2018a).

Moyjil's landscape elements: headland and stacks

A steeply cliffed shoreline with residual stacks is developed at Moyjil (Figure 3). Two prominent stacks, East Stack nearer the Hopkins River and West Stack 50 m to the west, project seawards and are separated by a sandy embayment. Our interest lies primarily in the stratigraphic relationships between the headland and West Stack. The headland is marked by cliffs 7–11 m high. A stepped topography is developed due to the presence of two erosional benches underlain by calcrete. The two stacks, East and West, are both cliffed (heights of 10 m and 8 m respectively) and both have flat tops. West Stack (Ws) is linked to the headland by a low ridge, ~15 m long and largely covered with decimetre-scale displaced blocks. The stack is divided by a vertical fracture into two slightly separated and tilted blocks, West Stack North (WsN) and West Stack South (WsS, Figure 4), in addition to which another large slab has fallen at the stack's eastern side, and now lies at beach level. The Moyjil shell deposit occurs in two places, as a thin veneer on the surface of West Stack, and within a sand between two calcrete layers on the headland.

Elevated wave-cut notches and gravel beach

Deep wave-cut notches are preserved at ten locations around the headland area. Located 3–6 m above the present wave cut platform (~0.2 m AHD) and filled with carbonate-cemented gravel, sand and shell debris, they are consistent in elevation with records of the LIG highstand along the southern Australian coast (Murray-Wallace 2002; Hearty et al. 2007; Murray-Wallace et al. 2016). On East Stack a prominent visored notch on the seaward side is up to 1.7 m high with its base at 2.9 m AHD. It contains large rounded boulders packed with shell and coarse sand to 0.6–0.7 m and above this is a coarse sand layer filling the notch (Figures 5A, B). On West Stack, the notches are best preserved in two places: (i) one with a collapsed visor on the northern side of WsN where it is infilled by 1.5 m of calcareous sands with rounded gravel and shells at its base (Figure 5C, D), and (ii) in the south-west corner of WsS where a layered sand (1.4 m thick) almost completely fills a visored notch 1.75 m high (Figure 5E). When WsN and WsS are rotated to their original positions, the base of the notches lies at ~+5 m AHD. This provides control for determining the elevation of the MIS 5e shoreline and corroborates Nair and Sherwood's (2007) conclusion

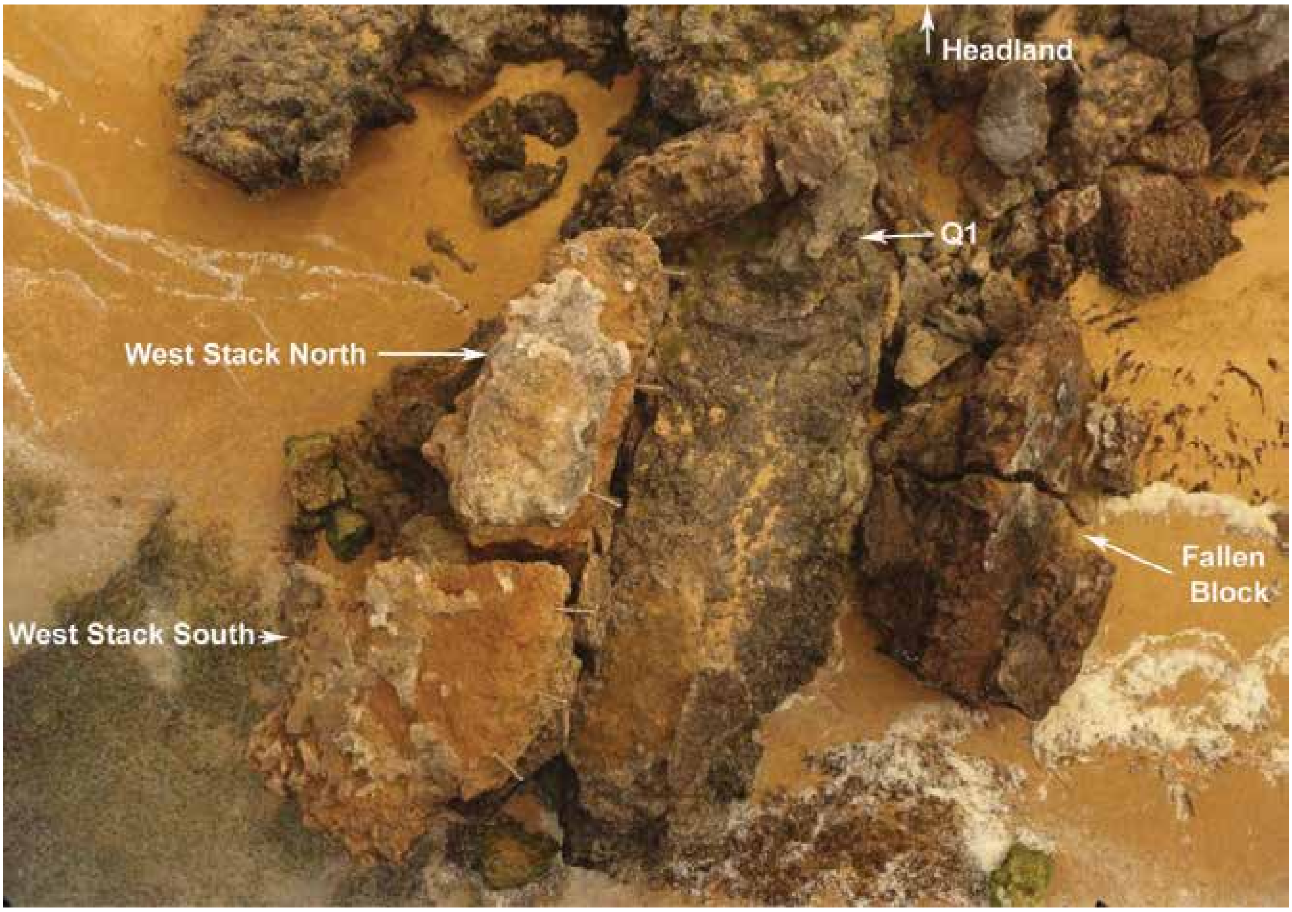

Figure 4: Aerial view of West Stack (Moyjil, Warrnambool) showing West Stack North, West Stack South, a major fallen block, an occurrence of LIG beach sediment (unit Q1), and the stack's relation to the headland. Drone imagery courtesy D. Ierodiaconou. (Linear features on eastern side of West Stack are horizontal supports for fence that now deters access to top of stack.)

that Warrnambool's coastline has been relatively stable since the LIG, notwithstanding substantial uplift of older shorelines (Dickinson et al. 2002; Sandiford 2003; VandenBerg 2016), volcanism at nearby Tower Hill and evidence for seismicity (see below).

Midway between West Stack and the headland, a cemented remnant beach deposit of rounded gravel and shelly fragments occurs at +6 m AHD. The deposit is 5.5 m from the headland platform and 2 m below it, indicating a sea impinging on the cliff at the time of its formation.

Fallen blocks

In addition to the more or less undisturbed evidence of the cliffed shoreline, certain fallen blocks located on and in front of the cliffs provide useful insights into the stratigraphy and for the reconstruction of palaeo-landforms (see Stratigraphy). Of many examples, one block, Block B (Figure 3), is of particular importance. Measuring 4 m x 4 m, it lies on the beach in a near-vertical (overturned) position relative to its primary stratification. It consists mostly of reddish limestone and its upper surface is a palaeosurface regarded here as a marine abrasion surface. Block B can be restored to its original position on the cliff with reference to the stratigraphy of both block and cliff (see below). The stratigraphic (abrasional) top of Block B is planar in gross form, though blocky in detail, and is smoothed and partially blackened. Relief on the surface is in the form of strongly pitted potholes and linear depressions which are partially filled with heterogeneous stones. Much of the surface is fractured. At one point, a linear depression is bridged by a post-erosional rhizomorph (diameter ~5 mm; Figure 2B).

Another block, vertically oriented Block F (Figure 3), features an apparently potholed surface with stones cemented to it (Figure 2C). The block, approximately 3 m x 2 m x 1 m, is on the saddle between the headland and West Stack, and has been rotated through 90°. The nine depressions (potholes?) on the eastern surface are 20–30 cm broad and 10–20 cm deep. The surface generally, and depressions specifically, are coated with a layer of calcite cement. Pebble-sized stones, some rounded, occupy three of the depressions, while a 35 cm limestone clast of reddish palaeosol is fixed to the surface.

Hopkins River bank

A *terra rossa* (Figure 2D) occurs below the Tower Hill Tuff in the steep west bank of the Hopkins River, 200 m

Figure 5: Wave-cut notches and beach deposits (unit Q1) formed during the LIG at Moyjil, Warrnambool. **A.** Notch occupied by unit Q1 (arrow), East Stack, view east; stack largely consists of unit V. **B.** Detail of gravel–sand–shell deposit (unit Q1), East Stack (scale = 20 cm). **C.** Units Q1 and V, West Stack North (view west). **D.** Detail of gravel–sand–shell deposit (unit Q1), West Stack North (lens cap = 5.8 cm). **E.** Notch partially filled with sand (unit Q1, arrow), West Stack South, view east (stack is tilted). Scales in C, E = 100 cm.

upstream from the mouth, 3–4 m above river level and 5–6 m in lateral exposure. It is significant as an example of the soil mantle which is likely to have covered the uppermost of the calcrete surfaces now exposed at Moyjil.

STRATIGRAPHY

Bridgewater Formation (Pleistocene)

The materials of possible archaeological origin at Moyjil lie within the Bridgewater Formation, which includes the sedimentary deposits of the Dennington and other Pleistocene dune systems at Warrnambool. Variation in the concept of the Bridgewater Formation as a lithostratigraphic unit necessitates clarification of our usage of the term. The Bridgewater Formation was established by Boutakoff and Sprigg (1953) to include Pleistocene dune limestones (calcarenites/aeolianites) and palaeosols of the Portland–Cape Bridgewater area of Victoria. Subsequently, the Bridgewater Formation was mapped along coastal and palaeocoastal areas of South Australia and Victoria, and its similarity to the Tamala Limestone of Western Australia was noted (Brooke 2001). Equivalent deposits at Warrnambool were initially subdivided into a number of formations (Gill 1967, 1976), without reference to the Bridgewater Formation, but Reeckmann and Gill (1981), as well as Orth (1988) and Cupper et al. (2003), later allocated them to their Bridgewater Group. We follow VandenBerg (2009) in regarding the rank of formation as being appropriate to the Bridgewater. Thus, components of the Bridgewater Formation at Warrnambool (Reeckmann & Gill 1981; Orth 1988) have the rank of member. Similarly, in its type area, the Bridgewater Formation has recently been subdivided into members (Lipar & Webb 2015), while in South Australia two informal units, the upper and lower members, are widely recognised (Belperio 1995; James & Bone 2015, 2017). The archaeologically intriguing member at Moyjil is the Dennington Member, which occurs in the Dennington and Thunder Point dune systems (see Gill 1976). Older parts of the Bridgewater Formation at Moyjil are of uncertain relationship to Gill's subdivision.

Informal stratigraphic subdivision

To describe the geology of Moyjil, we use a detailed informal lithostratigraphy (units Q2, R, S, T, V: Figure 6, Table 1) for that part of the Bridgewater Formation exposed there. Heavily overprinted in part by calcareous palaeosols, units S, T and V form the basal sequence beneath a complex of calcarenite and calcrete with shell, pedified volcanic tuff and ancillary deposits (units P, Q1, Q2, R: Table 1). Possible archaeological features are in unit Q2. Major stratigraphic breaks are marked by pronounced surfaces at the top of unit R (Ground surface α; Gsα) and the top of unit Q2 (Ground surface β; Gsβ). Brief descriptions of the units follow, and the stratigraphy of select geomorphic features is summarised in the next section.

Unit V. Unit V is a calcarenite–palaeosol body with an exposed maximum thickness of 9.5 m that occurs in the headland, East Stack and the lower part of West Stack (Figures 5A, C, 6). The calcarenite is a cross-laminated, very fine-grained bioclastic sandstone. The palaeosol developed upon the calcarenite was previously identified by Gill and Segnit (1982) as loess, and is best preserved in the swale of a palaeodune. The upper surface of unit V is distinct and undulating, and is erosional except in the palaeoswale.

Unit T. Unit T is a calcarenite–palaeosol layer with an exposed maximum thickness of 3.5 m found in the headland, West Stack and Block B (Figure 6). The calcarenite is cross-bedded, fine-grained bioclastic sandstone with ~10% quartz and common rhizomorphs. The palaeosol consists of bioclastic carbonate (80% acid-soluble), quartz (10%) and clay (10%), and features a prominent (20–30 mm thick) calcrete at its base. The upper surface of unit T is, in part, a sharp and conformable boundary with unit S; and, in part, an erosional boundary overlain by unit R.

Unit S. Unit S is a calcarenite–palaeosol body in the headland (Figure 6) and fallen Block B. Its maximum exposed thickness is 2.9 m. The calcarenite is sub-horizontally bedded with minor cross bedding, and consists of fine bioclastic sandstone with minor pebbly conglomerate and gravelly sandstone. The palaeosol is of bioclastic carbonate (68% acid soluble), quartz (10–12%, silt to fine sand-sized, modal diameter ~60 μm) and clay (15–20%). The upper boundary with unit R is part conformable, part erosional, and occurs at the base of a calcrete layer (Rcp). The TL age of 111 ± 16 ka (Oyston 1996, table 1) is doubtful, as unit S predates the LIG Dennington Member and is older than 200 ka (Sherwood et al. 2018a).

Unit R. Unit R is a calcarenite–calcrete body exposed on the headland, the top of West Stack and the adjacent collapsed block to the east, and on the flanks of the Dennington dune up to 400 m west of Moyjil (Kay 2014; Figure 6); it also occurs as displaced calcrete blocks on the top of East Stack. It has three components— a basal calcrete

Figure 6: Stratigraphic section, Bridgewater Formation (Pleistocene), Moyjil, Warrnambool. Formation is divided into informal units, mostly of calcarenite–palaeosol. The surface at the top of unit R is Gsα, and is exposed as a platform at the top of the main cliff.

Table 1: Summary of informal lithostratigraphy for part of Bridgewater Formation (Dennington Member incorporating unit Q2; units R, S, T, V probably belonging to older members), Tower Hill Tuff (unit P) and minor ancillary deposits (units Q1,) at Moyjil, Warrnambool. Q1 and Q2 are related only in that they are of similar age. Geochronology from Oyston's (1996) thermoluminescence age determination for Moyjil, subject to major revision in this study (Sherwood et al., 2018a).

Unit notation	Description	TL Age Oyston (1996)
Holocene	Holocene soil with post-glacial middens	
P	Tower Hill Tuff of volcanic ash, partly reworked	35 ± 3 ka*
Ground surface beta (Gsβ)	Erosional surface on calcrete Q2cs	
Q2	Q2cs: pedogenic calcrete cap, Upper Calcrete of Nair & Sherwood (2007); on Q2s: aeolian calcarenite with occasional marine shells, overlying Gsα; at base, thin layer of marine shells and transported and discoloured stones (limestone clasts); belongs to Dennington Member (Gill 1967); Headland Bed of Nair and Sherwood (2007) Q2cp: groundwater calcrete, ~1 mm thick	93 ± 11 ka 80 ± 10 ka
Q1	Gravel, sand and shells, consolidated with $CaCO_3$ cement (LIG beach deposit)	
Ground surface alpha (Gsα)	Prominent erosional platform on calcrete (Rcp)	
R	Rcs: pedogenic calcrete cap, best exposed 150–300 m NE of Moyjil; on Rs, aeolian calcarenite Rcp: basal groundwater calcrete, Lower Calcrete of Nair & Sherwood (2007), developed partly on calcareous sands (Rs), partly on erosional surface truncating units T & S, and partly in veins below Gsα	
S	Lithified yellow-brown calcarenite with capping of reddish palaeosol	111 ± 16 ka
T	Lithified yellow-brown calcarenite with capping of reddish palaeosol, upper part with locally abundant cm-scale blackened clasts. Thick (20–30 mm) calcrete at the base of the palaeosol.	136 ± 15 ka
V	Basal lithified yellow-brown aeolian calcarenite (East Stack Calcarenite of Nair & Sherwood 2007) with capping of calcareous very fine sand/silt (palaeosol; loess of Gill and Segnit 1982)	190 ± 16 ka

* Sherwood et al. (2004)

(Rcp), a calcarenite (Rs) and an upper calcrete (Rcs)—though nowhere are all three exposed in a single outcrop. The calcarenite is up to 1.4 m thick in the headland cliff and was sampled for OSL age determination (Sherwood et al. 2018a). Unit R's lower boundary is unconformable upon units S and T, while the upper boundary with unit Q2 is erosional (Ground surface alpha, Gsα; see below) and cuts across either Rcp (where unit R is very thin) or Rcs. The calcarenite is horizontally bedded with subordinate low-angle cross-bedding, and consists of fine-grained bioclastic sand with ~20% quartz.

The basal calcrete (Rcp, Figure 7A) is exposed on the headland and the tops of East and West stacks. On West Stack, it is the only part of unit R present, except for minor relict calcarenite (Figure 7B). Rcp consists of two phreatic phases, one at Gsα and the other locally binding carbonate sand of unit R.

Calcrete Rcs occurs at the top of unit R 150–300 m north-west of the headland on the higher south-facing slopes of the Dennington dune (Kay 2014; Figure 1). It has been removed from the headland by the erosional phase that produced Gsα. Rcs is a dense micrite, 5–40 cm thick with an irregular base, and represents a portion of a palaeosol from which the overlying A-horizon has been stripped.

Ground surface alpha (Gsα) (Figure 7C). Gsα is a surface cut by lateral erosion across gently dipping calcarenite–palaeosol units R, S and T, and overlain by unit Q2. The surface is partly exhumed on Moyjil headland and forms the top of West Stack. Essentially horizontal where

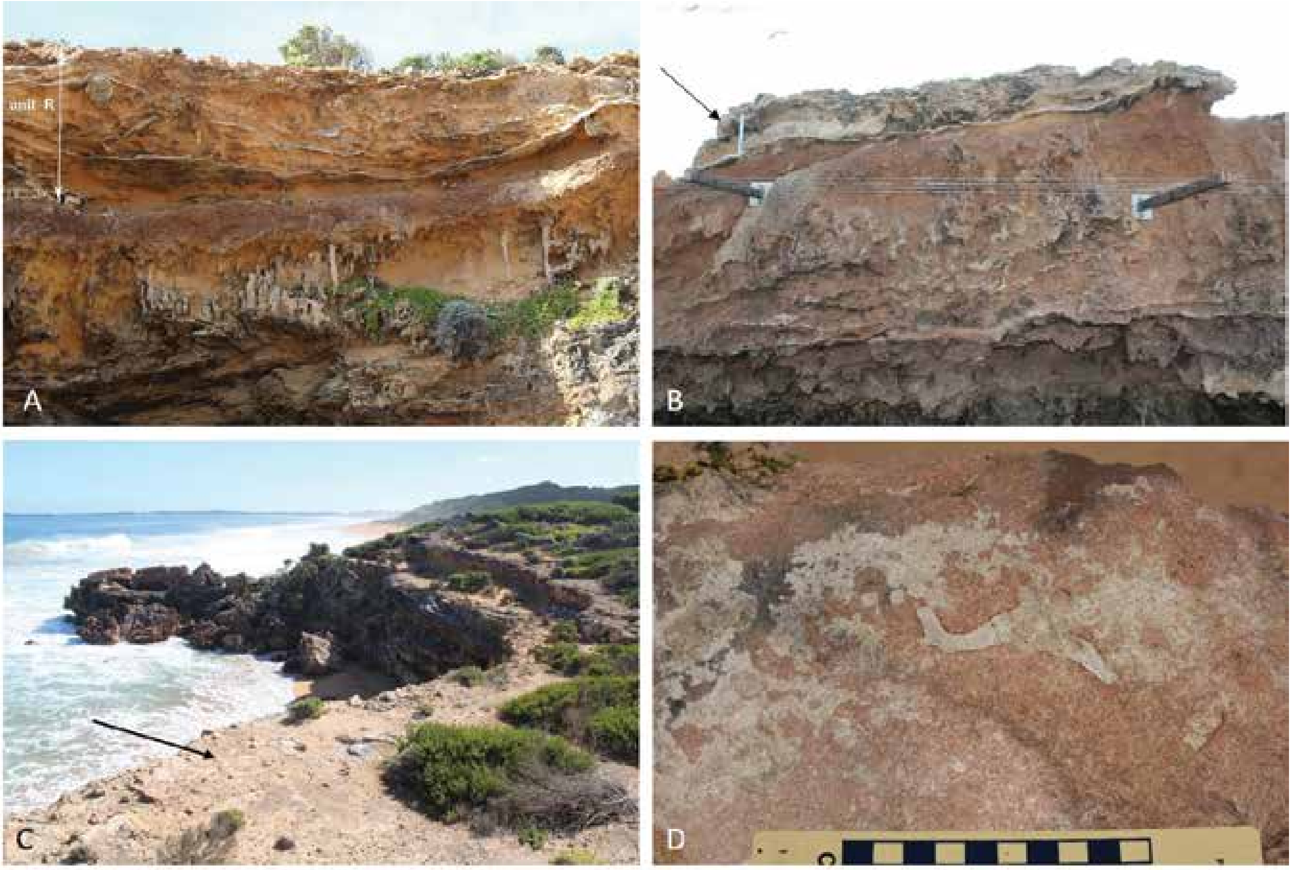

Figure 7: **A**. Unit R, headland: calcrete Rcp planar at top of cliff and sheetlike below to top of unit S (reddish palaeosol). Maximum thickness of unit R ~1.4 m. **B**. Calcrete Rcp and residual sand, unit R (arrow), capping West Stack; overlie unit T (reddish palaeosol). Scale = 25 cm. **C**. Gsα, exposed as horizontal platform (arrow) on headland at top of cliffs; overlies calcrete Rcp, underlies unit Q2. **D**. Gsα (detail), showing section through possible burrow exposed at abrasion surface, with partial coating of calcrete Q2cp (scale in centimetres).

developed on Rcp (West Stack and headland), it steps upward to cut across Rcs (exposures 150–300 m north-west of Moyjil; Kay 2014). Abrasion on Gsα in the western part of the headland (adjacent to the point of restoration of Block B; see below) has truncated a possible burrow in the palaeosol of unit S (Figure 7D). On West Stack, the calcrete below Gsα is pervasively fractured to produce polygonal blocks, some of which have been displaced (Figures 8A, B). Cemented to Gsα on West Stack is the basal part of unit Q2, which contains features of archaeological interest, including marine shells (Figure 2A; Nair & Sherwood 2007) and an assemblage of calcrete fragments, many with dark-grey surface staining and some showing evidence of displacement (Figure 8C).

Shallow erosional pits expose the limestone (unit T) below the calcrete in places (Figures 8D, 9).

Unit Q1. Units Q1 and Q2 are both dominantly carbonate units that were deposited during the LIG. Otherwise, however, they are not related. In particular, Q2 belongs to the Bridgewater Formation as part of the Dennington Member whereas Q1 has no formal assignation.

Unit Q1 consists of coarse conglomerate and calcareous sandstone that occupies the LIG wave-cut notches of East and West stacks and is also found as thin lenses around the cliff face and on an island in the Hopkins estuary entrance. Variable in thickness up to 1.7 m, it is disconformable upon units T and V. Pebble- to boulder-sized rounded clasts of calcarenite and calcrete have a matrix of bioclastic sand and rounded shelly fragments. The deposits are cemented by secondary calcite.

Unit Q2. The archaeologically intriguing unit Q2 consists of calcareous sand (Q2s) and a calcrete cap (Q2cs) exposed in cliffs of the headland (Figure 10A) and locally up to 400 m west of Moyjil on the flanks of the Dennington dune (Kay 2014) (Figure 10B). It also includes shells, calcrete fragments and sandy matrix at its base that are distinct from the overlying sand (Q2s) and that are cemented to the top of Rcp (= Gsα; see below). A maximum ~2 m thick on the headland, unit Q2 thins towards the Hopkins River where the two calcrete layers, Rcp and Q2cs, converge, and thickens to over 3 m ~30 m inland, as determined by augering. It is separated from Rcp below by erosion surface Gsα, and is overlain conformably by unit P. The parent sand is massive, well sorted and fine- to medium-grained, and bioclastic, with 15–20% quartz and traces of charcoal. While mostly pale grey, the basal

Figure 8: **A**. Fractured calcrete Rcp, West Stack North (scale = 100 cm). **B**. Imbricated calcrete blocks, West Stack North. **C**. Limestone clasts, including blackened stones, West Stack North. **D**. Erosional pit in Gsα partially filled with shelly sandstone, West Stack South. Scale in **B**, **C**, **D** in centimetres.

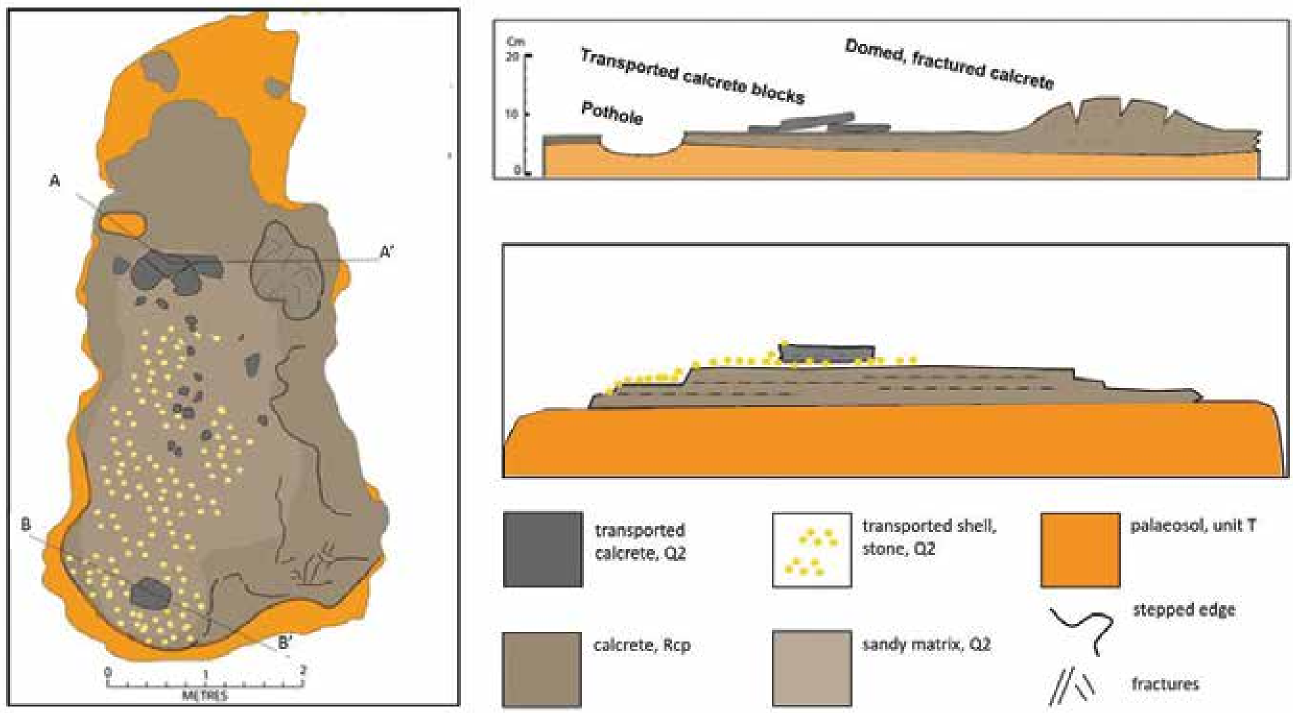

Figure 9: Map and sections showing features associated with Gsα on top of West Stack North. Cross section A-A' is the upper section (right), which shows fractured calcrete (unit R/Rcp), calcrete blocks from unit R (Rcp) that have been transported and imbricated, and an erosional depression in Gsα. B-B' is the lower section (right), showing a transported calcrete block with sandy matrix on Gsα and overlying *in situ* calcrete of unit R (Rcp).

20–30 cm is a red-brown sand with minor clay in the form of detrital ferric clay flakes on some quartz grains. Q2cs is a banded calcrete, 5–100 mm thick, variably of filamentous micrite or micrite-cemented bioclastic grainstone with associated calcareous rhizomorphs. The A-horizon of the calcrete-bearing profile is preserved in one place only, on the west bank of the Hopkins River ~200 m upstream from the headland (Figure 2D). Here, a *terra rossa* ≥1 m thick includes abundant calcareous nodules that increase in size with depth until they coalesce to form calcrete Q2cs. In addition, a minor groundwater calcrete (Q2cp) occurs within and at the base of unit Q2. Unit Q2's fossil assemblage of marine and terrestrial gastropods, foraminifers, crustacean claw fragments and a fish otolith has been described by Nair and Sherwood (2007), with additional taxa (including *Haliotis rubra*) since recovered by JS. Three samples were taken from unit Q2 for OSL age determination (Sherwood et al. 2018a). Associated with unit Q2 is a calcarenite dyke that is exposed on the headland and in Block B. It lies below and mostly parallel to Gsα, and is hosted by units S and T. Locally it transects the palaeosol of unit S. It is 15–50 mm thick and filled largely with massive calcarenite (silt to fine sand) consisting of bioclasts and rounded quartz, together with rare angular limestone clasts, up to 10 mm across, of pale micrite, and is cemented with micritic $CaCO_3$. Locally in the dyke are occurrences of crinkly-laminated micritic $CaCO_3$ with calcified filaments.

The markedly heterogeneous shell–stone (limestone clast) deposit at the base of unit Q2 on the top of West Stack aroused the initial archaeological interest in Moyjil (Sherwood et al. 1994). Several centimetres thick on WsN, the shell–stone layer becomes finer to the south and terminates abruptly on WsS where part of the deposit occupies pits in calcrete (Rcp; Figure 8D). On the headland, similar stones are cemented to Gsα but shells are absent, though similar shells are scattered through the overlying sands of unit Q2. Stones include white calcrete, reddish limestone and dark limestone. In particular, we make the following observations:

- Pale calcrete blocks are commonly angular (Figures 8A, B). Lozenge-shaped examples on the northern margin of WsN have moved a short distance (up to 1 m) from their source in the underlying calcrete (Rcp), while on the south-west margin of WsN another block,

Figure 10: **A**. Unit Q2 on Moyjil headland showing friable sand capped by calcrete. **B**. Two calcrete horizons in Dennington dune, ~300 m north-west of Moyjil. Lower calcrete is Rcs at top of unit R; upper calcrete is Q2cs, part of unit Q2 which includes unconsolidated sand between the two calcretes. **C**. Calcrete and palaeosol blocks, shells and sandy matrix on top of West Stack North. Scale is in centimetres. **D**. Discoloured calcrete blocks (arrows), one on top of the other, and cemented together, at base of unit Q2; Moyjil headland. Lens cap = 7.2 cm.

25–30 cm wide and 4–5 cm thick, appears to have been thrust into and over shell debris (Figure 10D). Some stones display post-rounding fractures.

- Dark (grey to black) stones are typically smaller than other stones, and are rounded and polished.
- The concentration of stones diminishes towards the south as the proportion of shell debris increases.
- The deposit has a matrix of reddish muddy sand. Reddish matrix fills *Lunella* shells.

Goede (1989) measured equivalent doses (ED) for *L. undulata* from two LIG beach deposits (unit Q1) and from the top of West Stack (unit Q2):

– LIG beach deposit (East Stack), ED = 126 Gray (Gy), 149 Gy (duplicate measurements)
– LIG beach deposit (north-east of East Stack), ED = 176 Gy
– West Stack, ED = 106 Gy.

He concluded all shells were from the LIG, with West Stack shells possibly younger than the LIG beach deposits.

Ground surface beta (Gsβ). Gsβ is exposed as a horizontal platform at the top of Moyjil headland. It is developed on the calcrete (Q2cs) at the top of unit Q2, and underlies unit P. Surficial features include mammillary calcite and minor karstic corrosion. Comparison of the headland and Hopkins River sections, where a virtually complete palaeosol profile includes Q2cs ~2.4 m below the palaeosol's top, demonstrates the erosional nature of Gsβ. On Moyjil's eastern side calcrete and palaeosol fragments (stones), 5–135 cm across, together with shell fragments, are cemented to Gsβ. The stones occur in at least four circular hearth-like arrangements (~0.5 m diameter) and, like the shell fragments, show varying degrees of blackening. These features do not form part of the present paper and will be reported elsewhere.

Unit P. Unit P is a weathered and/or pedified deposit with volcanogenic components that suggest at least partial derivation from the Tower Hill Tuff (Sherwood et al. 2004), part of the Newer Volcanic Group (VandenBerg 2009). In the Hopkins River section, where it is best preserved, it is 80 cm thick with black soil above and retains some volcanic stratification. Here it overlies the *terra rossa* of unit Q2 with virtually no erosional break (Figure 2D). On the headland, unit P overlies Gsβ and calcrete Q2cs. Here it is massive and largely calcareous, with marine bioclasts and quartz grains commonly bearing thin opaque coatings. Trace mafic minerals are of volcanic origin. The headland occurrence may represent a pedified debris-flow deposit derived from the remobilisation of tuff, calcareous sand and limestone clasts.

Stratigraphy of geomorphic units at Moyjil

Because of lateral variation in the distribution of stratigraphic units at Moyjil, the stratigraphic composition varies from one geomorphic feature to another, and is summarised in Table 2.

Correlation, West Stack–headland. The relationship of the erosional surface on West Stack, the substrate of the critical shelly deposit, to the erosional surface on the adjacent headland, the substrate of unit Q2 with its dispersed assemblage of shells and hearth-like features, is of primary importance. If the erosional surfaces in the two areas both belong to Gsα and can therefore be correlated,

Table 2: Distribution of informal stratigraphic units across selected geomorphic units at Moyjil. Tick (✓) = unit is present; v = vestigial occurrence; Rcp = occurrence of calcrete Rcp but no other part of unit R. On WsN, unit R is represented by Rcp and vestigial calcarenite. Headland (west) is west of the East Stack lookout; headland (east) is east of it. Note that calcretes Rcp and Q2cs merge on the eastern side of the headland.

<table>
<tr><th>Unit code</th><th>headland (west)</th><th>headland (east)</th><th>West Stack North</th><th>West Stack South</th><th>Block B</th><th>East Stack</th><th>Hopkins River Bank</th></tr>
<tr><td>P</td><td>×</td><td>✓</td><td>×</td><td>×</td><td>×</td><td>×</td><td>✓</td></tr>
<tr><td>Gsβ</td><td>✓</td><td>✓</td><td>×</td><td>×</td><td>×</td><td>×</td><td>✓</td></tr>
<tr><td>Q2</td><td>✓</td><td>✓</td><td>✓ v</td><td>✓ v</td><td>✓ Q2cs</td><td>×</td><td>✓</td></tr>
<tr><td>Q1</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td></td><td>✓</td><td>×</td></tr>
<tr><td>Gsα</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>×</td></tr>
<tr><td>R</td><td>✓</td><td rowspan="2">R or S</td><td>✓</td><td>✓ Rcp</td><td>✓ Rcp</td><td>✓ Rcp</td><td>×</td></tr>
<tr><td>S</td><td>✓</td><td>×</td><td>×</td><td>✓</td><td>×</td><td>×</td></tr>
<tr><td>T</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>×</td><td rowspan="2">T or V</td></tr>
<tr><td>V</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>×</td><td>✓</td></tr>
</table>

it is reasonable then to correlate the shelly deposit on West Stack with unit Q2 on the headland, as both rest upon Gsα in close proximity to each other. That is, the shelly deposit on West Stack belongs to Q2. Equivalence of the two erosional surfaces and of the overlying deposits is demonstrated by the following:

1. Equivalent elevation. While West Stack is now tilted due to partial collapse, a 1907 postcard (Figure 11) shows it in pre-collapse position with a horizontal upper (erosional) surface. Restoration to its original position brings the top of the stack to 8.2 ± 0.2 m AHD. The erosional surface on the headland directly opposite at a distance of <15 m is at 8.2 ± 0.2 m AHD.
2. Presence of LIG index fossil. An operculum from *Lunella torquata* syn. *Turbo torquatus* has been identified in sand on WsS. This is an index fossil for the LIG in western Victoria (Valentine 1965), and no longer occurs there. Unit Q2 on the headland is also of LIG age (Sherwood et al. 2018a).
3. The same dominant species and preservational style of shell deposits directly overlying the erosional surfaces. *Lunella undulata* and *Sabia conica* are dominant in each shell assemblage. Fragmented shells in both assemblages show no signs of abrasion.
4. Comparable racemisation ratios of *L. undulata* shell and opercula from deposits directly overlying the erosional surfaces. An amino acid racemisation study of three West Stack shells and one operculum yielded scattered but comparable D/L ratios to one whole shell and one operculum from unit Q2 on the headland, based on 11 amino acids. Consequently, the results for both locations and types of sample were combined in Sherwood et al. (1994).
5. Uniformly old radiocarbon ages of shells from deposits directly overlying the erosional surfaces. *L. undulata* shells from headland and stack give carbon-14 ages at the limit of the method (Sherwood et al. 1994, Nair & Sherwood 2007):

- Headland unit Q2 (whole shell) >30 ka (ARL131)
- West Stack (whole shell) 42.1 ka (SUA2271)
- West Stack (aragonite fraction of a shell) 35.7 ka (SUA2491)
- West Stack (calcitic fraction of same shell) 27.9 ka (SUA2491B)
- West Stack (whole shell) >40 ka (Wk 17335).

The relatively old ages distinguish these shells from, for instance, shells in Holocene middens that also occur along the coastline at Warrnambool.

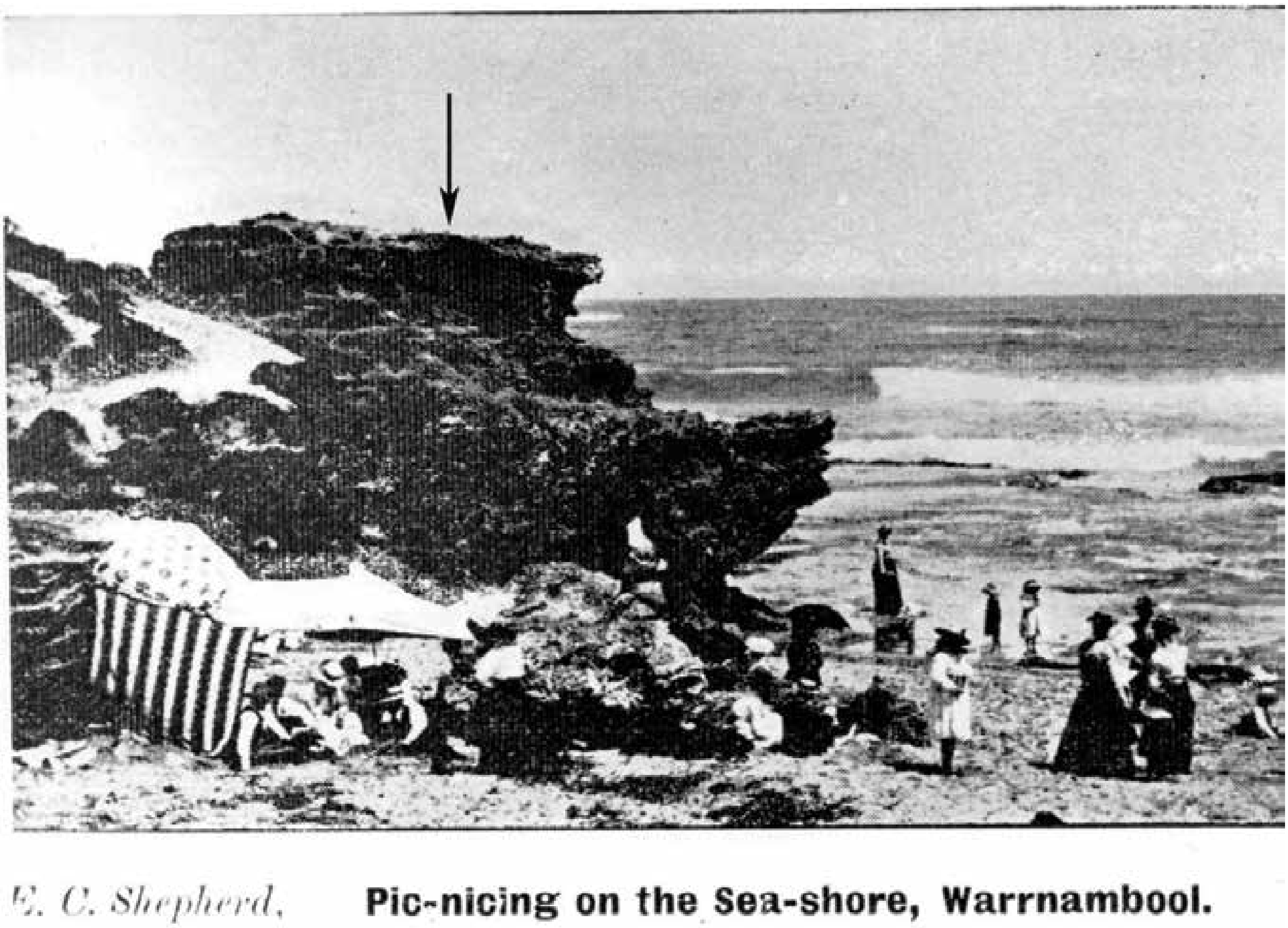

Figure 11: Postcard from 1907 showing West Stack (arrow; view east) prior to partial collapse that took place at an unknown time in the twentieth century.

Block B. Block B best displays a marine abrasion surface (Gsα) at its upper stratigraphic surface and is significant in showing the sea level at the time of its formation. It can be restored to its original position on the cliff above (~+8 m AHD) by matching shared stratigraphic features, including: a reddish palaeosol with fine rhizomorphs at the top of unit T; a graded pebbly calcareous sand 5–15 cm thick at the base of unit S; fragmentation of part of the unit S palaeosol; the Gsα-mantling calcrete Rcp; and the calcarenite dyke that transects unit S. When restored, the grossly planar abrasion surface is continuous with Gsα of the headland. The heterogeneous stones in potholes in the abrasion surface are dominated by reddish clasts derived from the planated palaeosol, but include small pebbles of dark grey to black limestone and a single flake of calcrete. One large pebble consists of reddish palaeosol with a 1-cm crust of laminated calcrete on one side, and is derived from the contact of units S and Rcp. A calcareous rhizomorph (diameter ~5 mm) bridging a linear depression on the abrasion surface, together with other rhizomorphs, is related to a later generation of calcrete, Q2cs (Figure 2B).

DISCUSSION

Major disturbance

Rock fracturing and the presence of probable mass-flow deposits at several levels of the Moyjil succession attest to repeated violent events. Here we discuss the oldest of these, designated the Z-event.

Z-event. Evidence for the Z-event is associated with the erosional surface, Gsα, and appears across the headland and the top of West Stack. Prior to the event, Gsα had been exposed by erosion of the unit R sands from above calcrete Rcp, and was an unbroken surface from the headland to what is now West Stack. During the event, Rcp and the underlying palaeosol of unit S were fractured to depths of up to 30–40 cm and some of the resultant blocks underwent transport over distances of decimetres. Simultaneously, smaller blackened stones, fragmented shells and a calcareous matrix of muddy sand were carried across West Stack as a debris flow, which mixed with the newly formed calcrete blocks and caused some of the latter to over-ride each other (Figures 8A, B). The source of the debris flow is envisaged to be the seaward slope of the Dennington dune just landward of the exposed Gsα, with liquefaction of well-sorted dune sand facilitated by groundwater flow within the dune toward the sea. The flow came to rest as it crossed West Stack, with its distal deposits consisting of shells and matrix and only a few small stones. The resultant layer, a debrite, is a few centimetres thick and was cemented to Gsα to form the basal part of unit Q2. Given the widespread volcanism of the Newer Volcanics Province from the late Miocene to the present, related seismicity is likely to have provided the trigger for the Z-event. This is consistent with historical records of an earthquake of magnitude ML = 5.3 causing significant damage to infrastructure at Warrnambool in 1903 (McCue 1978). Very soon after the Z-event, groups of stones now incorporated into unit Q2 sands on the headland were moved, with some balanced on others (Figure 10D), and subjected to blackening, possibly by fire.

Fire

Dark staining of calcrete stones, which occur on Gsα and the marine abrasion surface of Block B, has raised the question of causation by fire (Bowler et al. 2018). A detailed study to test the fire hypothesis examined the colour change from pale calcrete to dark grey/black stones (Bowler et al. 2018). The colour change can be replicated in small, hearth-sized wood fires. Correlations between the size of stones and their colour, and between their colour and magnetic susceptibility, support the conclusion that fire controlled the variation in the three attributes. In addition, the ages determined by thermoluminescence analysis of small black stones from Gsα on the headland reflect thermal resetting near the time of their deposition as part of unit Q2 rather than the age of their source, unit R. Spatial clustering of the darkened stones in some cases may be reminiscent of hearths of human agency (see Bowler et al. 2018 and McNiven et al. 2018 for discussion).

Marine abrasion surface

We identify a well-developed marine abrasion surface (Gsα) extending across part of the headland, West Stack and Block B, which formed a platform upon which a variety of processes subsequently took place, including some that have been suggested to be associated with human activities. The formation of the surface is interpreted as follows, with particular reference to Block B because of the excellent exposure of its features.

1. Erosion of a surface, planar and polished and at an elevation of +8 m AHD, across the palaeosol of unit S on Block B and the headland was due to vigorous sand-armoured wave abrasion. The measured elevation approximates the +7.5 m AHD level identified as marking the LIG highstand in the Warrnambool area by Gill and Amin (1975). Abrasion occurred in a coastal setting similar to today's at Moyjil but when sea level was higher (LIG). High-energy wave action in the LIG coastal zone eroded unit R sands down to the basal Rcp calcrete and, in part on West Stack and Block B, through the calcrete to the underlying unit.

2. Depressions interpreted as potholes are smaller-scale features of the surface. The pronounced elongation of some depressions on Block B may be controlled by jointing, in contrast to the depressions on Block F that lack elongation. The rounded edges of the depressions on both blocks suggest erosion similar to what occurs on shore platforms cut into the Bridgewater Formation today.
3. Some of the stones in the depressions (potholes) are reddish and clearly derived from the palaeosol of unit S directly beneath the abrasion surface. One, a reddish clast mantled with laminated calcrete, was evidently eroded from the calcrete (Rcp)-coated palaeosol of unit S. A single large clast of pale calcrete presumably came from Rcp.
4. Partial blackening of the surface is reminiscent of blackening of stones in the potholes and at the base of unit Q2 on the headland. The blackened stones may have played no role in formation of the potholes but subsequently accumulated there.
5. Preservation of the stones in the potholes suggests a slight fall in sea level from the LIG highstand after which blackening occurred.
6. Fracturing of the surface, including calcrete Rcp, reflects an energetic event (Z-event, see above) for which evidence, including the transport of shelly fossils, is seen on West Stack. Preservation of the fractured rock *in situ* implies retreat of the sea prior to the Z-event.
7. A thin veneer of pale carbonate with small rhizomorphs (Figure 2B) coats part of the surface and testifies to burial beneath later sand cover (unit Q2).

Sequence of events, with reference to geochronology

The stratigraphy and geomorphology of Moyjil are here interpreted in terms of sea-level variation and other processes that provide context for the accumulation there of the archaeologically interesting materials (marine shells and blackened stones).

Dune superposition. While the succession of Pleistocene coastal dunes at Warrnambool displays a general progradational pattern (Gill 1976), the present study clearly shows that the Dennington dune system at Moyjil is a complex of older and younger components. The Dennington Member, represented here by unit Q2, is LIG in age, as suggested by Reeckmann and Gill (1981). However, it rests on the significantly older unit R (>200 ka; Sherwood et al. 2018a), with units S, T and V older again. At the commencement of deposition of unit Q2, a debris flow, sourced from a dune just landward of Moyjil and triggered by an event (Z-event) such as an earthquake, delivered heterogeneous sediment including shells and stones to Gsα. Particularly significant, the flow lines of infiltrating soil water, on meeting less permeable boundaries, would trend towards the southern toe of the dune. In the highly calcareous Dennington dune, such waters may be responsible for substantial downslope diagenetic changes, including solution and precipitation resulting in cementation (see also Reeckmann & Gill 1981).

Geochronological control. The host unit Q2 is part of the Dennington Member, which Reeckmann and Gill (1981) ascribed to the Last Interglacial. Oyston (1996) provided thermoluminescence (TL) ages of 93 ± 11 ka and 80 ± 10 ka for unit Q2, and additional ages determined by a range of methods were summarised by Sherwood et al. (1994) and Nair and Sherwood (2007). New ages (Sherwood et al. 2018a) clarify the age of unit Q2 and the underlying unit R as follows:

- Amino acid racemisation analysis of shells from unit Q2, by Colin Murray-Wallace, Wollongong University, showed *Lunella undulata* opercula in unit Q2 had similar D/L ratios to those of LIG beach deposits (unit Q1) on East and West Stacks.
- Optically stimulated luminescence analysis, performed by Nigel Spooner, University of Adelaide, on three samples from different levels within unit Q2 sand showed considerable overdispersion. A three-component Finite Mixing Model gave ages of 123–146 ka, with a likely depositional age near 125 ka. An additional sample from unit R calcrete (Rcp) yielded an age of 239 ± 17 ka using a Central Age Model.

Thus, the sand of unit Q2 was deposited during the LIG, and is older than estimated by Oyston (1996). The sand of unit R is about 100 ky older than unit Q2.

Summary. Units V, T and S represent early phases of coastal dune and palaeosol development of the Bridgewater Formation at Moyjil, with dune formation requiring high sea levels and palaeosols forming at lower sea levels when source calcareous sands were distant. Prior to the formation of archaeologically intriguing features, the aeolian sand of unit R, with an OSL age of ~240 ka, was deposited and its two calcretes (Rcs and Rcp) developed in response to pedogenesis and groundwater processes, respectively. Erosion of the seaward part of unit R down to calcrete Rcp created a distinctive marine abrasion surface, Gsα, at a time of high sea level. Gsα was buried by unit Q2 whose OSL ages, in the range 123–146 ka, are consistent with deposition following the +8 m MIS 5 highstand at 120–125 ka. The various wave-cut notches and their associated coarse beach deposits (Q1) at +3–6 m AHD also formed around this time, just before Q2. This suggests that Gsα formed close to 125 ka and, prior to burial, (i) hosted shell accumulation and possibly fire; (ii) was shattered, perhaps by a seismic event; and (iii) had a shell/stone-bearing debris flow at least partially derived from a landward dune coming to rest on it. The debrite was then buried by sand with occasional shells and charcoal fragments before being stabilised by vegetation and developing a soil, including a calcrete (Q2cs), during an interval of lower sea level. Pedogenesis of unit Q2 essentially concluded with the eruption of Tower Hill and deposition of the Tower Hill Tuff at ~35 ka.

CONCLUSION

Shelly remains and blackened stones on surfaces at Moyjil have been suggested to have a human origin. In examining the geological context to these features, we establish an informal stratigraphy of the Bridgewater Formation and associated deposits at Moyjil. The Bridgewater Formation consists of several calcarenite–palaeosol units (units Q2, R, S, T and V) formed as coastal dune-barrier systems. Of these, unit Q2 is important in hosting the putative archaeological features. Unit Q2's position below unit P, the Tower Hill Tuff (~35 ka), establishes a substantial age for those features. Pronounced breaks in the succession, represented by the surfaces Gsα (between units R and Q2) and Gsβ (top of unit Q2), are erosional in character. Gsα was cut in unit R during the LIG highstand (~120–125 ka). As sea level began to fall, wave-cut notches and coarse beach deposits (unit Q1) developed at +3–6 m AHD. Gsα hosted both local blackening, probably due to fire, and a debris flow, whose constituents included shells and blackened stones, both of archaeological interest. Continuing eustatic fall was accompanied by soil development (including calcrete) on unit Q2 until the Tower Hill Tuff buried the area.

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