

Coquina beach-ridge system sedimentary architecture and evolution in Hamelin Pool, Shark Bay

Arquitetura sedimentar e evolução de um sistema de cordões litorâneos bioclásticos em Hamelin Pool, Shark Bay

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ABSTRACT

Shark Bay displays a unique Holocene bioclastic (coquina) beach-ridge system in Hamelin Pool and L'Haridon Bight hypersaline basins. Aerial imagery, GPR profiles, radiocarbon chronology and sedimentological data were used to delineate a depositional and evolutionary model for bioclastic beach-ridge deposits in Hamelin Pool eastern and western shores. The onset of the bioclastic beach-ridge system took place about 5000 ¹⁴C years BP facilitated by abundant shell supply and falling sea level conditions under episodes of high-water levels induced by storms. Prograding seaward inclined GPR reflections are the prevailing architectural elements and result from swash-backwash processes in the beachface during elevated water level episodes. Another important feature is a diachronous blanket of deposits generated by storm-surge events and eolian processes. During the latest Holocene, marked environmental changes within Hamelin Pool are suggested by a number of indications such as change in the depositional style of beach-ridge deposits; overall lower ridge elevations and the occurrence of an important erosive period after 1450 ¹⁴C years BP in the western shore. Although the ages obtained for the ridge sets mapped in both eastern and western shores of Hamelin Pool are roughly similar, they exhibit differences in sedimentary architecture and coastal morphology as a result of different degrees of vulnerability to storms, and secondarily to variable reworking processes such as tidal currents, waves and longshore currents which may also be energetic enough during fair-weather conditions to transport sediment in the nearshore environment. A depositional model is proposed where washovers and storm-surge ridges are deposited by overwash episodes at the peak of major storms while berm construction occurs during the waning phase by swash, backwash, overtopping and minor overwashing processes. This model provides an example of high-resolution depositional architecture that is useful for reservoir characterization and prediction.

Keywords: coquina, beach ridges, Shark Bay, GPR, bioclastic deposits.

RESUMO

Em Shark Bay, nas bacias hipersalinas de Hamelin Pool e L'Haridon Bight, ocorre um singular sistema holocênico de cordões litorâneos bioclásticos. Objetivando delinear um modelo deposicional e evolutivo para os cordões litorâneos nas margens leste e oeste de Hamelin Pool, foram utilizados perfis de GPR, imagens aéreas, cronologia de radiocarbono e dados sedimentológicos. O início do sistema ocorreu há cerca de 5000 anos ¹⁴C, facilitado pela abundância de conchas e condições de rebaixamento do nível do mar, com episódios de aumento do nível de água induzidos por tempestades. Os principais elementos arquiteturais observados nas seções de GPR são refletores inclinados progradantes em direção ao mar, que resultam de processos de swash-backwash na face da praia durante episódios de elevação do nível da água. Outra característica importante são depósitos diacrônicos gerados por eventos de tempestades e processos eólicos. No final do Holoceno, mudanças ambientais marcantes em Hamelin Pool são sugeridas por uma série de indicadores, como a alteração no estilo deposicional dos cordões, em geral mais baixos, e a ocorrência de um importante período erosivo após 1450 anos ¹⁴C na margem oeste. Embora as idades obtidas para os conjuntos de cordões mapeados nas margens leste e oeste de Hamelin Pool sejam semelhantes, elas exibem diferenças na arquitetura sedimentar e na morfologia costeira como resultado de diferentes graus de vulnerabilidade a tempestades e, secundariamente, a diferentes processos de ressedimentação relacionados à ação de correntes de maré, de ondas e de correntes paralelas à costa, que podem ter energia suficiente para o transporte de sedimentos no ambiente costeiro em condições de tempo bom. Propõe-se um modelo deposicional onde washovers e storm-surge ridges são depositados por episódios de overwash no pico de grandes tempestades, enquanto a construção de bermas ocorre durante a fase de waning por meio de processos de swash, backwash, transbordamento e pequenas ocorrências de overwashing.

Palavras-chave: coquina, cordões litorâneos, Shark Bay, GPR, depósitos bioclásticos.

1. INTRODUCTION

Beach ridges are coastal progradational landforms, approximately parallel to the coast. They develop in various settings around the world as a result of multiple coastal and nearshore processes where sediment supply is sufficiently high.

In Shark Bay (Figure 1), *Fragum erugatum* coquina beaches and beach ridges are a typical coastal feature. They form when large quantities of shells are transported to the supratidal environment by storm events. The high productivity and availability of *Fragum* shells is characteristic of Shark Bay hypersaline environments where this bivalve mollusk thrives by benefiting from an endosymbiotic relationship with zooxanthellae algae (Berry and Playford, 1997).

Storms and tsunamis are extreme events that cause temporary marine inundations of coastal areas. Such inundations combine with waves and transport marine coarse sediment onto the shore and deposit it on the supratidal zone. Worldwide, a number of shell-rich deposits have been interpreted as products of extreme events (Aigner, 1985; Boyajian and Thayer, 1995; Carvalho

et al., 2000; Morales et al., 2008; Massari et al., 2009; Nott, 2011; Varela et al., 2011; Jahnert et al., 2012). Scheffers et al. (2008) demonstrate a number of coastal areas in Western Australia that provide evidence of tsunami effects but reject any direct tsunami impact to the inner parts of Shark Bay since they are relatively protected from the open sea. On the other hand, tropical cyclones are common hazards in the area, with a historical average (since 1906) of about one cyclone impact in the vicinity of Shark Bay per five years, potentially causing storm surges as high as 4.3 m (Bureau of Meteorology, n.d., b).

After the regional work of Logan et al. (1970) and Logan et al. (1974), only recently Shark Bay coquinas have attracted scientific interest with respect to their evolution and sedimentary architecture. Nott (2011) used numerical modelling of palaeo-cyclone intensities and radiocarbon chronology to appraise palaeotempestological aspects of the Holocene climate in the Shark Bay area. Jahnert et al. (2012) focused on the depositional evolution of coquina beach ridges in Shark Bay describing their sedimentary architecture and assessing their chronology.

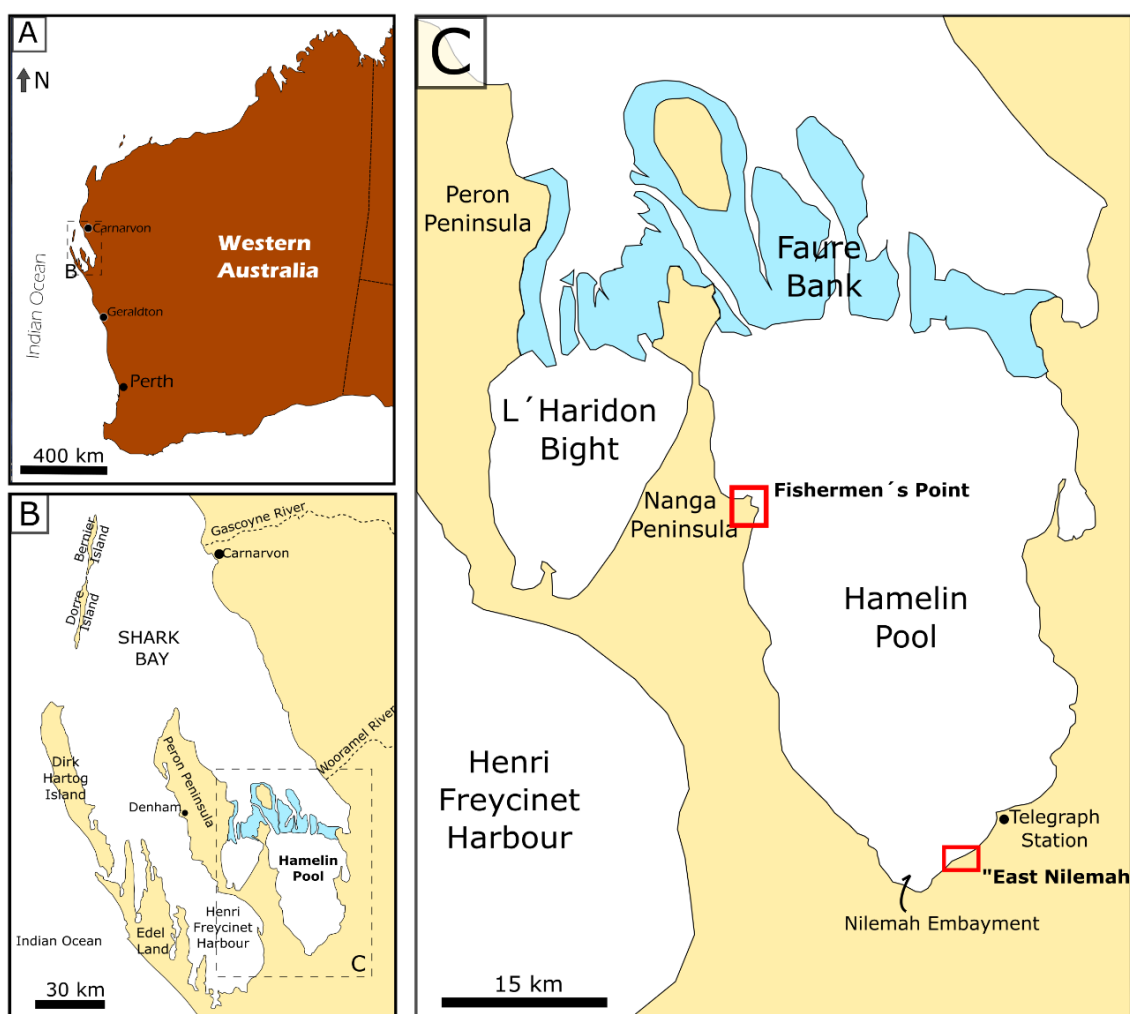


Figure 1. Location map of Shark Bay showing the study areas in Hamelin Pool named 'East Nilemah' and Fishermen's Point.

The aim of this paper is to document the architectural and sedimentary characteristics of coquina beach ridges using GPR, radiocarbon chronology, outcrop, trench and core data proposing a depositional model that outlines an evolutionary framework for coquinas and associated facies deposited in Shark Bay, Western Australia.

2. GENERAL SETTING

Shark Bay is a large shallow embayment of approximately 8000 km² area, where overall water depths are less than 30 m. It is separated from the Indian Ocean by Edel Land, Dirk Hartog Island and the Bernier-Dorre Island chain (Figure 1B). The peninsulas and islands within Shark Bay display an overall north-trending orientation, which is linked to controlling subsurface Tertiary anticlines (Playford and Cockbain, 1976 apud Butcher et al., 1984).

The climate is semi-arid with an average rainfall between 200 and 300 mm which is surpassed by the annual evaporation of 2400–2800 mm (Logan and Cebulski, 1970; Bureau of Meteorology, n.d.a). The Gascoyne and Wooramel rivers drain into Shark Bay, but their flow is spasmodic, and their runoff is negligible, only transporting sediments after heavy rains caused by storms and cyclones (Logan and Cebulski, 1970; Logan, Read and Davies, 1970).

The dominant wind direction in Shark Bay is from the south, nonetheless winds tend to be more easterly and southeasterly, occasionally northerly during winter (Bureau of Meteorology, n.d.c). Intense barometric depressions originate in the Timor Sea and progress south-west along the coast before weakening. These tropical cyclones and storms occur periodically and are accompanied by heavy rainfall and gales that can gust up to 180 km/hour (Logan and Cebulski, 1970; Hagan and Logan, 1974; Bureau of Meteorology, n.d.b).

Hamelin Pool has different geological foundations in its eastern and western shores. To the east and southeast Hamelin Pool waters reach Carbla Plateau which is underlain by the Cretaceous Toolonga Calcilutite. To the west, Hamelin Pool waters encounter Nanga Peninsula, whose country rock is composed of Plio-Pleistocene Peron Sandstone (Hagan and Logan, 1974).

An additional distinctive aspect between eastern and western shores is the degree of exposure to storms. Tropical cyclones and storms progress in a south-west direction after originating in the Timor Sea. For that reason, coasts facing west or north-west like those occurring in the eastern shore are more vulnerable to storm impacts and tend to experience higher energy processes and higher elevation surges than east-facing coasts in the western shore.

Shark Bay salinity distribution is affected by the restriction of water exchange with the ocean provided by

a number of islands, flats, and sills. Furthermore, Shark Bay salinities increase to the south, from normal marine at the seaward opening to hypersaline in the bay heads. Logan and Cebulski (1970) subdivided Shark Bay waters into three separate categories: oceanic, with salinities ranging from 30 to 40 ‰; metahaline, where salinities range from 40 to 56 ‰ and; hypersaline, with salinities from 56 to 70 ‰.

The onset of an hypersaline environment took place in Hamelin Pool and L'Haridon Bight (Figure 1C) as a result of (1) restriction to oceanic water circulation within the bay provided by Faure seagrass bank growth; (2) High evaporation under semi-arid climatic setting; and (3) Falling sea-level conditions after a Holocene post glacial transgressive period (Logan and Cebulski, 1970; Logan et al., 1974). Collins et al. (2006) indicate a Holocene highstand of about +2 m at approximately 6800 U/Th years BP using coral pavement data from Houtman Abrolhos Islands, Western Australia. Other authors have also recognized evidence for falling sea-level conditions in Shark Bay during the last 6000 years BP (e.g. Logan et al., 1974; Jahnert and Collins, 2011; Jahnert and Collins, 2013).

The small bivalve mollusk (< 15 mm long) *Fragum erugatum* has a high skeletal productivity within Shark Bay hypersaline environments where competition and predation are limited. Despite living *Fragum* occurring in the subtidal zone between 1.2 and 6.5 m depth (Berry and Playford, 1997), a vast amount of shells are washed ashore by storms and accumulated as supratidal coquina ridges.

In the hypersaline basins of Shark Bay, the sediments consist mainly of microbial mats, stromatolites, thrombolites, cryptomicrobial deposits and coquinas (Logan et al., 1970; Logan et al., 1974; Jahnert and Collins, 2012). Ooid, bioclast and quartz sands are also important lithologies observed in the Hamelin Pool nearshore environment.

3. MATERIALS AND METHODS

Georeferenced maps were constructed using high resolution (50 cm/pixel) Shark Bay orthophotos from Department of Parks and Wildlife and from Landgate (Perth, Western Australia) on ArcGIS software.

Transects were produced using a high resolution DGPS system (SOKKIA antenna and Allegro System) to provide elevation within 25 cm precision and horizontal positioning accuracy of 50 cm.

Ground Penetrating Radar (GPR) equipment from Mala Professional Explorer coupled with a high precision real time kinematic (RTK) GPS system was employed to obtain subsurface images. GPR data was acquired using 250 and 500 MHz antennas. The trace increment was 5 cm, and the time sampling interval 0.2 ns. The Thales ZMAX RTK GPS system consists of a base station with radio

transmitter continuously correcting positions measured by the mobile Rover unit to obtain centimeter accurate elevations. Coordinates were directly linked to the recorded GPR traces by the acquisition software Groundvision 2, while GPR measurements were triggered in the distance domain with a wheel. Radar penetration depth was limited by the saline water table. Thirteen different radar facies were identified in the GPR lines (Figure 2). A standard terminology which is summarized by Neal (2004) was used with minor adaptations for the description of radar reflection geometries.

Sediment sampling consisted of push cores and hand samples. The cores have a maximum depth of 2 m, using 50 mm PVC tubes. Sedimentary structures were generally not preserved in the push cores as coring was performed by percussion in mostly dry loose sediment. Only the last few centimeters of the core bottoms

intercepted the water table where sand or finer sediments tend to be more compact. Hand samples were collected at the surface or in pits with a maximum depth of 1.9 m.

^{14}C ages were determined using analytical procedures of Beta Analytic Radiocarbon Dating Laboratory, Florida, USA. All samples were counted using AMS techniques on *Fragum erugatum* shells.

Thin sections were produced by Minerex Services, Esperance, Australia and analyzed using a Nikon ECLIPSE LV100POL microscope (Nikon Corporation, Tokyo, Japan) and imaged with Nikon NIS Elements software at Curtin University, Australia.

Mineralogical analyses using X-ray diffraction were performed by the Centre for Materials Research X-ray laboratory at Curtin University.

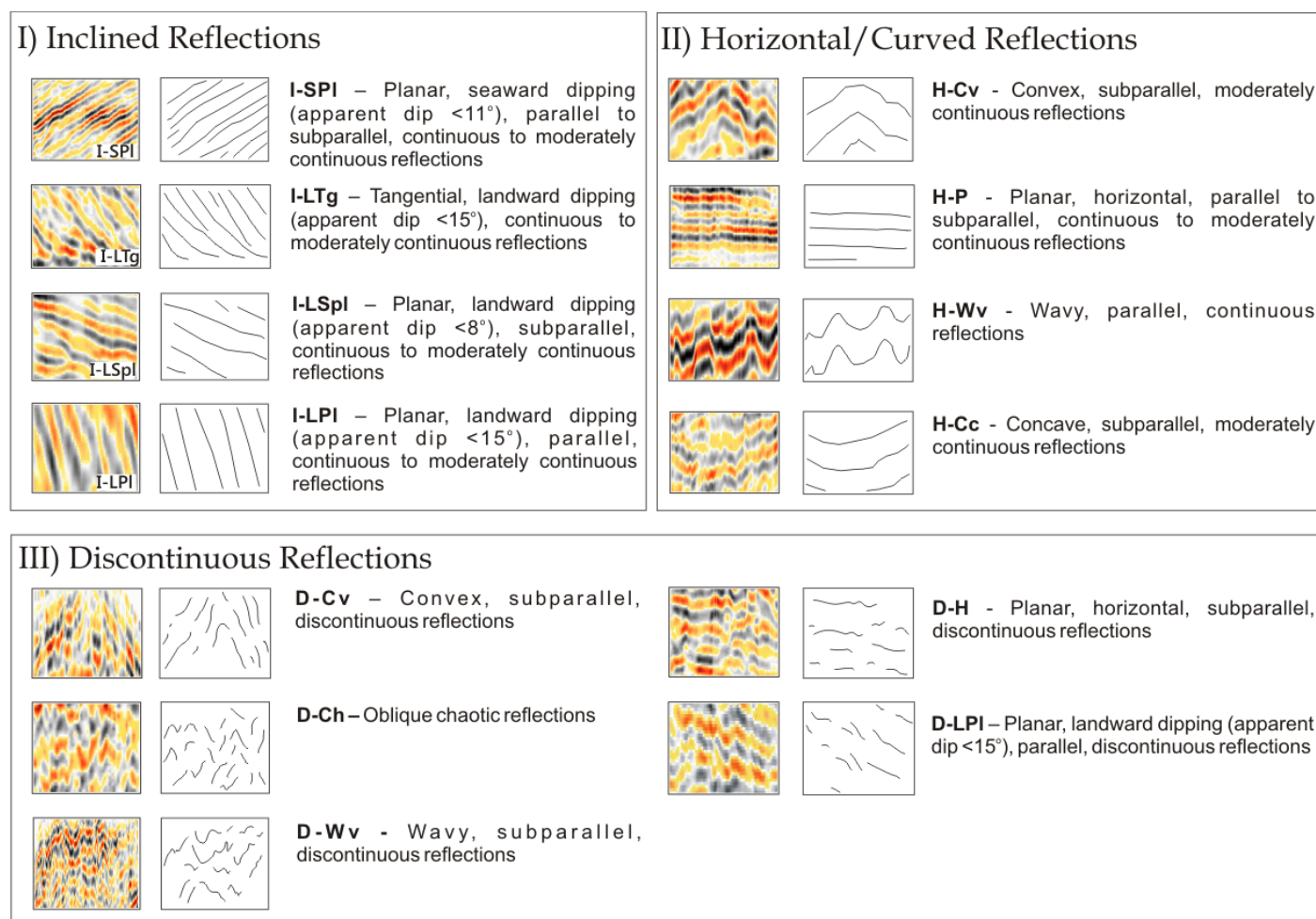


Figure 2. The main radar facies identified in GPR lines can be divided into three major groups: inclined, horizontal/curved and discontinuous reflections.

4. RESULTS

Shark Bay region is subject to sporadic storm events, especially tropical cyclones that exert important control on coastal geomorphology inducing complex cut-and-fill structures and extensive sediment remobilization in the nearshore environment. To address the depositional complexity of coquinas and related deposits in the beach-ridge system, multiple approaches were used emphasizing the geomorphology, geometric and textural characteristics of deposits and their temporal relationships. Three elementary categories were used to guide the interpretation of the processes that governed the formation, shaping and evolution of the beach-ridge system in the study area. These categories are geomorphic elements, depositional elements and depositional domains.

4.1. Geomorphic elements

Geomorphic elements are the surficial expression of beach ridge system building processes. Geomorphic elements of different hierarchies were recognized based on aerial imagery of the studied sites (Figure 3): beach ridges, spit ridges, longshore bars, washover fans, beach-ridge sets, tidal flats, eolian dunes, beach-ridge system and a flat eroded area where an indurated pavement occasionally outcrops in Fishermen's Point. Their size ranges from a few meters (longshore bars) to several kilometers (beach ridge system).

4.2. Depositional elements and depositional domains

The term 'depositional element' is here used to distinguish genetically linked sedimentary bodies with

particular geometries and associated textures. Thus, depositional elements reflect specific sedimentary processes that generate geometries which can be interpreted in GPR lines, outcrops and trenches complemented by push-cores that provided textural information in selected locations. In view of that, five depositional elements were recognized based on GPR profiles, cores, orthophoto images and field observations (Table 1): beach, washover, welded longshore bar, spit and storm-surge ridge.

The beach depositional element results from sedimentation on the sloping face of the beach (beachface) and on the berm crest resulting from swash, backwash, overtopping and minor overwashing processes. Figure 4A illustrates an active berm in Hamelin Pool during low water level. In GPR profiles, this element exhibits seaward dipping reflectors with gentle slope. Occasionally, high-water shell strands and berm crests are preserved from erosion. They display mounded external geometry and internally possess horizontally parallel, convex-up or reflection-free radar facies.

The washover depositional element refers to sedimentary deposits that result from the overwashing of a barrier under high-energy conditions. Figure 4D illustrates a washover fan on the western shore of Hamelin Pool. In GPR profiles washovers were identified by horizontal to landward dipping reflectors occurring in the landward side of a ridge. Figure 3A illustrates an example of a washover fan at 'East Nilemah' site as seen in aerial imagery.

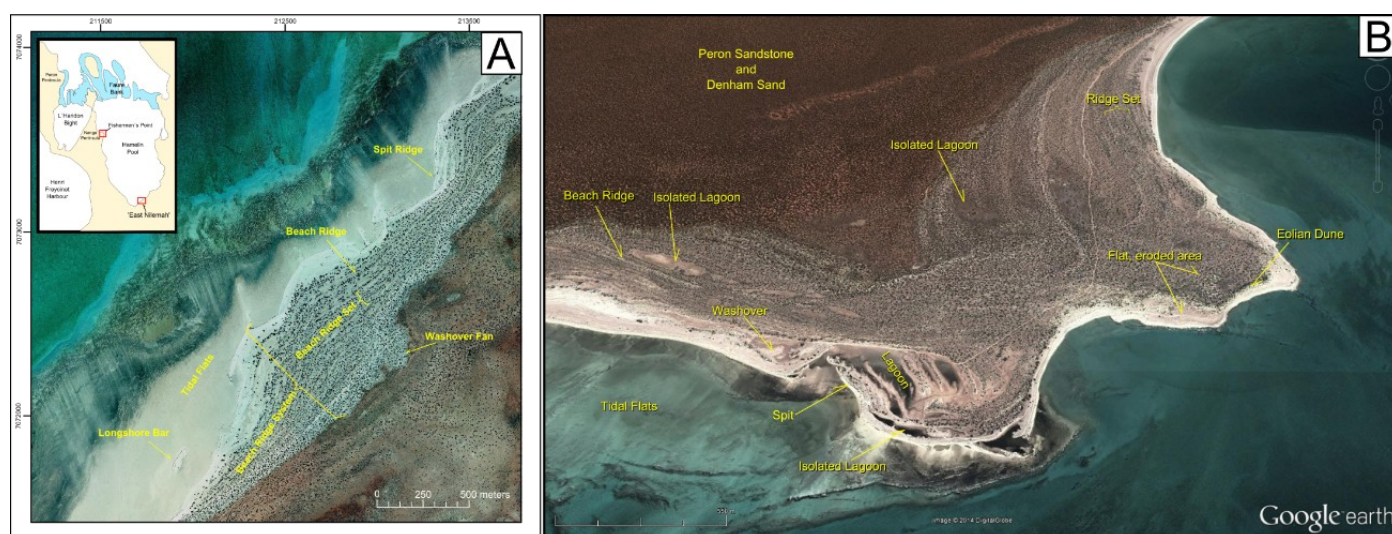


Figure 3. Major geomorphic elements at 'East Nilemah' and Fishermen's Point. **A.** Orthophoto providing a plan view of geomorphic elements in 'East Nilemah'. **B.** Geomorphic elements in Fishermen's Point shown in a perspective image from Google Earth software version 7.1.2.2041 accessed in 30/01/2014.

Table 1. Depositional elements and their textural and geometric characteristics. For radar facies description see Figure 2.

Depositional Element	Lithology and Sedimentary Structures	Shape	Internal Geometry	Geometric Relationships
Beach	Bioclastic sand; shell gravel with or without coarse bioclastic sand matrix and ooid sands. Plane-parallel lamination and oriented shells are common	Wedge or Lens	Seaward dipping parallel to moderately oblique bedding. Updip may display gently landward dipping, horizontal or curved convex bedding.	Progradational feature. Radar Facies: I-Spl; (H-P; H-Cv)
Washover	Bioclastic sand; shell gravel with or without coarse bioclastic sand matrix and ooid sands	Wedge or mound (fan)	Horizontal bedding or low to moderate angle landward dipping stratification	Occurs landward of a pre-existing adjacent ridge. Radar Facies: I-LTg; H-P; D-H; D-Wv; D-Cv; (D-Ch)
Welded Longshore/swash bar	Bioclastic sand; shell gravel; ooid sands.	Mound (bar)	Low to moderate angle landward dipping stratification	Welds to the beachface. Radar Facies: I-LTg
Spit	Coarse bioclastic sand; shell gravel with coarse bioclastic sand matrix; shell gravel; ooid sands	Elongate Mound (ridge)	Bedding dips low angle shore parallel. Locally may exhibit shore normal foreset stratification	Occur either grouped or as isolated features. Radar Facies: H-P; I-LSpl; H-Cv; I-Lpl
Storm-surge ridge	Shell gravel	Mound (ridge)	Horizontal, moderately wavy or curved convex bedding	Commonly on top of an erosive surface over the beachface element. Radar Facies: D-Cv; D-Wv; H-Cv; I-LSpl; D-Lpl; D-Ch

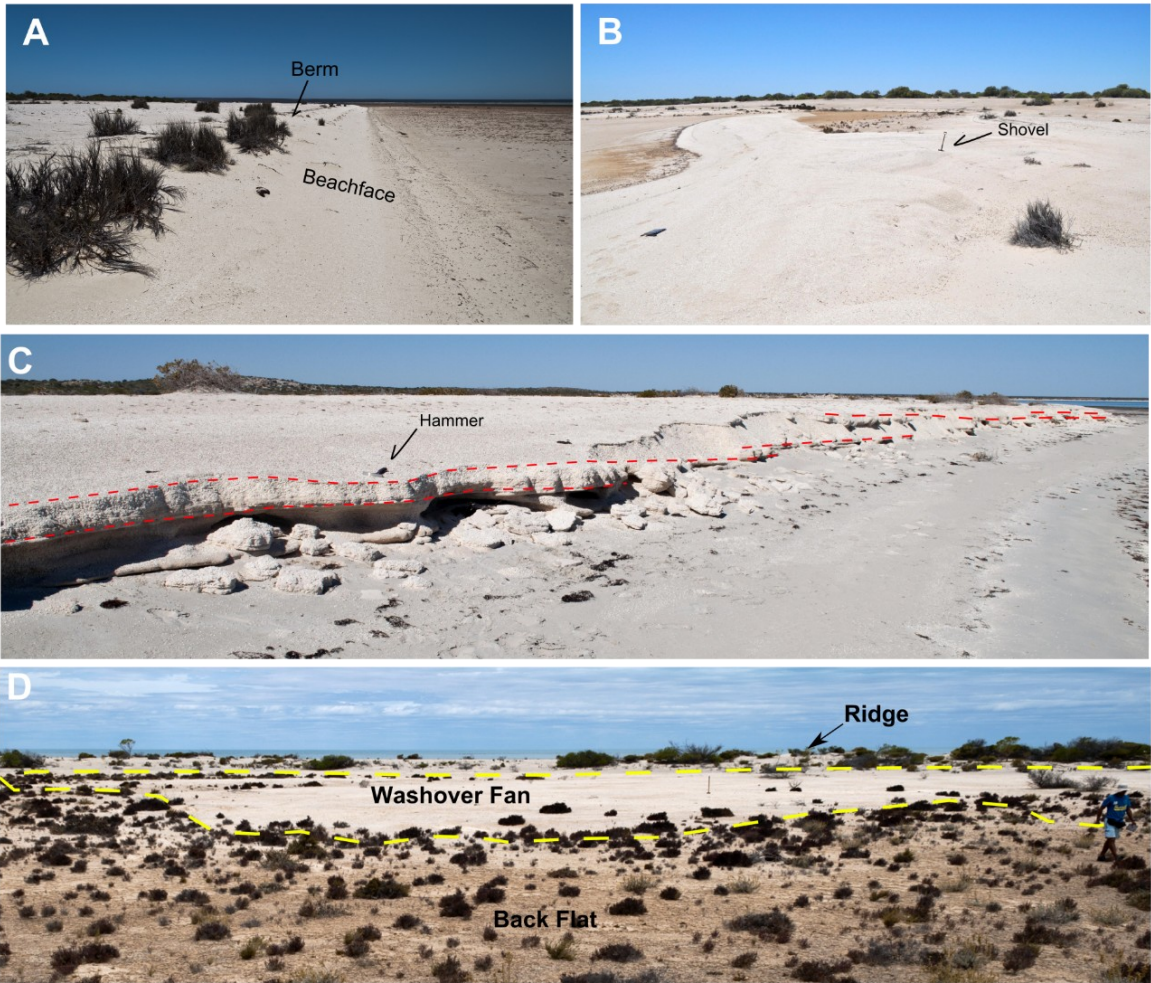


Figure 4. Field expression of depositional elements. **A.** Active berm in ‘East Nilemah’. **B.** Spit in ‘East Nilemah’. **C.** Internal structure of a spit ridge at Sweeney Mia, eastern shore of Hamelin Pool. Bedding dips southeast, parallel to the shore. **D.** Washover fan at Fishermen’s Point, western shore of Hamelin Pool.

The welded longshore bar (or swash bar) is a depositional element that consists of sandy or shelly bars with landward dipping stratification downlapping on the beachface. This kind of welded bar is usually not preserved being incorporated into the beachface deposits by swash and backwash processes.

The spit depositional element comprises a sedimentary body initially built by longshore currents. Figures 4B and 4C show modern spit ridges occurring on the eastern shore of Hamelin Pool and illustrate their internal and external geometry. This element commonly exhibits bedding that dips in the direction of the

prevailing longshore current, although horizontal and landward bedding are also observed when the ridge has been reworked by overwash and overtopping processes.

Storm-surge ridges are depositional elements that occur isolated and display horizontal, moderately wavy or convex-up bedding. These deposits are interpreted to be a result of sediment settling from suspension in the supratidal zone during a storm (Tanner, 1995; Keen and Stone, 2000). The facies and internal geometry of this element were accessed by trenching and the use of ground penetrating radar (Figure 5).

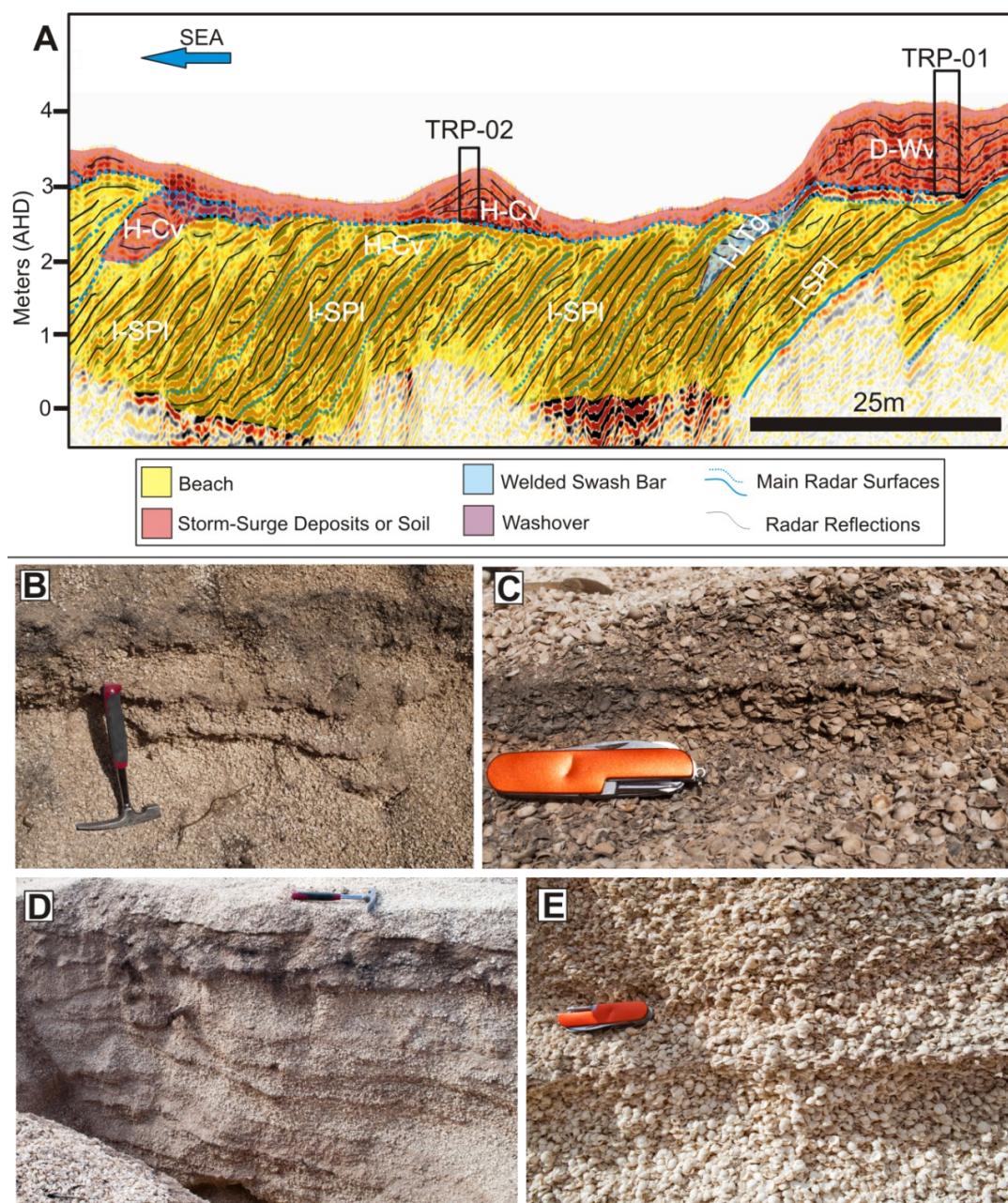


Figure 5. Architectural characteristics of storm-surge ridges in 'East Nilemah'. **A.** Segment of GPR line EN-A (figures 7 and 8) showing the internal geometry of two trenched storm-surge ridges and their relationship with beach deposits underneath. **B.** Trench TRP-02 showing sand-free shell gravels and centimetric irregular layers of shell gravels containing organic matter, plant roots and fine-grained particles (clay and silt). **C.** Detail of irregular layer of shell gravel containing windblown fine-grained sediment indicating incipient soil formation (exposure surface). Note the predominance of bedding concordant oriented shells. **D.** Trench TRP-01 exhibiting sand-free shell gravels and irregular layers of shell gravel with fine grained infiltrated sediment, roots and organic matter. **E.** Detail of sand-free shell gravel in trench TRP-01 showing roughly bed-concordant oriented shells.

Depositional domains are discrete areas of the beach-ridge system where a given depositional element predominates as a result of prevailing sedimentary processes and environmental conditions for a certain period of time.

Four depositional domains are identified and named according to the dominant depositional element occurring within each of them: Washover Domain, Beach Domain, Spit-Ridge Domain and Storm-surge Domain (Figure 8). Their architectural characteristics follow the predominant depositional element except for the spit ridge depositional domain which may locally display a mix of spit, swash bar, beach and washover element geometries.

4.3. Hamelin Pool's eastern shore

4.3.1. GPR profile interpretation

The radar profiles provide 2-D images of the coquina beach-ridge system internal architecture and together with facies information from cores, trenches and outcrops allow the interpretation of the depositional elements and the sedimentary evolution of the system.

Long radar lines (EN-A, EN-B, EN-C, EN-D and EN-E) were run perpendicular to the beach ridges (Figure 6)

revealing their geometry along the depositional dip. Additionally, two irregular grids (Figure 6 upper right) were acquired in the northernmost sector of 'East Nilemah' in order to obtain detailed architectural information of beach ridges adjacent to outcropping coquina deposits (the drainage outcrop of section 4.3.3). The radar reflections were grouped into radar facies according to their shape, dip and continuity (Figure 2).

4.3.1.1. GPR profile EN-A

Radar line EN-A is 650 m long and offers a clear image of 3 distinct domains (figures 7 and 8). The first and most landward domain has a predominance of washover deposits, while seaward of it follows a domain where seaward inclined reflectors of the beach depositional element prevail being capped by storm-surge deposits and soil. The spit ridge domain shows a complex reflector configuration and lower ridge elevations.

Occasionally, landward dipping reflectors rest on top of the beach element sloping face (beachface) and are interpreted as welded longshore (or swash) bars indicating that welding of intertidal and subtidal bars plays an important role in supplying the beach ridge system with new sediment during storms (Houser et al., 2006; Houser and Greenwood, 2007; Lindhorst et al., 2008).

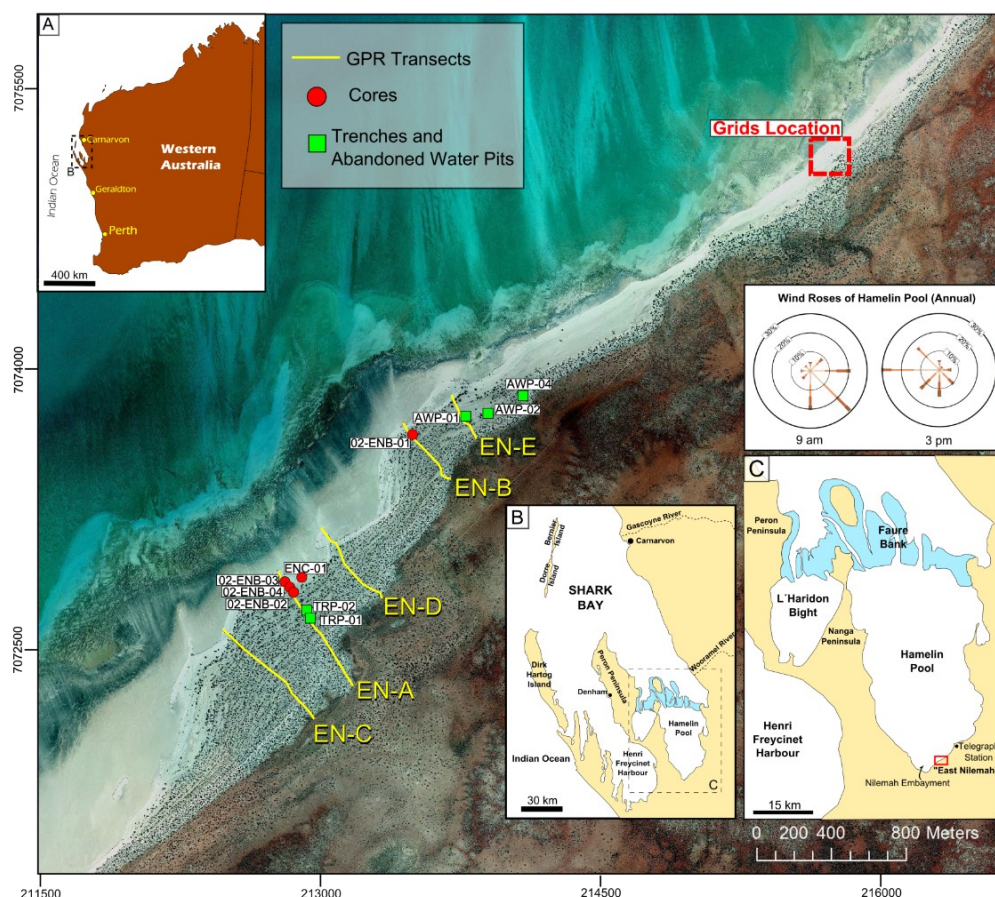


Figure 6. Aerial imagery of 'East Nilemah' displaying the coquina beach-ridge system and location of GPR transects, cores, trenches and abandoned water pits. Wind roses are from Bureau of Meteorology (n.d.c).

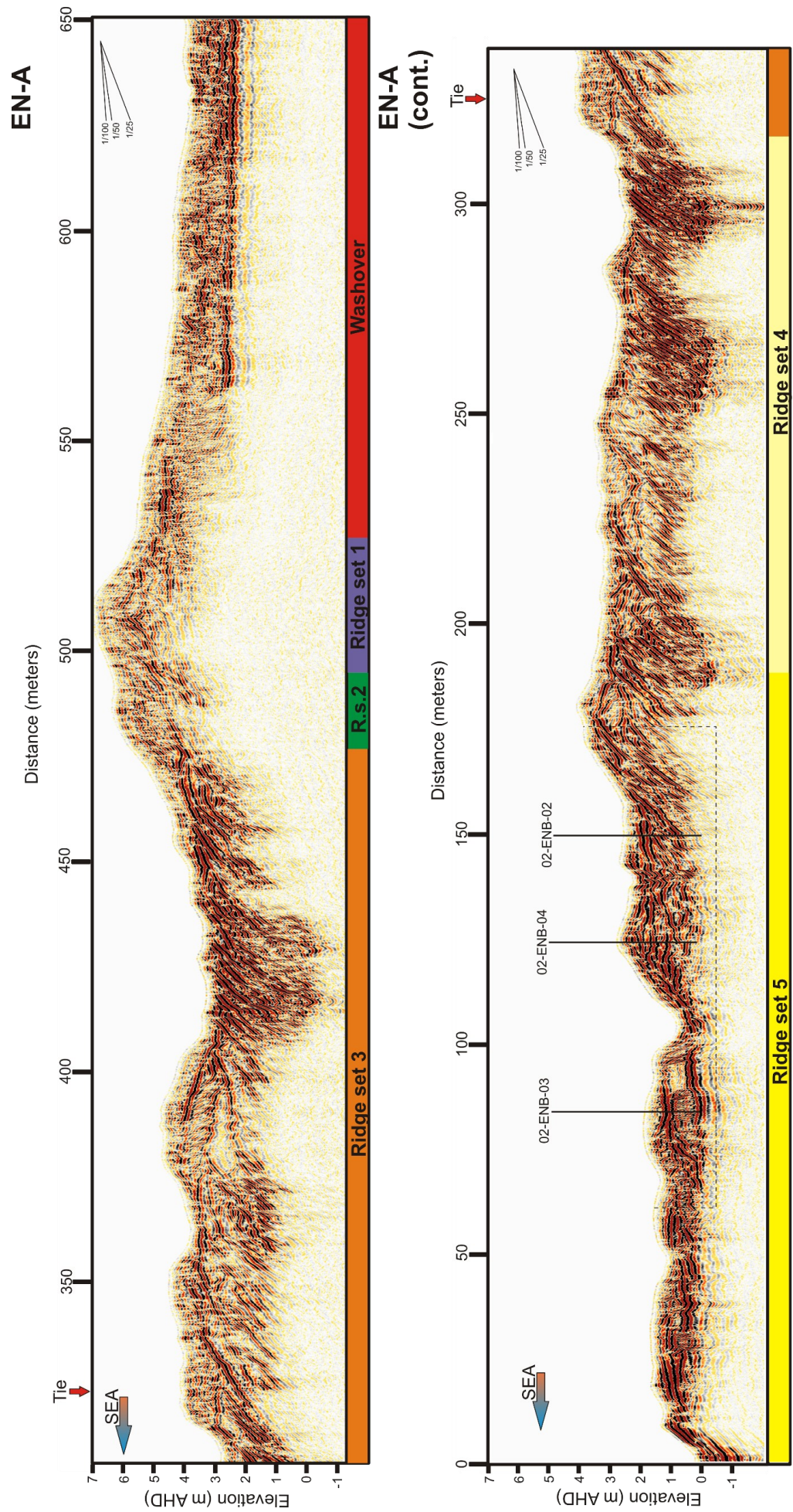


Figure 7. EN-A uninterpreted GPR line. Top and bottom figures are from a continuous transect and tie as indicated by the red arrow in the upper ruler.

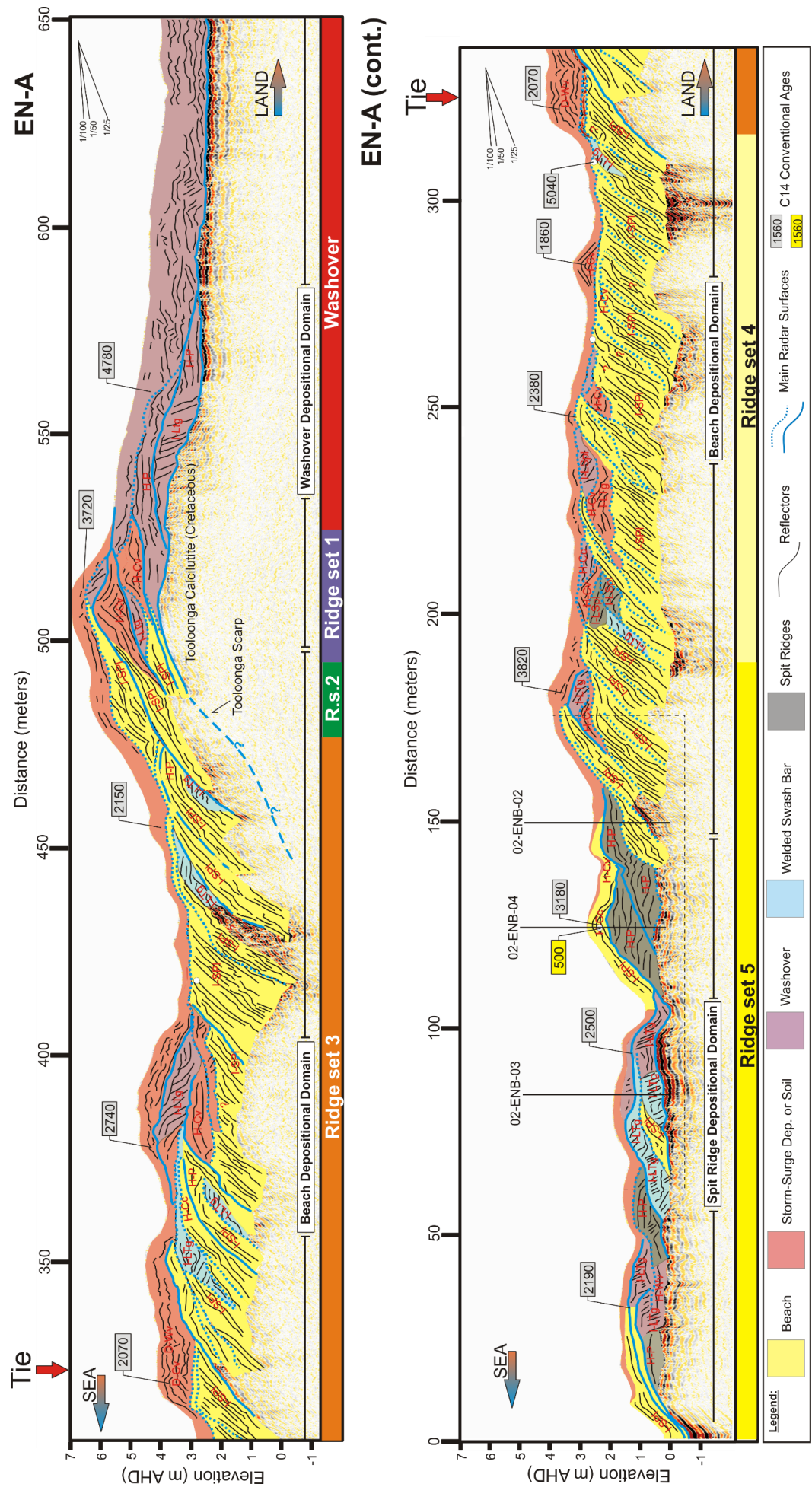


Figure 8. EN-A interpreted GPR line (see Figure 6 for location). Top and bottom figures are from a continuous transect and tie as indicated by the red arrow in the upper ruler. Depositional domains and ridge sets are indicated in the bottom of profiles. Note the complex internal architecture of the spit ridge domain in contrast with the beach domain which exhibits simpler geometries dominated by seaward dipping reflections. The transition from beach to spit ridge domain is marked by a pronounced elevation step. Storm-surge deposits and soil cap the beach and spit-ridge domains. The landward-most domain comprises washover deposits that date to the onset of the system exhibiting ages as old as 4760 ¹⁴C years BP. Figure 12 is an inset that shows details on the cores ENB-02, ENB-03 and ENB-04.

Mounded bodies resting on top of marked erosive surfaces are additional noteworthy features which display an internal geometry composed of curved convex and wavy reflectors. These sedimentary bodies cap older beach-ridge deposits and are interpreted as storm-surge ridges following observations of Keen and Stone (2000) and Tanner (1995) in Florida, United States and Jahnert et al. (2012) in Shark Bay, Western Australia. In order to investigate these storm-surge deposits, 2 trenches were made along line EN-A (Figure 5) and their sedimentary characteristics are described in Section 4.3.2.1.2.

The transition from the beach depositional domain to the spit ridge domain displays an overall decrease in ridge elevation and change in reflector configuration implying that hydrodynamic conditions have changed from swash and backwash dominated to more longshore current dominated processes.

4.3.1.2. GPR line EN-B

Radar Line EN-B is 410 m long in the depositional dip direction (Figure 9). The overall configuration of this line is characterized by the beach element progradational style capped by storm-surge and soil deposits. Welded swash bars are relatively common elements interpreted in this line.

An important feature in line EN-B observed around 300 m shows a complete beach depositional element radar image. This portion of EN-B displays the horizontally parallel radar facies of berm crests transitioning to seaward inclined reflectors of the beachface. Given that the berm crest is frequently eroded by succeeding storm events, the record of an entire berm, and not only the beachface, is uncommon in the study area.

4.3.1.3. GPR line EN-E

GPR line EN-E is the shortest line in 'East Nilemah' covering 309 m (Figure 10). The prograding beach element capped by storm-surge deposits and soil are the predominant depositional elements in this area. Both elements were accessed in an abandoned water pit intercepted by this line. In Figure 19, the detail in GPR line EN-E displays two distinct reflector configurations separated by a roughly horizontal radar surface (*rs.E1*). The top package, interpreted as storm-surge deposits, displays reflectors in conformable convex-up pattern blanketing a seaward inclined series of reflectors interpreted as prograding beachface deposits.

4.3.2. Sedimentary characteristics

The beach-ridge system at 'East Nilemah' site is made up of shell gravels composed of mollusks (almost

entirely *Fragum erugatum* bivalve) and bioclastic sands constituted by foraminifers, micro-gastropods, serpulids, bryozoans and shell fragments. Secondly, flat pebbles from the tidal flat breccia pavement (Logan et al., 1974; Jahnert and Collins, 2012), lithoclasts and ooids contribute with clasts to the system. Bed geometries observed in the field and GPR profiles are described as lenticular, wedge-shaped, mounded or tabular.

The main lithofacies present in the beach-ridge deposits (Figure 11) are composed of shell gravels with variable quantities of medium to very coarse bioclastic sand matrix. Sands, commonly shelly and composed of bioclasts (and more rarely ooids) are also important lithologies. Sedimentary structures observed in outcrops and trenches are plane-parallel lamination or stratification, foreset stratification, bed-concordant oriented shells and rare grading. When subaerially exposed for a sufficient amount of time, these sediments are subject to windblown silt and clay infiltration and soil forming processes. Moreover, bioclast micritization, peloid formation and micritic cementation are promoted by microbes present in either the marine environment or the saline phreatic zone. Table 2 summarizes the described lithofacies and their main characteristics.

4.3.2.1. Sediment cores and trenches

4.3.2.1.1. Cores

Four cores were obtained in 'East Nilemah'. Three of them are located in EN-A and one is in EN-B. Figures 12 and 13 show their core logs and location in the GPR lines context. Figure 14 presents a legend valid for all sediment logs.

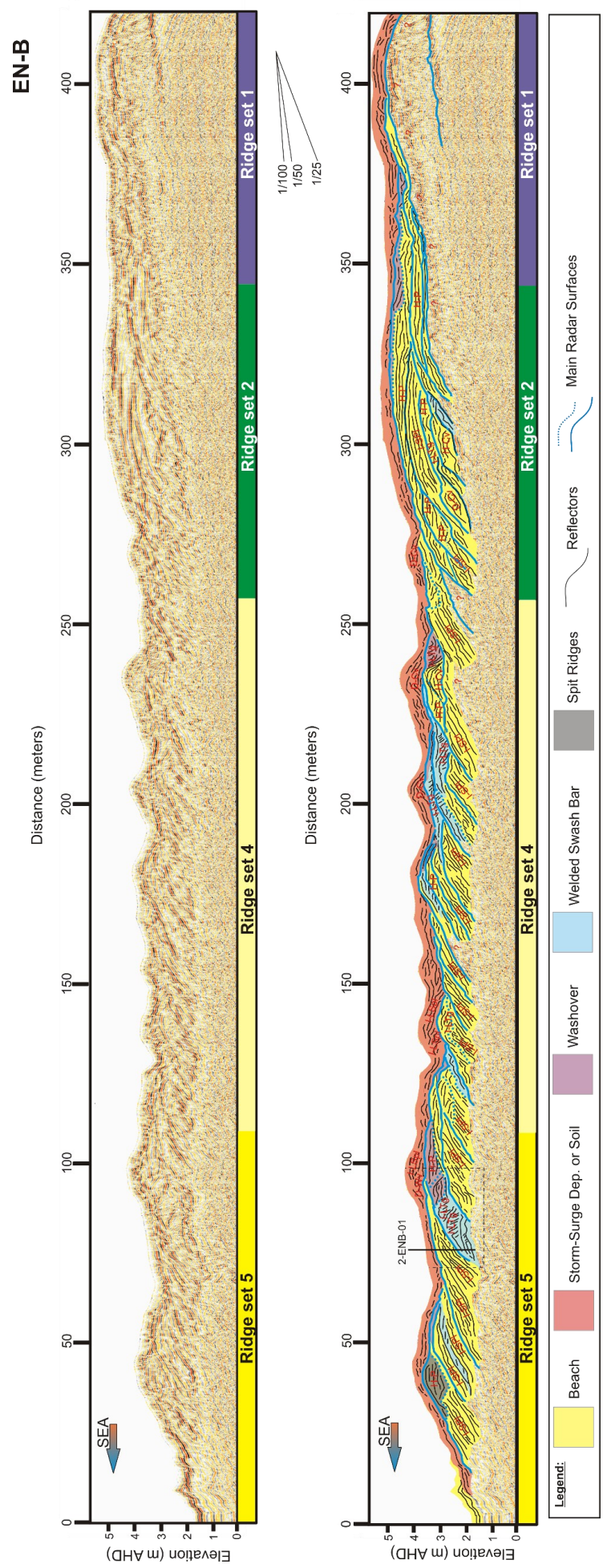


Figure 9. Uninterpreted (top) and interpreted (bottom) GPR line EN-B (see Figure 6 for location). Ridge sets are indicated in the bottom of profiles. Seaward dipping reflections of the beach depositional domain predominate and are capped by storm-surge deposits and soil. Note that in the area of ridge set 2 the beach depositional element displays its complete morphology showing mounded or wedge-shaped features, interpreted as berm crests, updip of seaward inclined reflections.

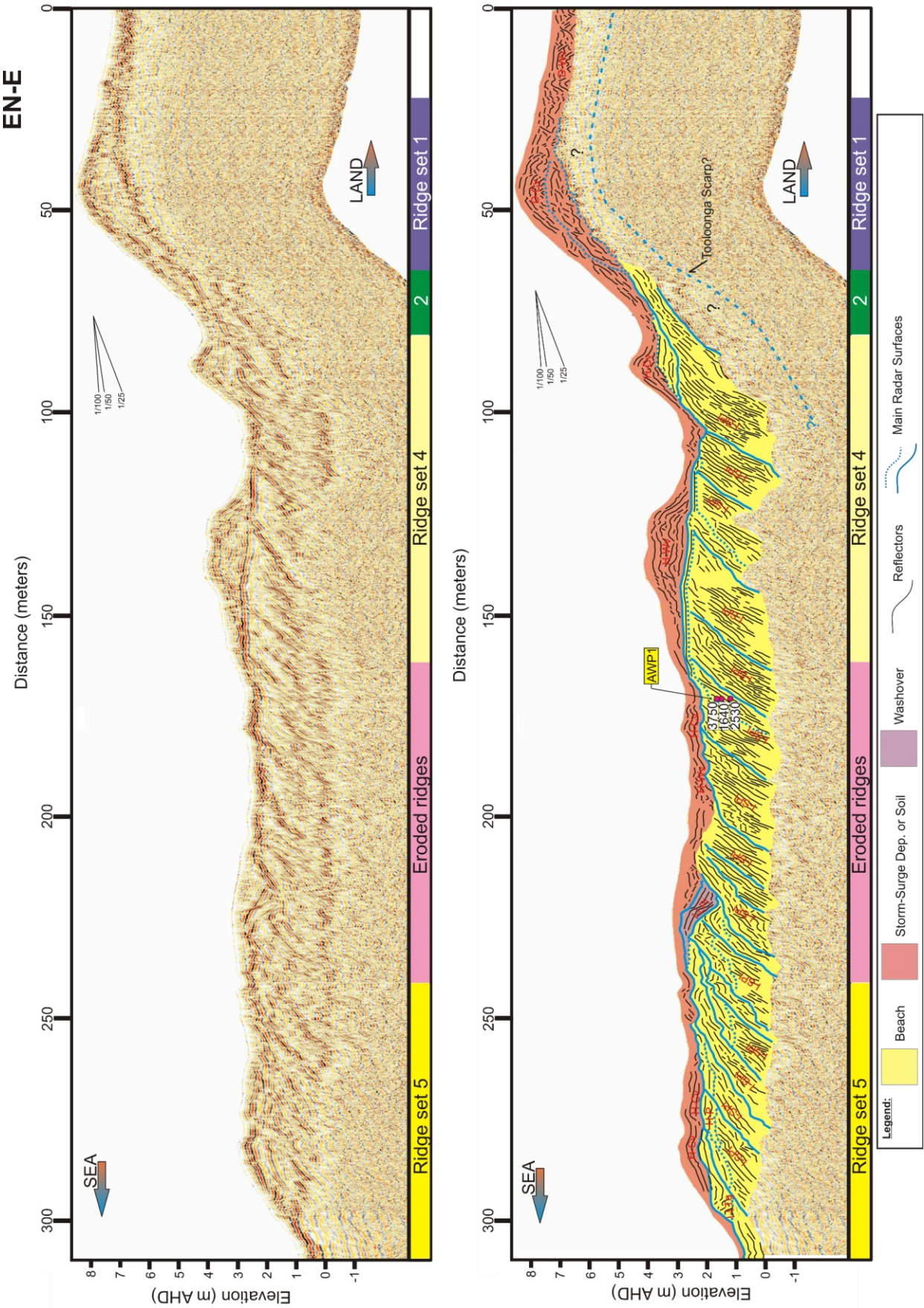


Figure 10. Uninterpreted (top) and interpreted (bottom) GPR line EN-E (see Figure 6 for location). Seaward dipping reflections of the beach depositional domain predominate and are capped by storm-surge deposits and soil. Abandoned water pit AWP-01 is located in this line and three ¹⁴C dates were obtained in the pit as indicated.

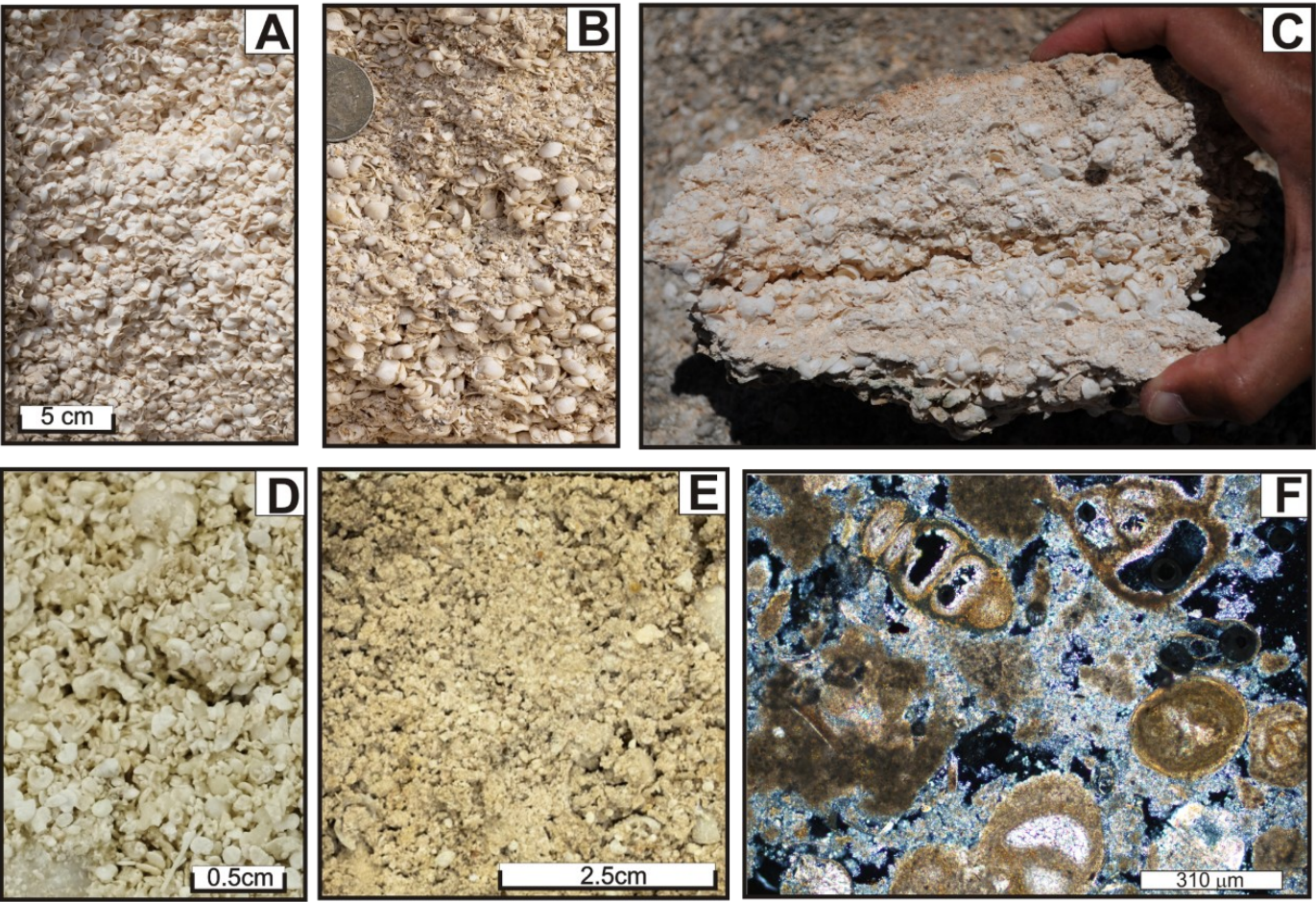


Figure 11. Main lithofacies in the beach-ridge system at ‘East Nilemah’. **A.** Shell gravel. **B.** Shell gravel with coarse/very coarse bioclastic sand matrix. **C.** Indurated shell gravel with coarse/very coarse bioclastic sand matrix. **D.** Shelly bioclastic sand. **E.** Medium to coarse bioclastic, ooid and peloidal sand cemented by micrite. **F.** Epoxy-impregnated thin-section of (E) displaying micritized bioclasts and superficial ooids, peloids and micrite cement.

Table 2. Characteristics of the main lithofacies observed at the beach-ridge system in ‘East Nilemah’. G: gravel; sh: shell; sm: sand matrix; VCS: very coarse sand; bi: bioclast; oo: ooids; ppl: plane-parallel lamination.

Lithofacies	Texture	Components	Sedimentary Structures	Occurrence
Gsh	Gravel	Whole disarticulated shells, shell fragments, occasional flat pebbles, very rare articulated shells.	Structureless; horizontally oriented shells (bed-concordant);	Storm-Surge ridges; Beachface; Berm crest
Gshsm	Gravel with medium to very coarse sand matrix	Whole disarticulated shells, shell fragments, variable proportions of lithoclasts, bioclasts and ooids in the sandy fraction.	Structureless or plane-parallel lamination	Beachface; washover deposits and berm crest
VCSbi(sh)(oo)	Coarse to Very Coarse Sand	Bioclasts (shell fragments, forams, gastropods, occasional serpulids and rare bryozoans). Variable amount of whole disarticulated bivalve shells, lithoclasts and ooids.	Structureless	Beachface; washover deposits and berm crest
VCSbish(oo)ppl	Coarse to Very Coarse Sand	Bioclasts (shell fragments, forams, gastropods, occasional serpulids and rare bryozoans), whole disarticulated bivalve shells. Variable amount of lithoclasts and ooids.	Plane-parallel lamination and bedding concordant oriented shells	Beachface

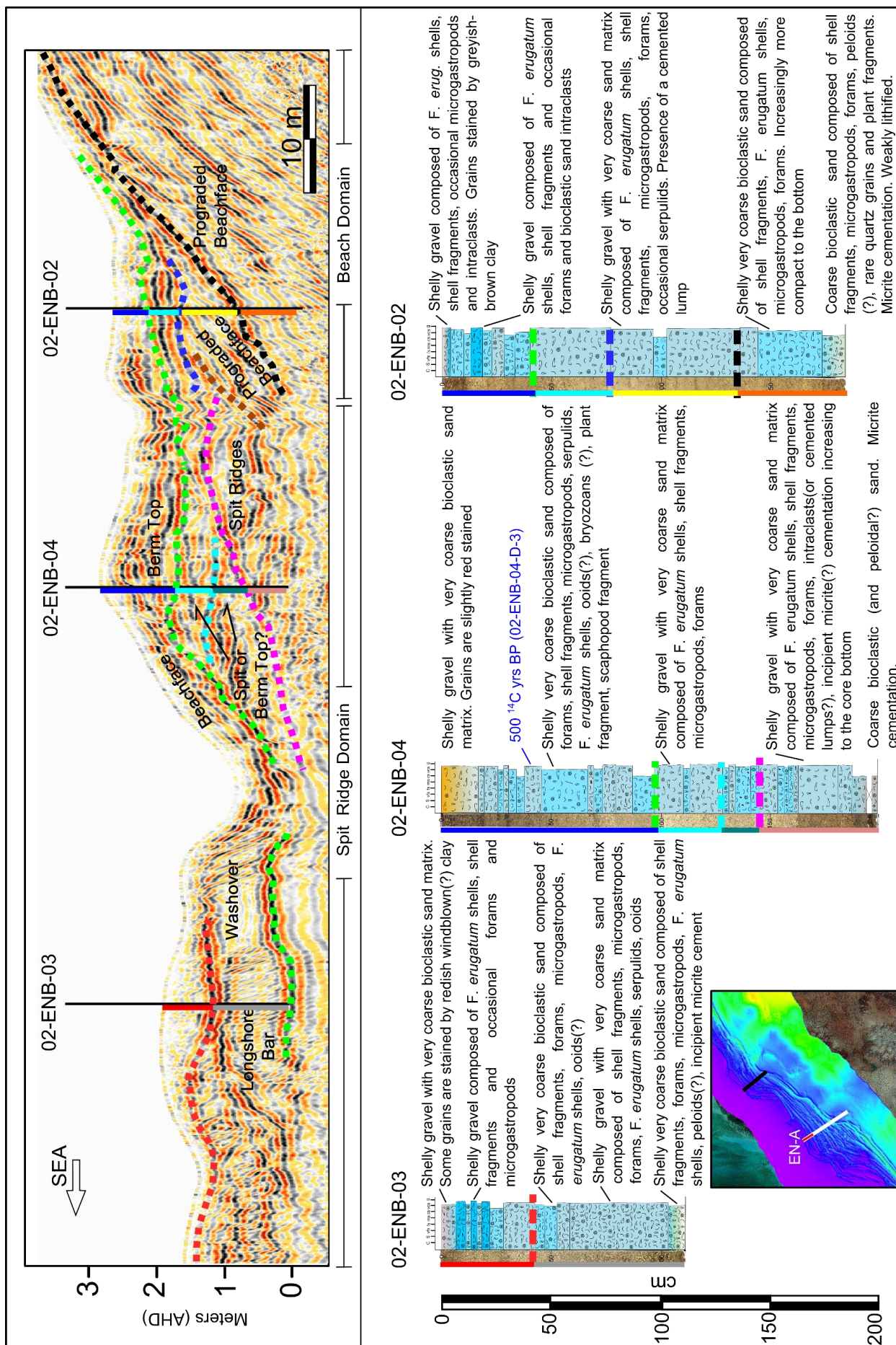


Figure 12. Segment of GPR line EN-A where 3 cores were obtained in the transition of the beach domain to the spit ridge domain. An articulated *F. erugatum* shell was dated in core 02-ENB-04. Bottom of the cores exhibit coarse bioclastic (and peloidal?) sands with micrite cementation. See Figure 14 which presents a legend for the sedimentary logs.

Core 02-ENB-02 intersected 4 different radar packages, predominantly in the beach and spit depositional elements. The topmost package is interpreted as berm top deposits resulting from overtopping and minor overwashing processes. The other three radar packages are interpreted as beachface deposits with a remarkable difference in slope angle between the second package and the other two on the bottom of the core (Figure 12).

Similarly, core 02-ENB-04 intersected 4 radar packages and the topmost represents berm top deposits. The packages below can be either interpreted as berm top or spit deposits as in radar profiles both may show horizontal radar facies in the depositional dip direction and textures alone do not provide unequivocal information for this interpretation (Figure 12).

Core 02-ENB-03 exhibits a dominance of shell gravels in the upper layers that overwash a package with landward dipping reflectors interpreted as a swash bar.

The lowermost beds in the cores located in EN-A display bioclastic and peloidal sands with micrite cement. These sands are interpreted as sand aprons on the lower beachface which undergoes early diagenesis when exposed to marine or saline phreatic waters for a sufficient amount of time (figures 11 and 11F).

The core 02-ENB-01 was obtained in line EN-B and intersected 3 different depositional elements: Storm-surge deposits and soil, beach deposits and welded longshore bars (Figure 13). The base of the storm-surge and soil package is marked by an 11 cm shell gravel bed with little or no sand content. The beach deposits are divided into two packages by radar surface rs.B2. The upper package displays interlayered beds of shell gravel with very coarse sand matrix and beds of shelly

coarse/very coarse bioclastic sand interpreted as the berm top. The package below rs.B2 has the same basic composition with thicker beds being interpreted as beachface deposits. At the bottom of the core, a bioclastic and peloidal sand layer with micrite cementation increasing with depth is also observed, as previously described in the cores of line EN-A.

4.3.2.1.2. 'East nilemah' trenches and pits

Two trenches located along GPR line EN-A were excavated to assess facies and internal geometries of selected storm-surge ridges (Figure 5). The trenches reached 0.60 and 1.20 m displaying sand-free shell gravels and centimetric irregular layers of shell gravels containing variable amounts of organic matter, plant roots and fine-grained particles (clay and silt). These fine particles are interpreted as windblown implying ridge construction by multiple episodes of sedimentation and subaerial exposure as opposed to a single event deposit. Smaller pits excavated for sediment sampling revealed this same alternation of sand-free shelly gravels and incipient soil characterized by fine-rich shell gravels with plant roots. Where weakly cemented portions of the sand-free shell gravels are found, it is observed that shells are oriented concordant to the bedding, commonly convex-up (figures 5C and 5E) as also observed by Jahnert et al. (2012) in deposits they named 'convex-up ridges' and interpreted as being generated by storm surges. The bottom of both trenches intersected the beach depositional element denoted by the occurrence of horizontally or gently seaward dipping indurated sandy coquina facies.

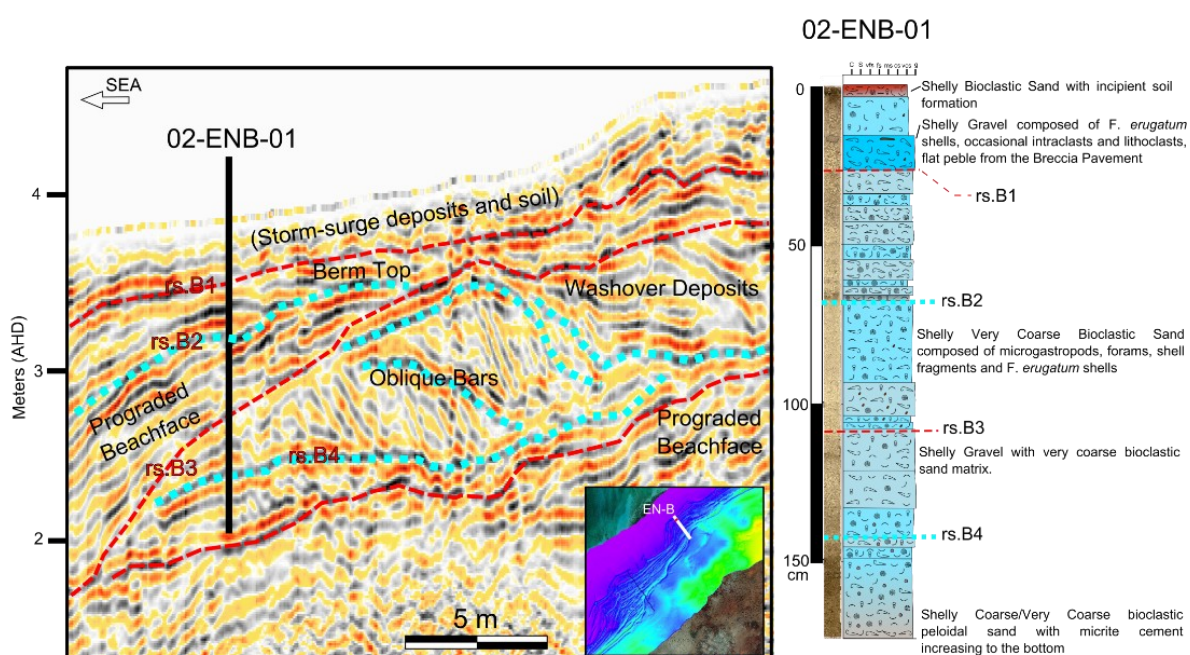


Figure 13. Segment of GPR line EN-B where core 02-ENB-01 was obtained intersecting storm-surge and soil deposits, berm top, beachface and oblique bar sediments as interpreted in the radar profile. See Figure 14 which presents a legend for the sedimentary log.

Additionally, one abandoned water pit was used to obtain sedimentary information at 'East Nilemah' site (Figure 6). Pit AWP-01 is 1.56 m deep and was intersected by GPR line EN-E (Figure 15) where it is possible to recognize two main radar facies occurring in the location of the core: an upper, curved convex reflector configuration, separated by a major radar surface (*rs.E1*) from a lower inclined seaward-dipping radar facies. The upper curved convex radar facies, interpreted as storm-surge deposits, consists of two sand-free shell gravel beds separated by a discontinuous layer of shell gravel with matrix of silt to coarse sand. The lower inclined, seaward dipping planar radar facies is interpreted as the beach depositional element relating to interlayered centimetric bioclastic sand and shell gravel layers with or without bioclastic sand matrix.

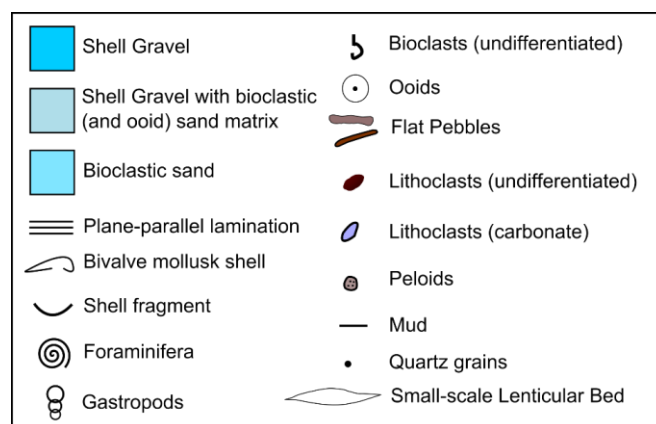


Figure 14. Legend valid for all sedimentary logs.

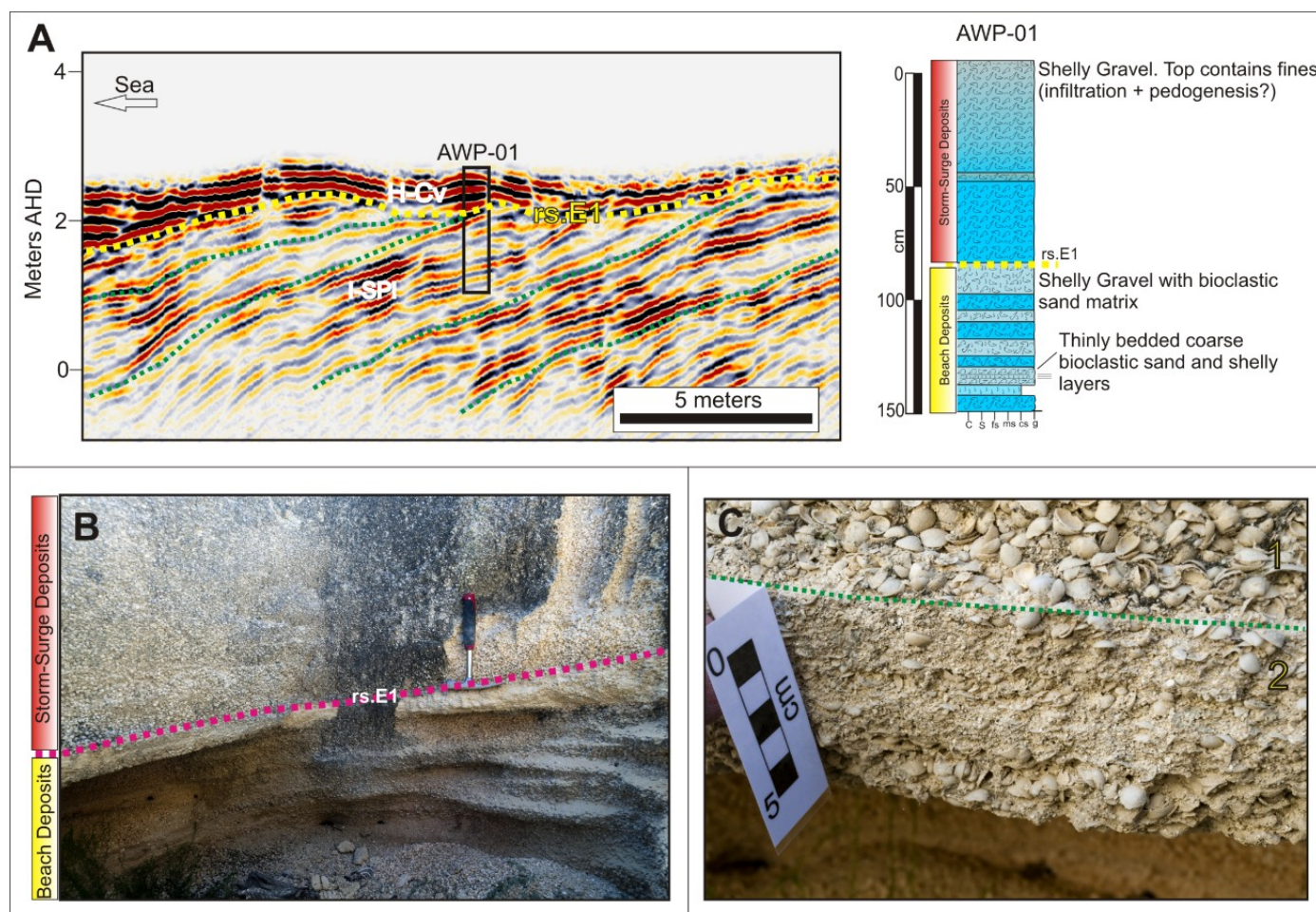


Figure 15. Abandoned water pit AWP-01. **A.** Segment of GPR line EN-E and composite sedimentary log made in AWP-01. Radar surface *rs.E1* is indicated in both GPR and log and separates storm-surge deposits and beach deposits. See Figure 14 which presents a legend for the sedimentary log. **B.** Photograph of AWP-01 wall showing sand-free shell gravel on top of radar surface *rs.E1* and interlayered shell gravels with and without bioclastic sand matrix below *rs.E1*. **C.** 1- Shell gravel with coarse/very coarse bioclastic sand matrix. 2 - Shelly coarse/very coarse bioclastic sand with plane-parallel lamination and bed concordant oriented shells.

4.3.3. GPR X outcrop correlation

A drainage channel cuts through a beach ridge at the northernmost part of the study area and partially exposes its facies and internal geometry (Figure 16). The bedding geometries observed are horizontal and seaward dipping being a result of berm construction by swash processes in the beachface and overtopping (and minor overwashing) on the berm crest. The facies are composed of bivalve mollusk shells (*F. erugatum* predominates) and bioclastic sands, which are present in each individual bed in variable proportions. Flat pebbles from the breccia pavement (Logan et al., 1974; Jahnert and Collins, 2012) and lithoclasts are also common in these deposits. Truncation surfaces identified on the

outcrop are interpreted on the GPR lines acquired in this site (Figure 16).

The exposure of the internal architecture of a ridge allowed the interpretation of different parts of a berm based on the bedding geometries observed. Facies were logged in distinct locations of the ridge and major truncation surfaces were correlated between logs (Figure 17). In the interpreted upper beachface, a predominance of shell gravels with bioclastic sand matrix and shell gravels with no matrix is observed. The facies in the lower beachface are composed of coarse shelly bioclastic sands exhibiting seaward-dipping layers, rich in shells oriented concordant to the bedding plane. The berm crest displays bioclastic sands and shell gravels with bioclastic sand matrix interlayered in centimetric beds.

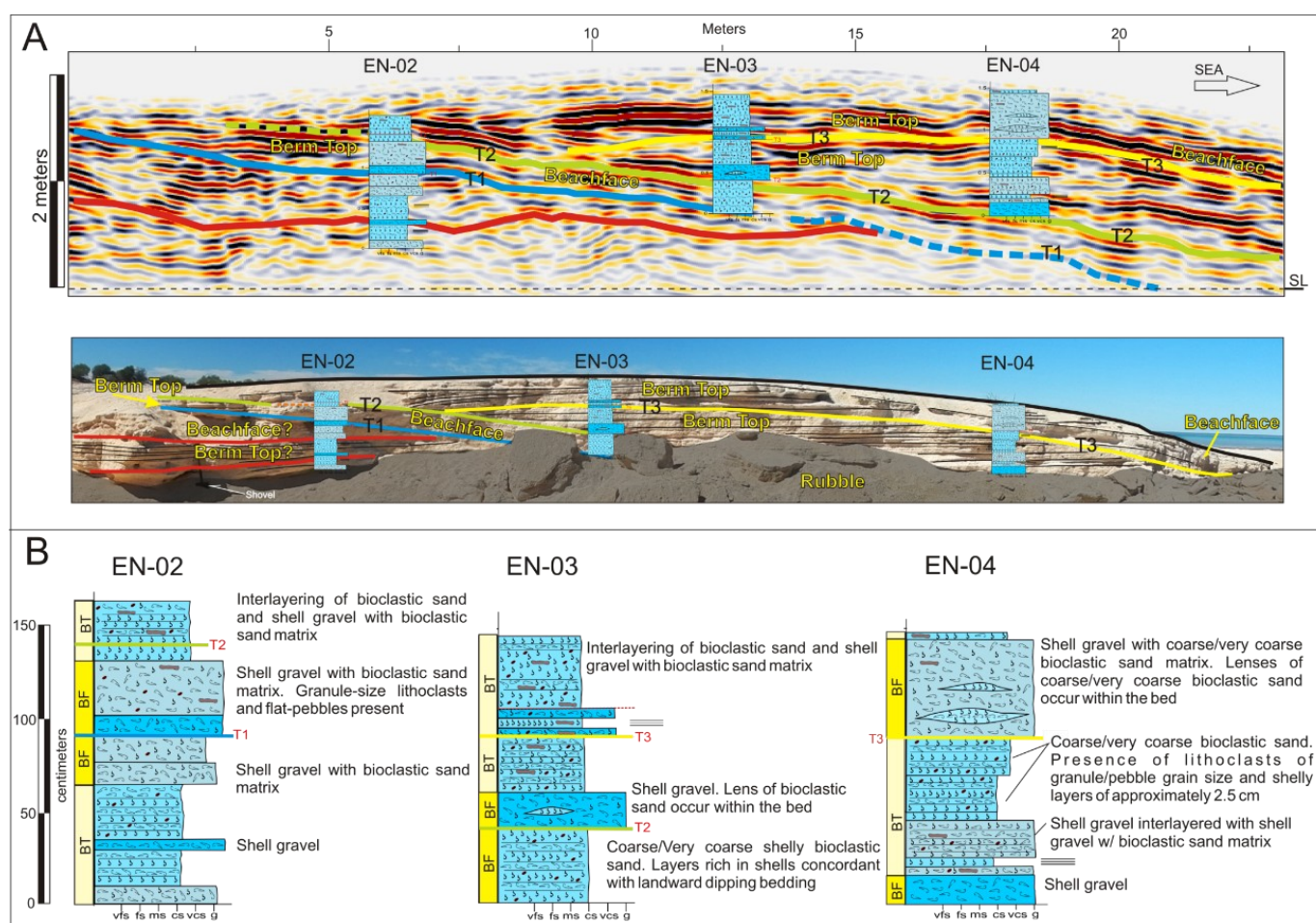


Figure 16. Drainage outcrop adjacent to the GPR irregular grids. **A.** Top: Interpreted GPR line parallel to outcrop (sedimentary logs are projected). T1, T2 and T3 are radar surfaces which correlate to truncation surfaces in the outcrop. Bottom: Photograph of the outcrop with truncation surfaces and sedimentary log locations indicated. **B.** Sedimentary logs of the drainage outcrop. BT – berm top deposits; BF – beachface deposits; T1, T2, T3 – truncation surfaces. See Figure 14 which presents a legend for the sedimentary logs.

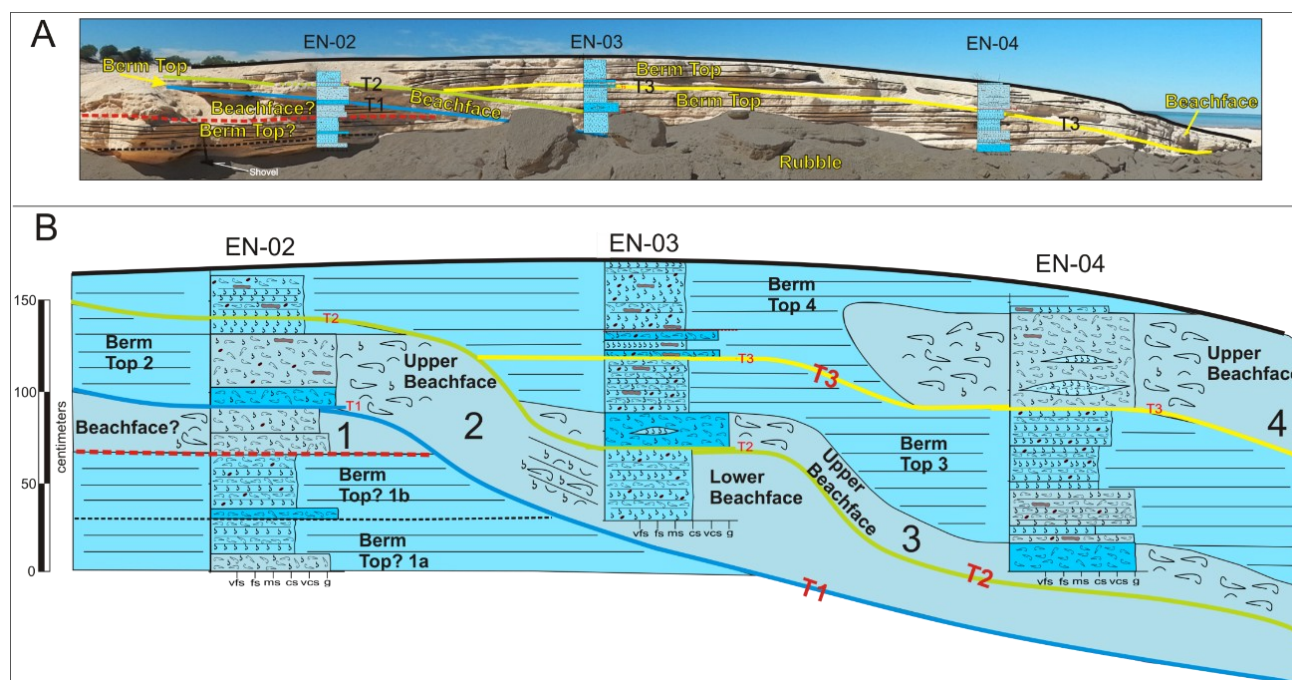


Figure 17. Ridge internal geometry, facies and interpreted depositional sub-environments. **A.** Photograph of the outcrop with truncation surfaces and sedimentary log locations indicated. T1, T2 and T3 are major truncation surfaces. **B.** Sedimentary log correlation based on outcrop and GPR geometries, truncation surfaces and facies. See Figure 14 which presents a legend for the sedimentary logs. At least 4 main episodes of erosion and deposition were responsible for the formation of this ridge.

4.3.4. Ridge and depositional domain chronology

For the purpose of assessing the chronology of ridge formation and their evolution, 19 shell samples were radiocarbon dated in 'East Nilemah' (Table 3). Some of the samples were collected before GPR acquisition, most of which were in storm-surge ridges prone to contain reworked material. For that reason, age reversals were observed in transects studied along the depositional dip of the beach-ridge system. Although other samples were carefully planned using the GPR profiles to avoid storm-surge deposits, some reworking was still evident in samples collected in the beach depositional element. Hence, dating results presented should be used as maximum ^{14}C ages, except for the sample where an articulated *Fragum erugatum* shell was obtained in core 02-ENB-04 (Figure 12). However, the time of residence of an articulated shell within the basin is unknown and is potentially a cause of error in the order of decades.

Of 19 radiocarbon dated samples, 11 were obtained in storm-surge deposits and 8 are from beach deposits. Figure 18 displays the location and depositional context of dated samples and the ages used to constrain the beach-ridge system evolution in 'East Nilemah', bearing in mind that prograded beach deposits get younger seaward and storm-surge deposits do not necessarily get younger seaward and are more likely to contain reworked material.

In the eastern shore study site, the initiation of the beach-ridge system construction, i.e. deposition of ridge

set 1 and the washover domain, started about 4500-5000 ^{14}C years BP as evidenced by the 4780 ^{14}C years date obtained in the washover domain and the oldest age measured in the area is 5040 ^{14}C years BP. This initiation at approximately 4500-5000 ^{14}C years BP is in accordance with results obtained by Jahnert et al. (2012) for the beach ridges at Telegraph Station site, to the north of 'East Nilemah'.

No dates were obtained in ridge set 2, which is discontinuous and truncated by ridge set 3 in the GPR line EN-D vicinity. Furthermore, ridge set 2 thins until becoming completely absent north of EN-E line (Figure 18).

The only reliable age measured in ridge set 3 is 2620 ^{14}C years BP evidencing an erosional gap in EN-A and EN-D transects of at least 1100 years between the onset of the system and the first overwash events over ridge set 1 and the deposition of ridge set 3. Similarly, the next reliable sample is in ridge set 4 displays a date of 1640 ^{14}C years BP.

Ridge set 5 has the most reliable sample, an articulated *Fragum erugatum* shell, having a measured age of 500 ^{14}C years BP. In GPR lines EN-A, EN-C and EN-D the transition from ridge set 4 to ridge set 5 is marked by the occurrence of a high elevation ridge followed by a step which is the boundary between a domain where prograding beach depositional elements predominate and a domain of spit ridges predominance. This transition is not visible in GPR lines EN-B and EN-E although it is clear in the orthophoto that spits do occur in ridge set 5 between lines EN-B and EN-D.

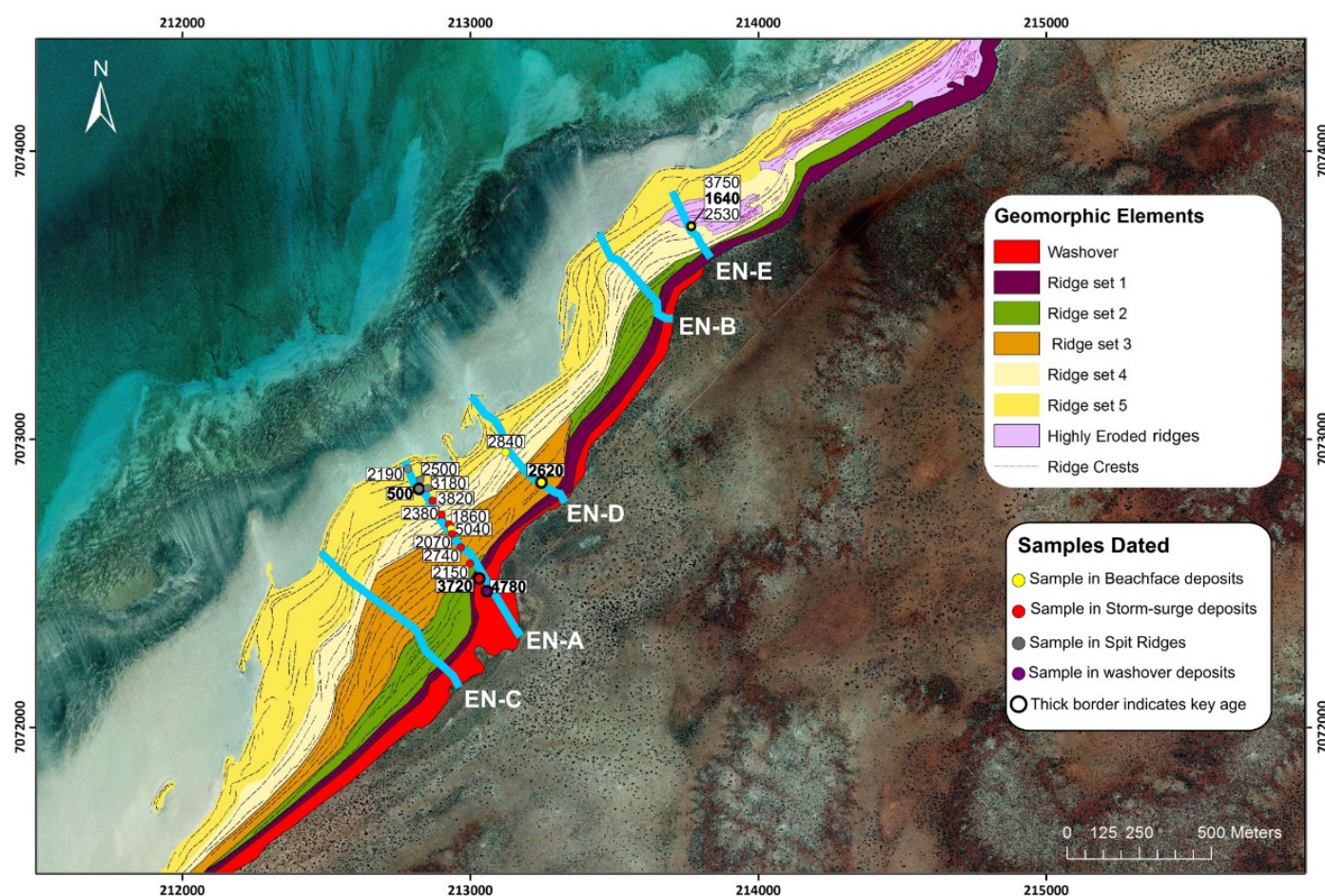


Figure 18. Geomorphic map and aerial image of the coquina beach ridge system in 'East Nilemah' site with ^{14}C ages and GPR transect locations. Key ages for the interpretation of ridge chronology are indicated by thick-bordered circles.

Table 3. Radiocarbon chronology for *F. erugatum* shells of selected coquina deposits. A delta R of 70 ± 50 was used for marine reservoir correction. Data calibrated against Marine09 calibration curve (Reimer et al., 2009).

Sample Id	Source of Carbon	^{14}C age (years BP)	Error (years)	^{14}C age (years BP) calibrated 2 sigma
END-11	Bivalve Shell	2190	30	1850/1540
END-10	Bivalve Shell	2500	30	2260/1910
END-09	Bivalve Shell	3180	30	3050/2740
END-08	Bivalve Shell	3820	30	3830/3540
END-07	Bivalve Shell	2380	30	2070/1800
END-06	Bivalve Shell	1860	30	1510/1200
END-05	Bivalve Shell	2070	30	1700/1400
END-04	Bivalve Shell	2740	30	2510/2260
END-03	Bivalve Shell	2150	30	1800/1510
END-02	Bivalve Shell	3720	30	3690/3400
END-01	Bivalve Shell	4780	30	5120/4810
END-D-108	Bivalve Shell	2620	30	2330/2070
END-D-107	Bivalve Shell	2840	30	2690/2320
ENA-D-101	Bivalve Shell	5040	30	5450/5200
EN-DR-D-110	Bivalve Shell	1360	30	940/700
AWP1-G-01	Bivalve Shell	2530	30	2280/1950
AWP1-D-02	Bivalve Shell	3750	30	3730/3440
AWP1-D-01	Bivalve Shell	1640	30	1250/970
02ENB04-D-3	Articulated Bivalve Shell	500	30	230 to post 1950 AD

4.3.5. Depositional model

The coquina beach-ridge system displays an internal structure in which the progradational style of the beach domain is prevalent. This depositional style is a result of the stacking of plane-parallel seaward dipping radar reflections produced by beachface progradation. Occasionally as is visible in some GPR transects (e.g. EN-B, Figure 9) the beach depositional element also exhibits up-dip mounded or wedge-shaped ridges interpreted as berm crests. Several authors state that berm formation is directly linked to high water levels, storm waves and onshore sediment transport (e.g. Komar, 1998; Neal et al., 2002; Bendixen et al., 2013). In 'East Nilemah' the beach depositional element occurs as high as 6 m AHD. Even considering a former higher than present sea level of +2 m (Collins et al., 2006), only storm-surges could be responsible for the deposition of beach sediments at that elevation. The berm crest expected updip of the beachface prograding reflections is commonly eroded by succeeding larger storms that paradoxically may build a berm at higher elevations because of increased wave heights and run-up (Bascom, 1953). Komar (1998) states that the progradation of the beach may leave behind a set of inactive storm berms recording a past of extreme storm events. Although most of the berm crests in the area are eroded and draped by other storm-surge deposits (the storm-surge domain) the plain view of the beach-ridge system suggests that berm progradation exerts an important control on the beach-ridge external morphology. GPR lines provided images that suggest berm progradation as an important mechanism of the beach-ridge system growth. Furthermore, the outcrop of a berm internal geometries in a drainage channel (figures 16 and 17), abandoned water pit and cores together with GPR profiles permitted the construction of a depositional model for the coquinas at 'East Nilemah'.

The berm (*sensu* Hine, 1979) is the building block of the beach depositional domain, and therefore of the

beach-ridge system in the area. An idealized sketch of the depositional model for coquina ridge formation during a set of a few storm events is presented in Figure 19. Although grain size is not expected to be the preponderant factor influencing hydraulic behaviour in heterogeneous bioclastic deposits (Kench and McLean, 1997) an adaptation of the model proposed by Orford et al. (1991) for clast sorting in coarse clastic coastal barriers is useful to understand the sedimentary dynamics for ridge construction under storm high-energy conditions.

During episodes of elevated water levels and moderate to high-energy conditions, bioclastic sediment is mobilized from the subtidal to the supratidal environment. At the upper beachface clast morphology and clast size partitioning will take place and its efficiency will depend on the characteristics of the storm (intensity, direction of approach and duration). This clast partitioning will lead to accumulation of *Fragum* shells in the upper beachface increasing beach permeability in this part of the beach. This high permeability zone favours percolation during uprush making the backwash motion negligible at the upper beachface. Backwash will regain importance at lower levels of the beachface and bioclastic deposits will exhibit plane-parallel lamination and oriented bivalve shells concordant with the bedding. These bioclastic deposits will be enriched in the sandy fraction as part of the *Fragum* shells have been transported further shoreward by clast partitioning. In even more energetic conditions, the bioclastic sediments are transported over the ridge crest and overtopping and minor overwashing will lead to berm ridge growth resulting in storm beach aggradation. The depositional model described above is expected to occur in the waning phase of major storms or during the passage of distant storms. On the other hand, the peak phase of major storms will be characterized by erosion and inundation overwash (Donnelly, 2006) leaving behind deposits that will comprise the storm-surge domain (figures 5 and 20).

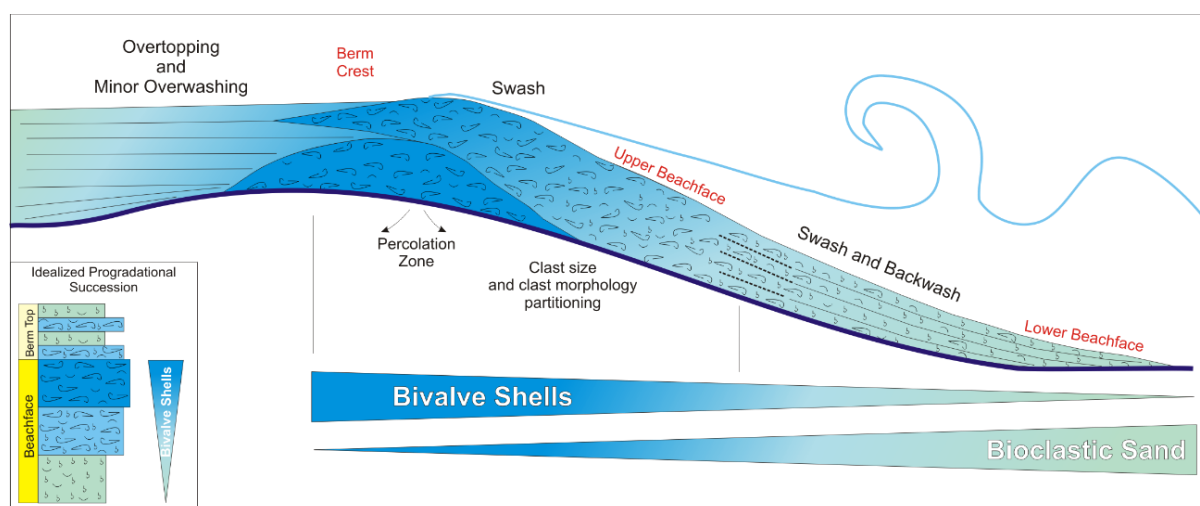


Figure 19. Elementary depositional model for a coquina ridge during the waning phase of storm events.

4.3.6. Evolution of the beach-ridge system in 'east Nilemah'

The onset of the Beach-ridge system in 'East Nilemah' took place with the washover domain deposition at about 5000 ^{14}C years BP. This was the beginning of a period when the sea level rose sufficiently under adequate storm periodicity and intensity, complemented by abundant sediment supply (i.e. high *F. erugatum* shell productivity) favoring the development of the progradational beach depositional domain (Figure 20). It is not possible to determine the exact time interval for the development of ridge set 2 due to lack of reliable samples however it can be constrained within 3720 and 2620 ^{14}C years BP interval. After 2620 ^{14}C years BP, deposition occurred in the area of ridge sets 3, 4 and 5. The spit ridge domain is within the area of deposition of ridge set 5. A well-pronounced difference in elevation is

observed between the spit depositional domain and the beach depositional domain. This elevation step was established between 500 and 1640 ^{14}C years BP (Figure 20). When lower sea levels are reached, it becomes difficult for storm-surges to overcome the coastal barriers. Thus, longshore currents are induced nearshore, and a series of spit ridges locally develop (Figure 21). Furthermore, environmental changes such as alteration of wind and wave climate, storminess and increase in sea-level fall rate are possible influences on the formation of this step and the deposition of the spit-ridge depositional domain. In this regard, Jahnert et al. (2012) also observed a change in layer organization and a shift in the focus of sediment deposition in Telegraph Station ridges they recognized to have occurred around 1000 years ago. Figure 21 illustrates this switch in the prevailing processes responsible for ridge construction, experienced in 'East Nilemah' during the latest Holocene.

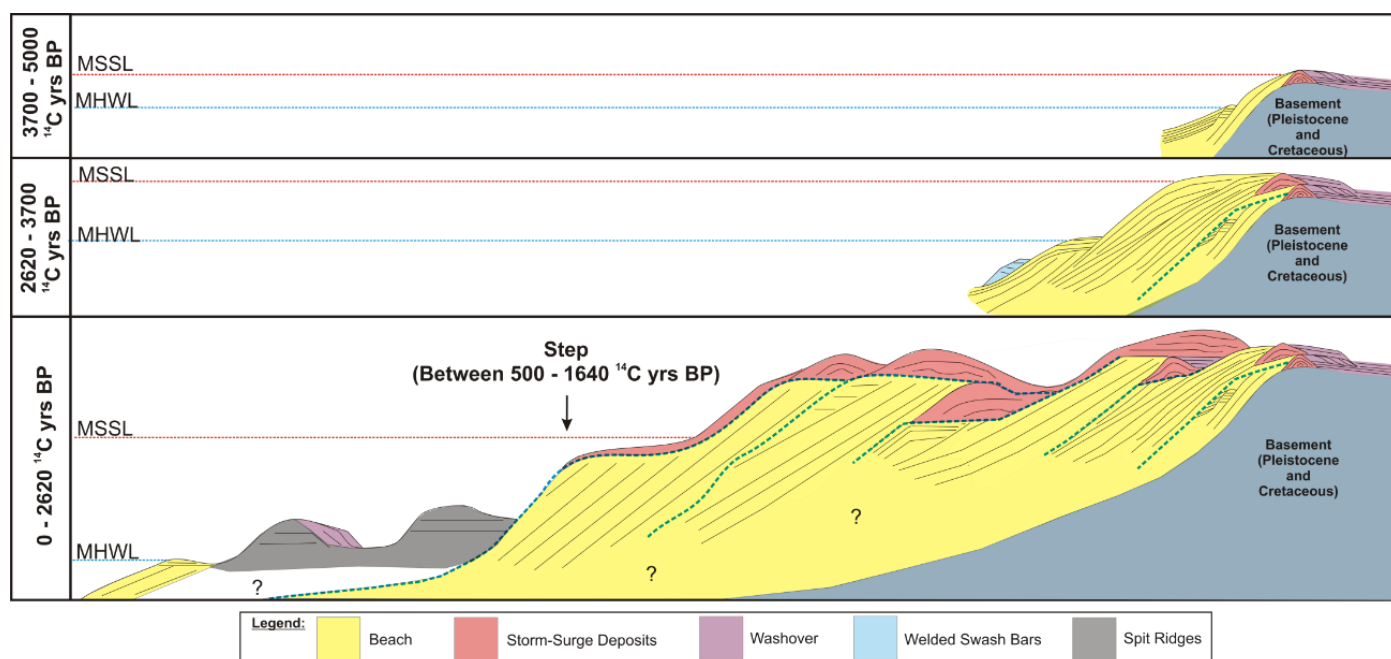


Figure 20. Simplified evolutionary model for the depositional domains in 'East Nilemah' beach ridges. Depositional elements and major erosional surfaces have the same colour code used in GPR profiles. MSSL – Mean Storm-surge Level; MHWL – Mean High Water Level.

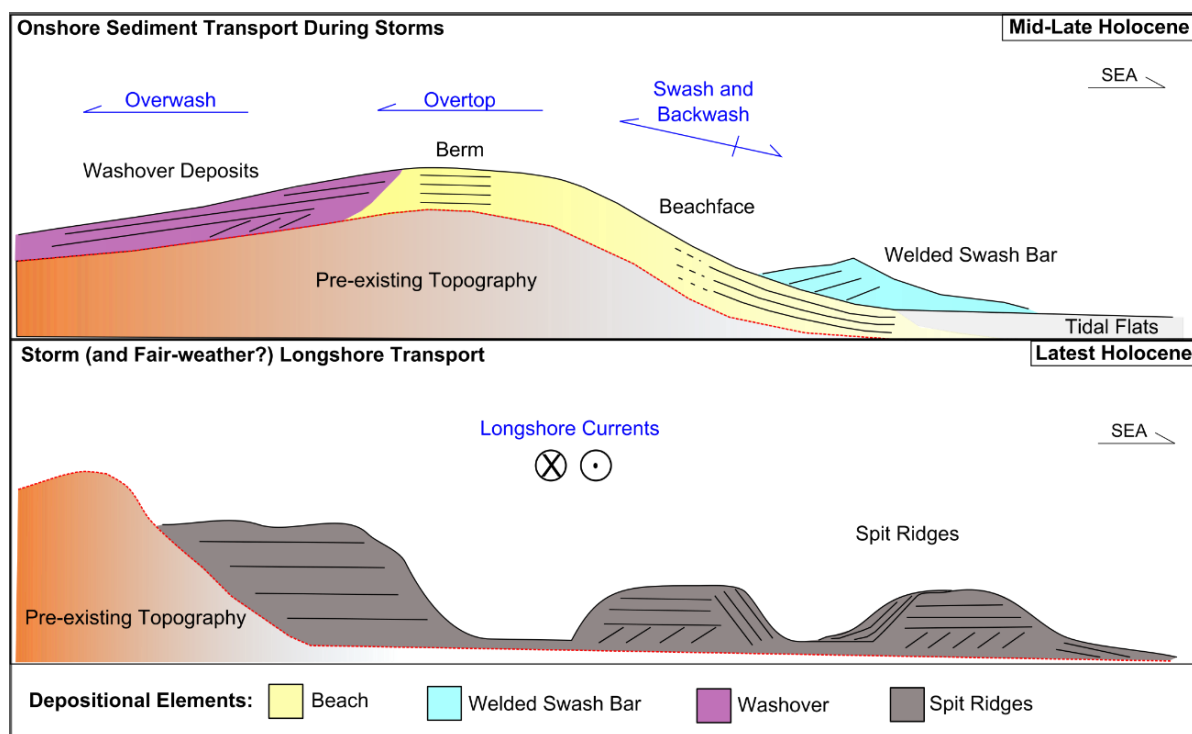


Figure 21. Idealized sketch illustrating the prevailing processes switch experienced in 'East Nilemah' during the latest Holocene. **Top:** Onshore sediment transport during storms and overwash, overtop and swash processes prevailed in the mid to late Holocene phase of ridge construction. **Bottom:** Longshore currents prevail in ridge construction processes and spit ridges develop during the latest Holocene.

4.4. Hamelin Pool's western shore

At Hamelin Pool's western shore two DGPS transects exemplify the overall ridge morphology in both north facing and east facing shores of Fishermen's Point site (figures 22 and 23). Both transects present trends of decreasing ridge elevation that can be related to the

signal of mid to late Holocene falling sea-level in the area. In transect DGPSFP-B, the floors of isolated lagoons display increasingly lower elevation seaward which is related to the gradient of the tidal flat over which the beach-ridge system is prograding rather than an imprint of the sea-level fall.

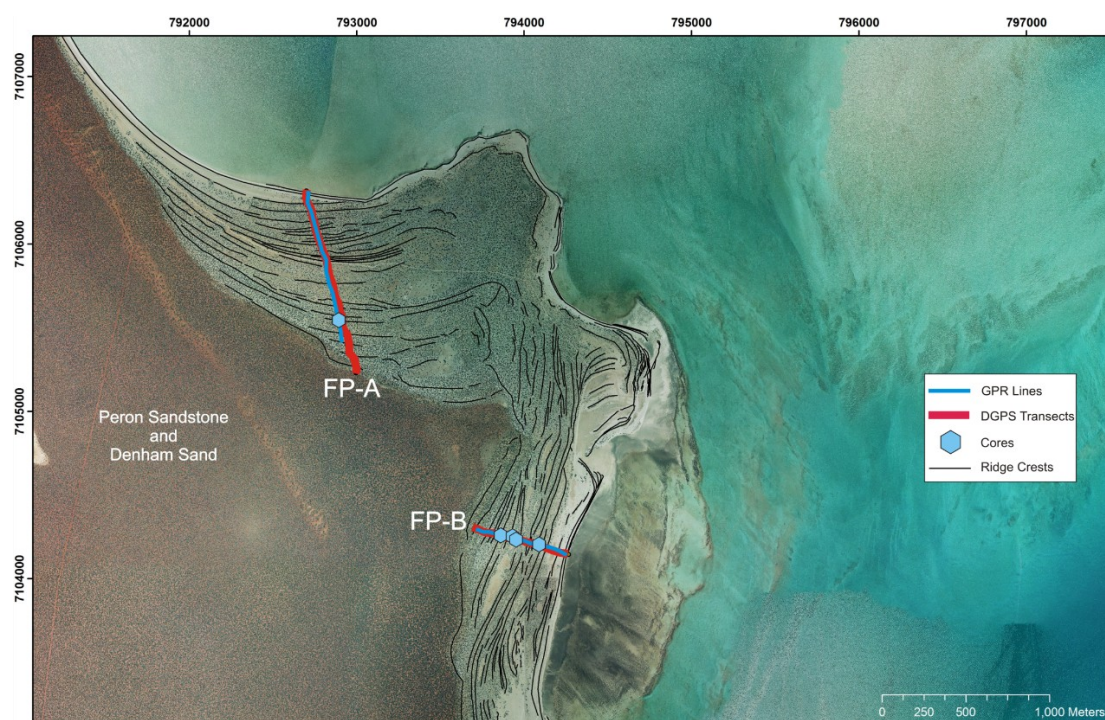


Figure 22. Aerial image of the study area showing the mapped ridge crests and the acquired GPR lines, DGPS transects and cores.

4.4.1. GPR profile interpretation

In Fishermen's Point site 2 GPR lines were run parallel to the depositional dip direction. Line FP-A is located on a north facing shore and FP-B is on the east facing shore (Figure 22). These lines were acquired with a lower resolution 250 MHz antenna as compared with 'East Nilemah' site (Section 4.3) where a 500 MHz antenna was used.

4.4.1.1. GPR line FP-A

GPR line FP-A is split into two lines A-607 and A-11 and will be treated here as a single line totaling 996 m (figures 24 and 25). Although orthophotos and geomorphic maps of the beach-ridge system at Fishermen's Point suggest that alongshore transport is an important component in ridge growth, the overall pattern of FP-A transect shows the predominance of seaward inclined reflections as a result of beachface progradation rather than more complex internal geometries of spit ridges. Between 300 and 450 m, horizontal to gently inclined seaward reflections, in a flat low-lying area, indicating an isolated lagoon bordered seaward by a spit ridge that exhibits convex-up, horizontal and seaward inclined reflections. This spit was responsible for the isolation of the lagoon from the bay. Landward inclined reflections on the flank of the spit ridge are interpreted as washover deposits. Blanketing

all these deposits there is an overall reflection-free package that is interpreted to represent deposits similar to the storm-surge domain characterized in Section 4.3 although some eolian decoration is possible as sand is abundant in the site.

4.4.1.2 GPR line FP-B

GPR line FP-B encompasses 600 m where two domains are discernible: one, between 550 and 350 m, where seaward inclined reflectors of the prograded beachface predominate, and another, starting approximately at 350 m, where alternating ridges and isolated lagoons dominate the scene (Figure 26). Occasionally, radar packages with landward dipping reflector configuration are observed adjacent to the landward flank of spit ridges, being interpreted as washover deposits. Although this east-facing shore at FP-B is more protected from storms reaching Shark Bay in northerly and westerly approaches, storm-surge deposits also blanket ridges in this location. However, ridge elevations are lower overall than in the eastern shore of Hamelin Pool and the north-facing shore of Fishermen's Point, not exceeding 3.5 m. Within the storm-surge blanket, quartz grains are likely as they are abundant in Nanga Peninsula.

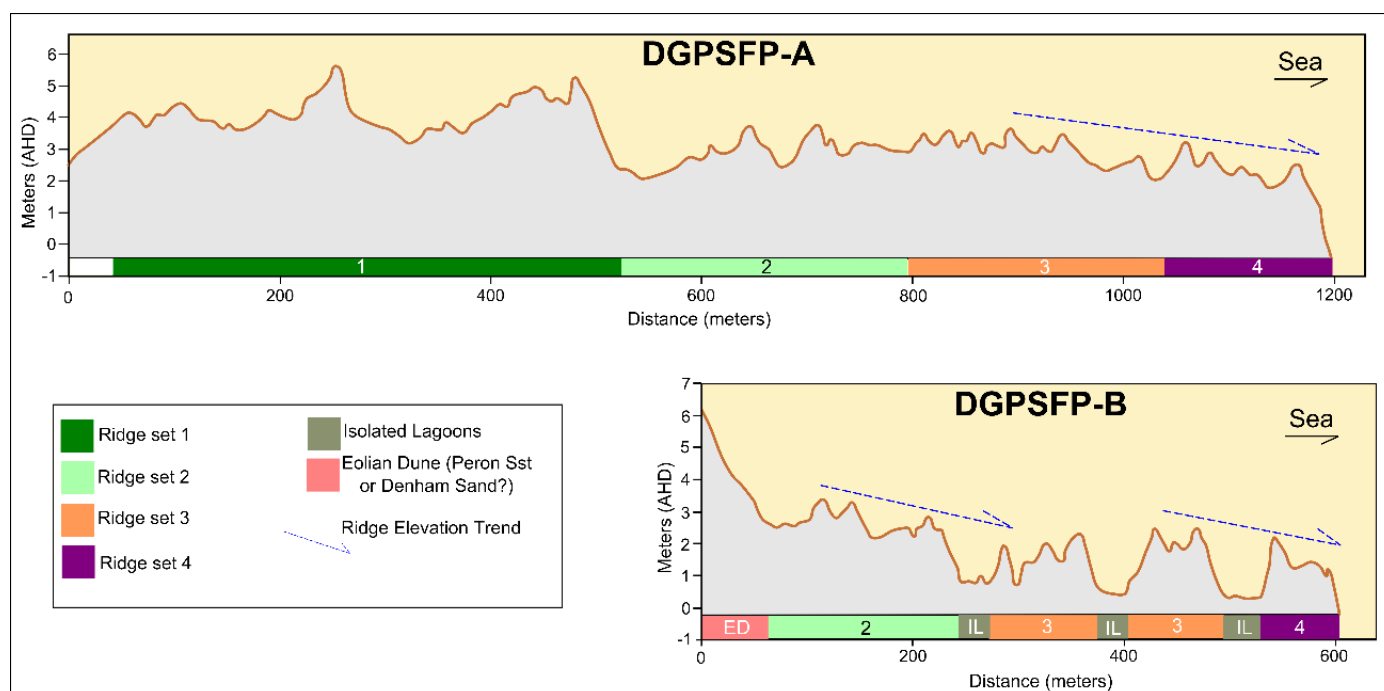


Figure 23. DGPS transects across Fishermen's Point Beach-ridge Plain. See Figure 22 for location.

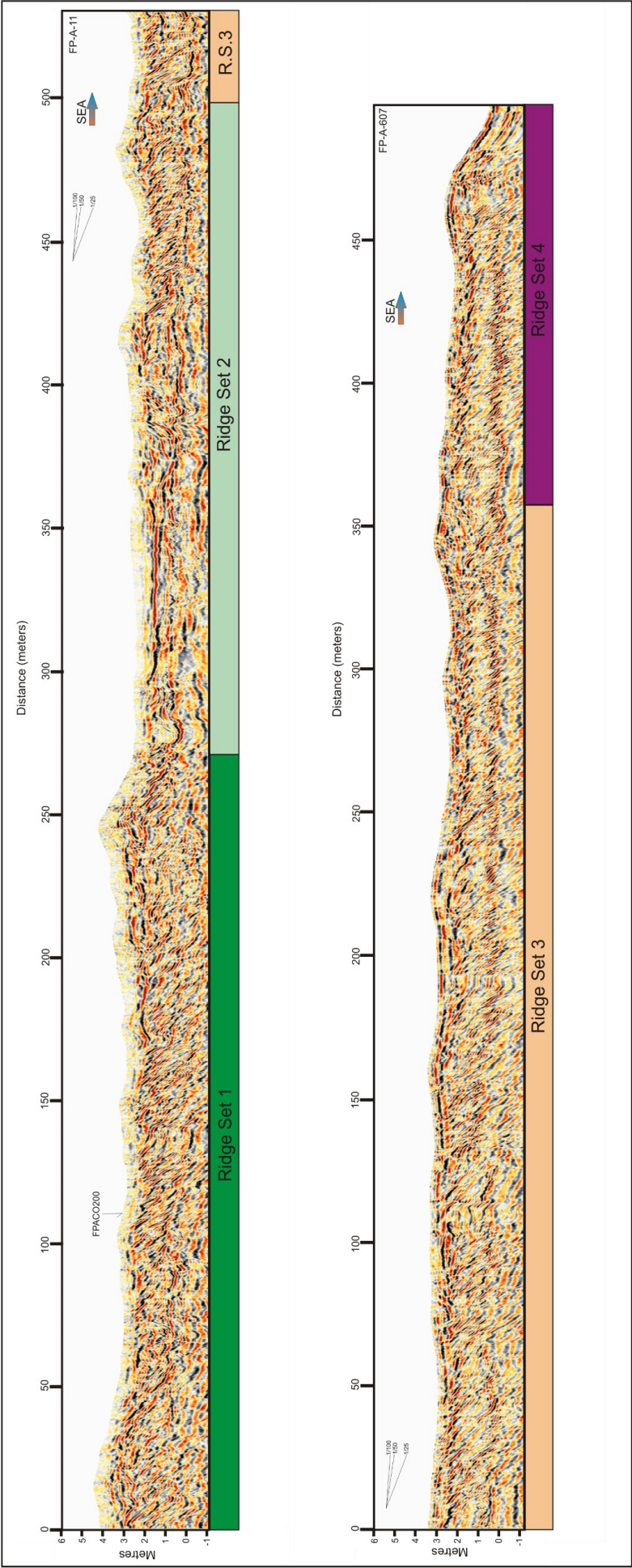


Figure 24. FP-A uninterpreted GPR lines. Lines FP-A11 and FP-A-607 are in continuity.

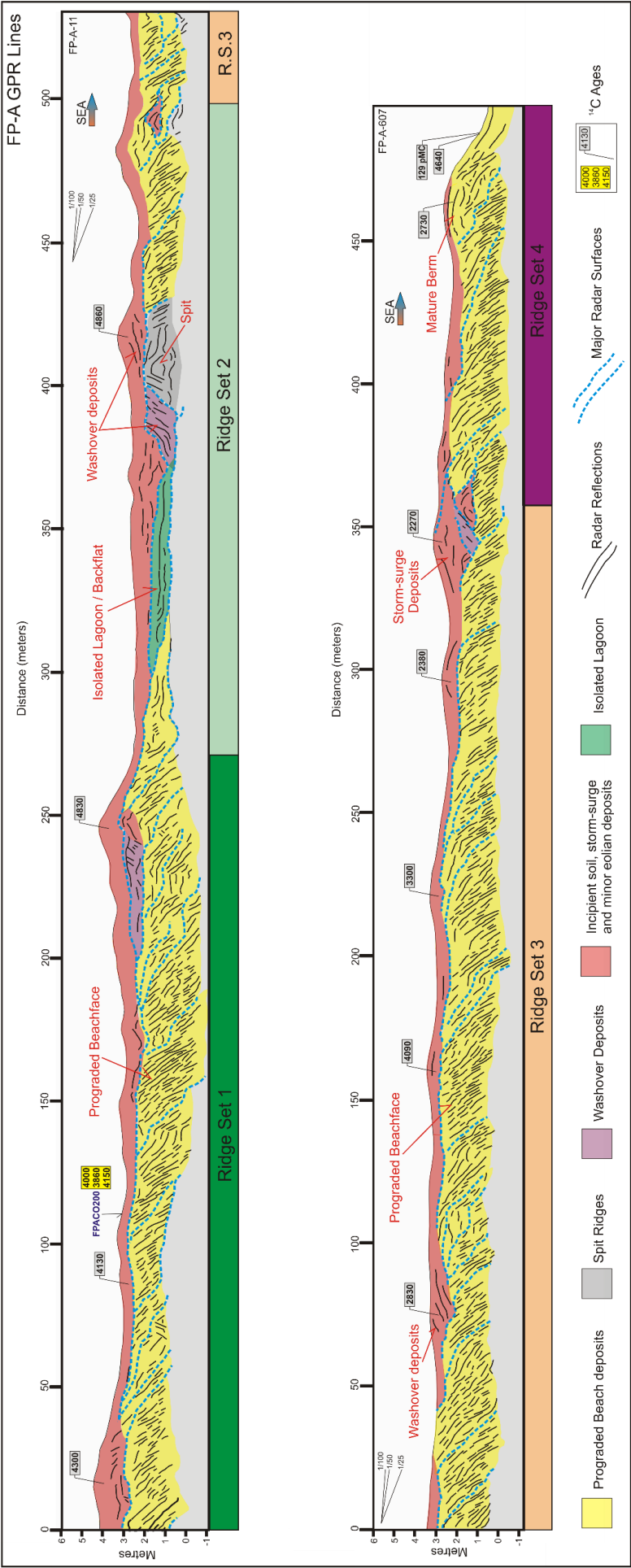


Figure 25. FP-A interpreted GPR transect. Lines FP-A-11 and FP-A-607 are in continuity. Seaward inclined reflectors of prograding beachface deposits capped by a blanket of storm-surge deposits, eolian sediments and incipient soil are prevalent in this transect. Between 300 and 450 m a spit ridge backed by an isolated lagoon occurs being covered by storm-surge and eolian deposits.

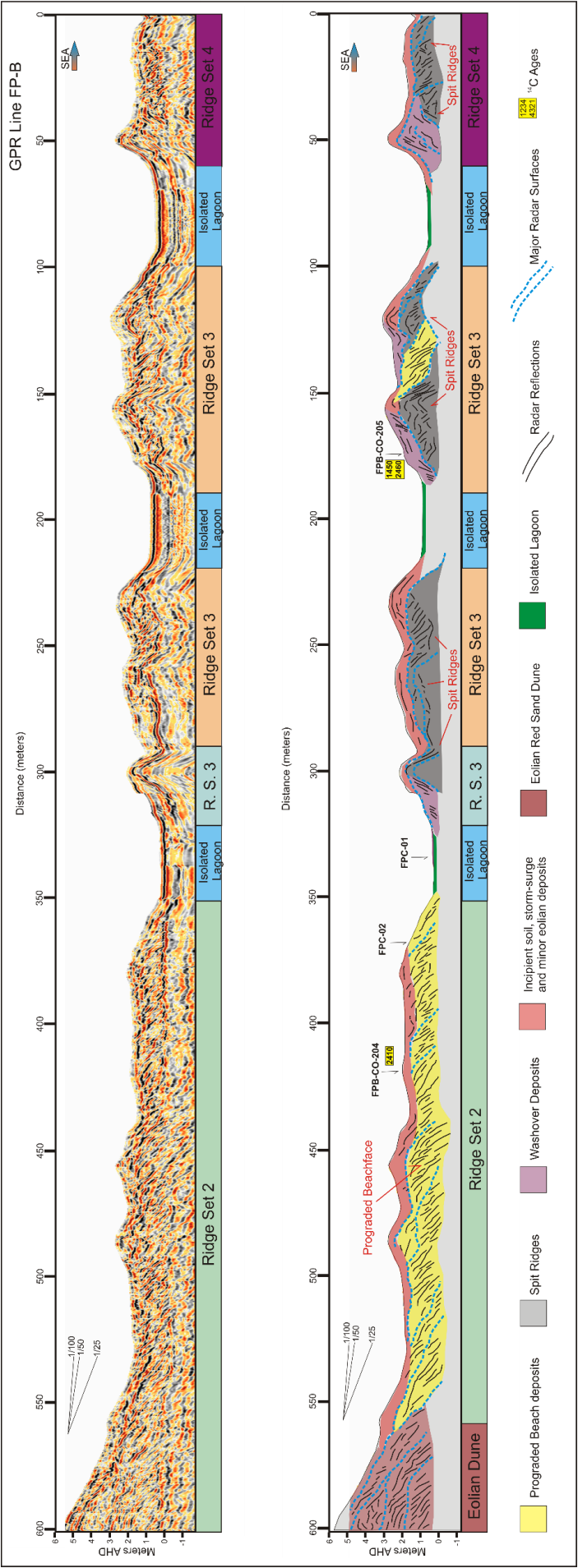


Figure 26. Uninterpreted (top) and interpreted (bottom) GPR line FP-B. Seaward inclined reflectors of prograding beachface deposits are dominant in the landward-most portion of the transect, being later replaced by a succession of isolated lagoons and spit ridges.

4.4.2. Sediment cores

In Fishermen's Point, 5 cores were obtained along the GPR lines and lithologies observed were shell gravels and shelly bioclastic ooid and quartz sands (Figure 27). Shell gravels are composed of bivalve mollusks, mainly *Fragum erugatum*, with variable amounts of sandy matrix. Furthermore, shelly, bioclastic ooid and quartz sands occasionally exhibit micritized grains, peloids and micritic cementation.

In FP-A, the core FP-A-CO-200 intersected 3 radar packages representing prograded beachfaces capped by storm-surge deposits and incipient soil (Figure 28). The beachface deposits have high contents of quartz, derived from adjoining Nanga Peninsula whose country rock is the Plio-Pleistocene Peron Sandstone.

In GPR line FP-B, four additional cores provided textural and compositional information on the sediments at Fishermen's Point (Figure 29). Cores FPB-CO-204 and FPC-02 intersect prograded beachface deposits rich in quartz sediments as observed in FP-A. In FPC-02, the lowermost radar package corresponds to medium to

coarse quartz sands where grain micritization and micritic cementation are common and are not only restricted to a few centimeters at the bottom of the core (Figure 29).

Core FPC-01 was obtained in an isolated lagoon and shows incipient soil and a shell gravel bed derived from a small scale washover overlying back flat deposits consisting of micrite-cemented quartz sands and a 2 cm-thick sandy mud layer with plant root fragments. Below this muddy layer, micrite-cemented bioclastic quartz sands occur and are assumed to represent subtidal deposits over which the beach-ridge system is prograding – a former sublittoral platform (cf. Logan et al., 1970).

Core FPB-CO-205 intersects the landward flank of a spit ridge and displays more shell gravels than the other cores in this transect. The upper 68 cm show a predominance of shell gravels associated with overwash events over the initial ridge deposits. To the bottom, sediments display higher quartz sand content and in GPR exhibit seaward and convex-up reflection configuration being interpreted as spit ridge deposits (Figure 29).

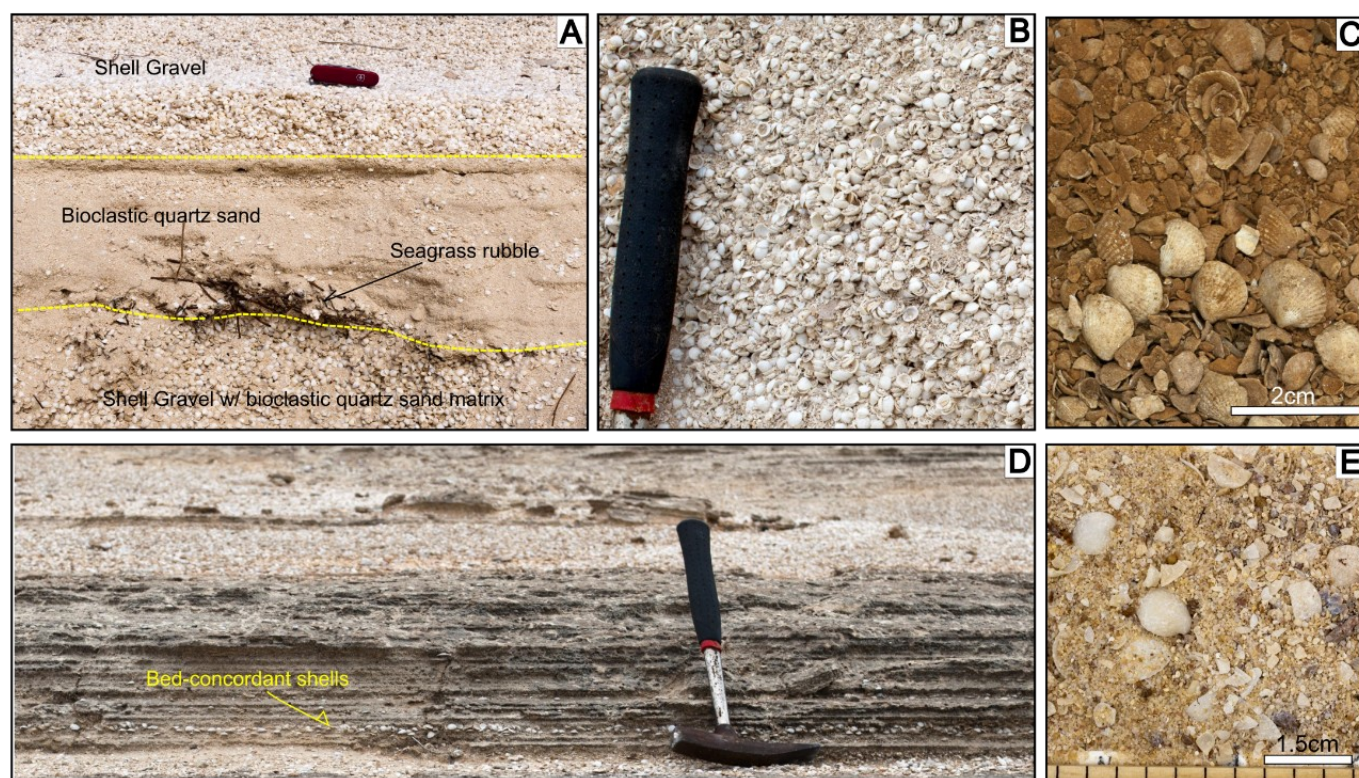
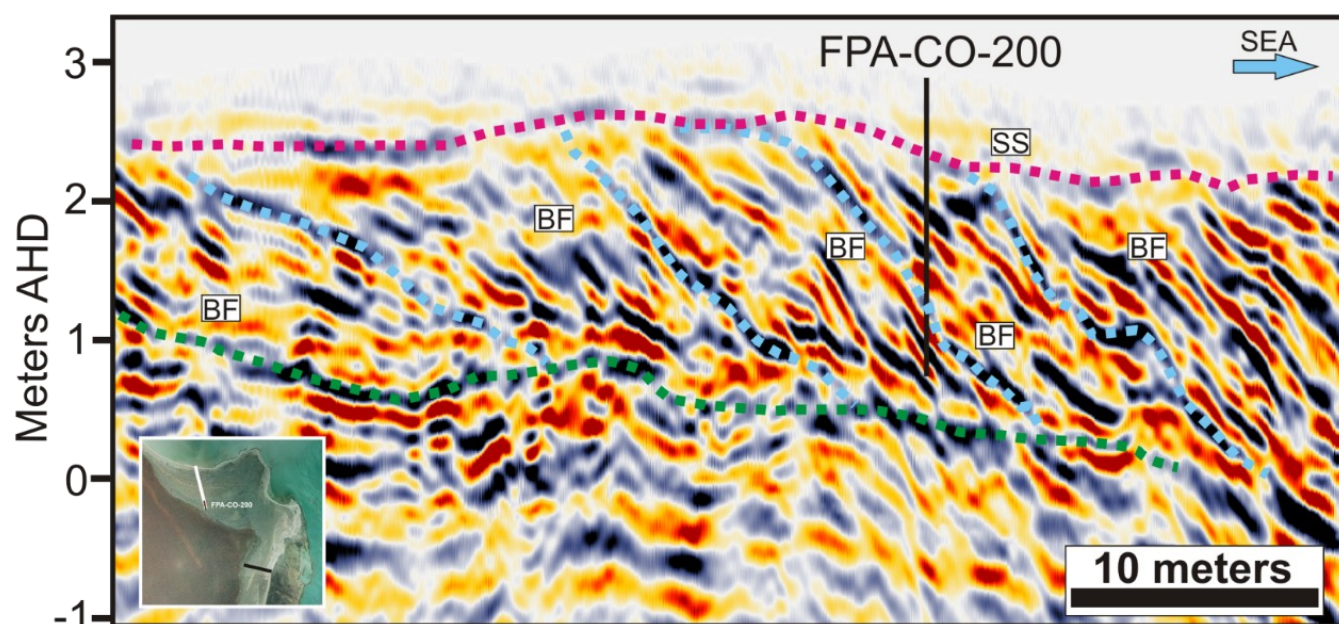


Figure 27. Sedimentary deposits in Fishermen's Point Beach-ridge plain. **A.** Lithologies in a beach terrace. **B.** Shell gravel with sand matrix. **C.** Shell gravel with infiltrated red clay and sand. **D.** Quartz, ooid and bioclast sand with plane parallel lamination and a layer of oriented bed-concordant shells. **E.** Shelly quartz sand with bioclasts and lithoclasts.



FPA-CO-200

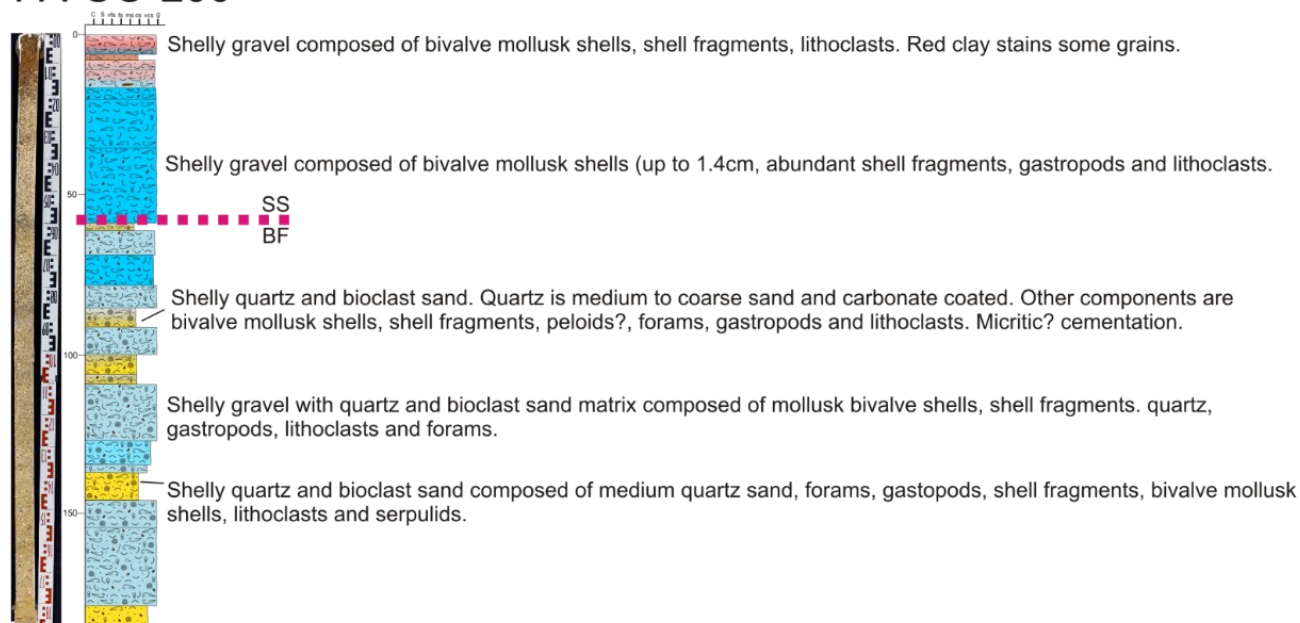


Figure 28. Segment of GPR line FP-A where core FPA-CO-200 intersects storm-surge deposits and soil blanketing beachface shell gravels and quartz sands. SS: Storm-surge deposits and soil; BF: Beachface deposits.

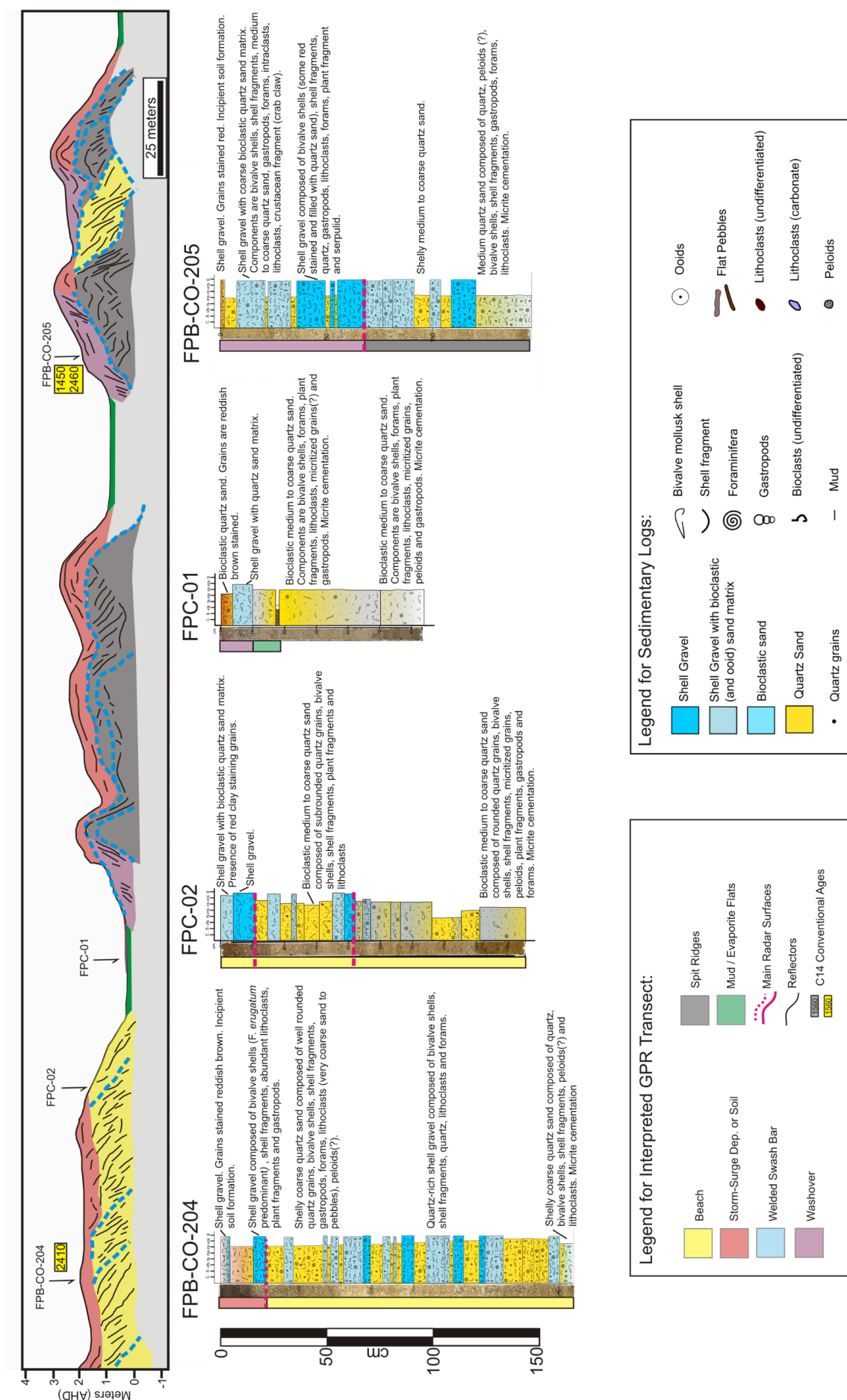


Figure 29. Segment of GPR line FP-B where four push cores were obtained intercepting beach, spit ridges, washover, isolated lagoon and storm-surge deposits.

4.4.3. Indurated pavement

Beach ridges in the north-facing shore of Fishermen's Point are interrupted by a low-elevation nearly flat area where an indurated pavement outcrops (figures 30A and 31). This interruption evidences an erosive episode that impacted the beach ridges that were prograding over this indurated pavement.

The pavement is composed of cemented shelly quartz sands or sandy shell gravels, occasionally displaying polygonal structures similar to those observed in modern beach rocks (figures 30B and 30D). These shelly quartz sands exhibit micritic cement later fringed by well-developed aragonite needles (Figure 30C). These marine cements suggest this pavement is a beachrock preserved from a major erosive event (or period) that disrupted the beach-ridge system. DGPS data demonstrate that this beachrock area is about 1.5 m in elevation implying it was formed at higher than present sea-level conditions. Although Kelletat (2006) question the use of beachrocks as sea-level indicators alone, other evidence of regressive conditions observed by some authors (e.g. Logan et al.,

1974; Jahnert and Collins, 2011; Jahnert and Collins, 2013) reinforce the interpretation of the pavement as an indication of higher sea-levels during the onset of the beach-ridge system in accordance with an Holocene highstand of +2 m at approximately 6800 U/Th years BP identified by Collins et al. (2006) in the Houtman Abrolhos Islands, Western Australia.

4.4.4. Ridge chronology

In order to establish a chronological framework for ridge formation and evolution, 22 shell samples were dated using the radiocarbon AMS technique at the Fishermen's Point site. Most of the samples were collected in storm-surge deposits prone to contain reworked material. For this reason, age reversals are common in the studied transects and radiocarbon dates from these samples can only be used as maximum ages. However, six articulated shell samples were obtained from the cores and provide reliable ^{14}C ages that were used as key ages to delineate ridge chronology (Figure 31).

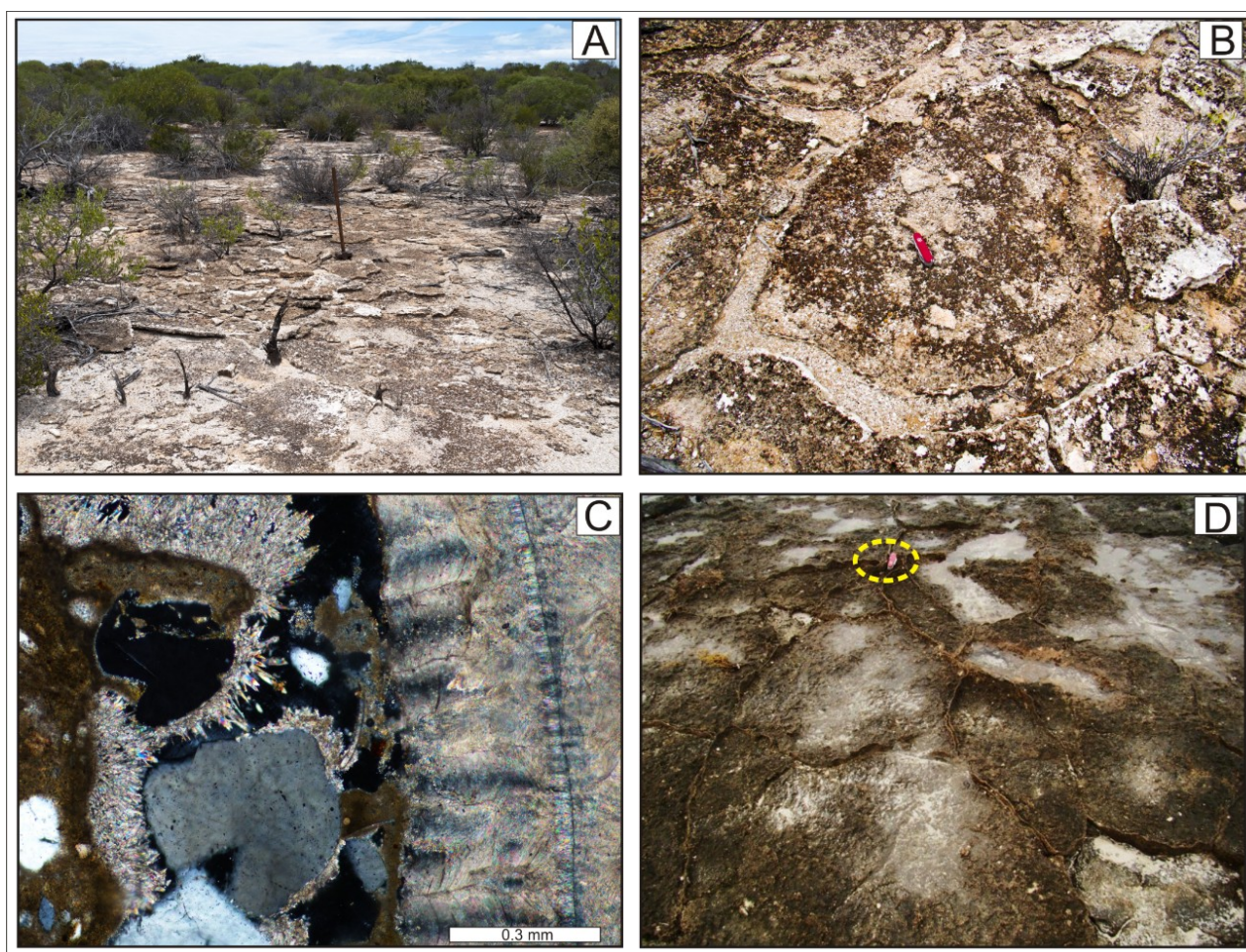


Figure 30. A. Flat eroded area where the indurated pavement outcrops. B. Indurated pavement exhibiting polygonal structures (red pocket-knife for scale). C. Epoxy-impregnated thin-section of indurated shelly bioclast and quartz sand cemented by dark brown micrite and acicular aragonite. D. Modern beachrock in Fishermen's Point exhibiting polygonal structures (red pocket-knife for scale in the upper part of the photo (yellow circle); photo courtesy of João Guerreiro).

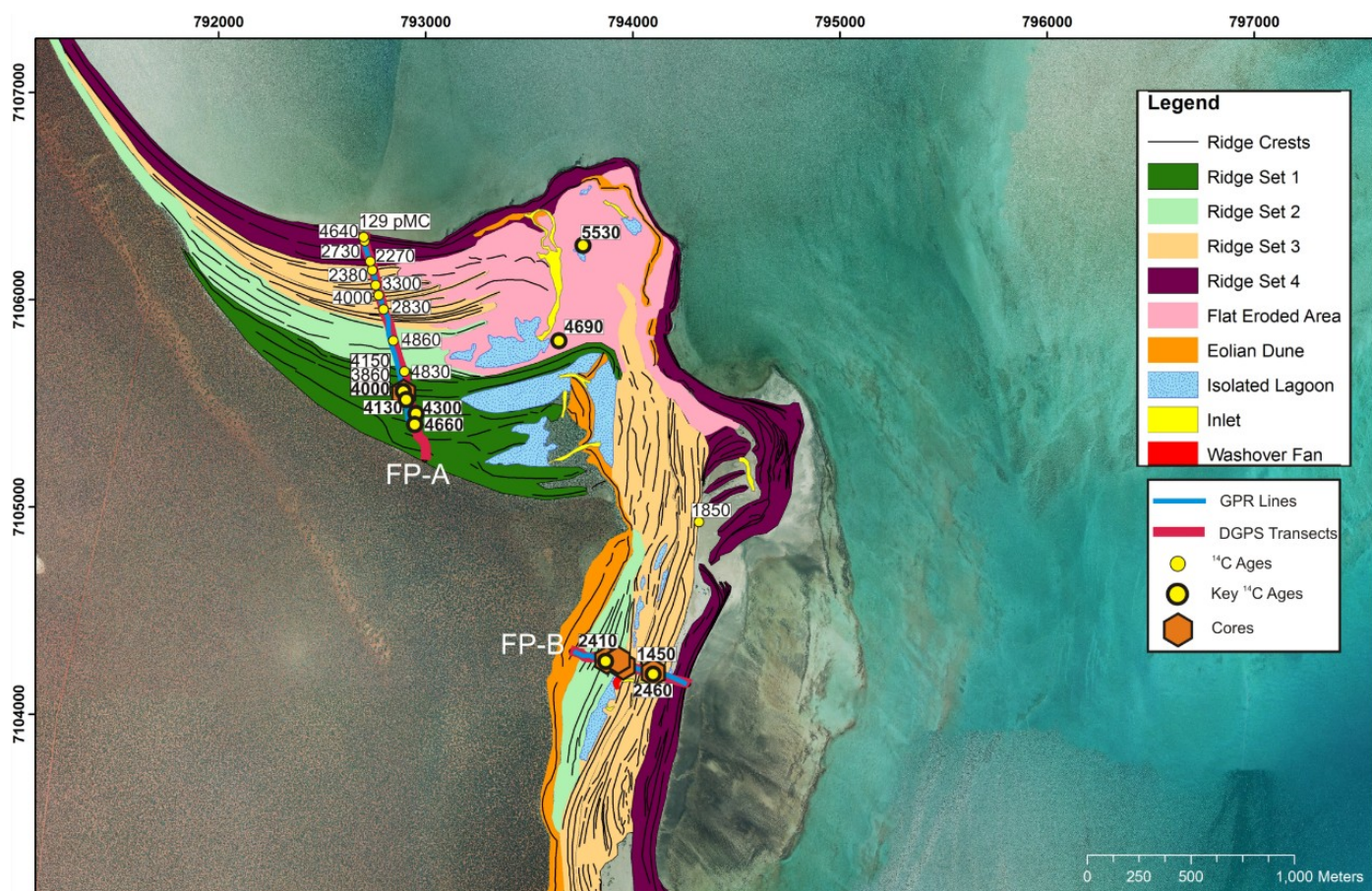


Figure 31. Geomorphic map and aerial image of Fishermen's Point beach-ridge plain with ^{14}C dates, cores, GPR and DGPS transect locations. Key ages for the interpretation of ridge chronology are indicated by thick-bordered circles.

Table 4. Radiocarbon chronology for *F. erugatum* shells of selected coquina deposits. A delta R of 70 ± 50 was used for marine reservoir correction. Data calibrated against Marine09 calibration curve (Reimer et al., 2009).

Sample Id	Source of Carbon	^{14}C age (years BP)	Error (years)	^{14}C age (years BP) calibrated 2 sigma
FPD-14	Bivalve Shell	129.9 pMC	0.3	
FPD-12	Bivalve Shell	4640	30	4880/4610
FPD-11	Bivalve Shell	2730	30	2490/2240
FPD-10	Bivalve Shell	2270	30	1920/1670
FPD-09	Bivalve Shell	2380	30	2070/1800
FPD-08	Bivalve Shell	3300	30	3210/2870
FPD-07	Bivalve Shell	4090	30	4210/3860
FPD-06	Bivalve Shell	2830	30	2680/2320
FPD-05	Bivalve Shell	4860	30	5260/4860
FPD-04	Bivalve Shell	4830	30	5270/4820
FPD-03	Bivalve Shell	4130	30	4250/3920
FPD-02	Bivalve Shell	4300	30	4490/4140
FPD-01	Bivalve Shell	4660	30	4930/4640
FPG-05B	Bivalve Shell	4690	30	4960/4700
FP-D-207	Bivalve Shell	5530	30	5940/5690
FP-D-205	Bivalve Shell	1850	30	1500/1170
FPBCO205-D2	Articulated Bivalve Shell	2460	30	2150/1870
FPBCO205-D1	Articulated Bivalve Shell	1450	30	1040/780
FPBCO204-D1	Articulated Bivalve Shell	2410	30	2140/1780
FPACO200-D3	Articulated Bivalve Shell	4150	30	4280/3950
FPACO200-D2	Articulated Bivalve Shell	3860	30	3880/3570
FPACO200-D1	Articulated Bivalve Shell	4000	30	4070/3760

The deposition of ridge set 1 took place between 4660–3860 ^{14}C years BP. An onset of the beach-ridge system around 4500–5000 ^{14}C years BP was also observed at 'East Nilemah' site (Section 4.3) and by Jahnert et al. (2012) at Telegraph Station, both in the eastern shore of Hamelin Pool.

An age of 5530 ^{14}C years BP was obtained in the indurated pavement, nevertheless the most reliable date for this unit is around 4690 ^{14}C years BP, very close to the oldest age considered in place for ridge set 1.

Ridge set 2 only possesses one reliable dated sample corresponding to 2410 ^{14}C years BP, obtained from an articulated shell in a core acquired at transect FP-B, located in the eastfacing shore of the site.

The next reliable dated sample is 2460 ^{14}C years BP in ridge set 3. Although this result is an apparent reversal, the ages can be considered in place as the results are within the uncertainty boundaries shown in Table 4. Another possible explanation for this reversal is that shells had a significant residence time in the basin before being transported ashore and the younger date of 1450 ^{14}C years BP obtained in ridge set 3 for washover deposits is closer to the actual age of the ridge.

The erosional event that exposed the underlying indurated pavement has an age of 1450 ^{14}C years BP or younger, as it affects ridge set 3 but not ridge set 4. This event can be related to the changes that led to the development of the spit ridge domain described in Section 4.3 ('East Nilemah') and the change in layer organization and shift in focus of sediment deposition observed by Jahnert et al. (2012) in Telegraph Station ridges.

Ridge set 4 initiation could not be dated but is inferred to have taken place soon after 1450 ^{14}C years BP and is still under development as it encompasses active berms and beachfaces. This age range is in accordance with the inferred ages observed for the younger ridge set in 'East Nilemah'.

5. DISCUSSION

The objective of this study was to contribute to the understanding of coquina deposits by documenting architectural and sedimentological characteristics of the Shark Bay coquina beach-ridge system. GPR, radiocarbon chronology, outcrop, trench and core data were used to propose a depositional model and outline an evolutionary framework for coquinas and associated facies deposited in two sites: one in the eastern shore of Hamelin Pool, and another, in the western shore of this hypersaline basin.

Shark Bay region is vulnerable to sporadic tropical cyclones and storm surges. However, the degree of exposure to these hazards within Hamelin Pool varies in relation to geographical and geomorphological particularities of different sites. For example, Hamelin Pool eastern shore is more exposed to storms, usually

approaching the bay from north and northwest quadrants. Furthermore, north- and west-facing shores tend to be more impacted by storms than south- and east-facing ones.

This difference in vulnerability to storms is revealed by a number of indications in the studied sites. 'East Nilemah', located on the eastern shore, has higher ridges, well developed washover fans and abundant flat pebbles originating in the tidal flats, deposited in the flanks of the seaward-most ridges. In contrast, coquina ridge elevations are lower at Fishermen's Point, not exceeding 5.6 m as opposed to 8 m at 'East Nilemah'. Moreover, DGPS transects at Fishermen's Point suggest declining trends of ridge elevation (Figure 23) indicating that the signal of falling sea levels during the Mid to Late Holocene is more evident in the western shore beach ridges than in those located in the eastern shore which is more vulnerable to storm impacts.

An important difference between 'East Nilemah' and Fishermen's Point sites refers to sediment composition. As Hamelin Pool possesses different geological foundations in eastern and western shores, the sandy fraction of sediment reflects that characteristic. The eastern shore is bordered by the Carbla Plateau which is underlain by the Cretaceous Toolonga Calcilutite. In contrast, the western shore of Hamelin Pool is at Nanga Peninsula whose country rock is composed of the Plio-Pleistocene Peron Sandstone, rich in quartz. Consequently, the sandy fraction of sediments in the western shore exhibits a high content of quartz, not observed in 'East Nilemah'. The beach-ridge plain at Fishermen's Point can be considered a mixed bioclastic-siliciclastic system as the reworking of quartz sands from the adjoining Nanga Peninsula by storms and other marine processes yields siliciclastics to the system despite the absence of any significant fluvial input.

Similarities were also observed between beach-ridge deposits in eastern and western shores, especially in their sedimentary architecture. In general, the seaward inclined reflections of prograding beachface deposits are the prevalent architectural element at both sites. In many of the GPR lines, these inclined reflectors are replaced in the seaward direction by the geometrically more complex spit ridges. Furthermore, a diachronous blanket of storm-surge deposits, incipient soil and eolian deposits also occur in both sites studied.

The differences observed in sedimentary architecture and coastal morphology in the studied sites result from variable degrees of vulnerability to storms. Additionally, reworking processes such as tidal currents, longshore currents and waves may also be energetic enough under fair-weather conditions to transport sediment and leave their imprint in coastal morphology (Figure 32A).

'East Nilemah' is highly exposed to storms because of the northeasterly aspect of its shore and has coastal

features that suggest processes operating in variable directions (Figure 32B). Apart from the NW direction of overwash, the spits indicating SW and NE direction of transport were generated by longshore currents which may operate either during storms or under fair-weather conditions. Furthermore, ebb tidal currents are expected to be dominant in the eastern shore of Hamelin Pool (Figure 32A), facilitated by wind set-up (Logan and Cebulski, 1970). An additional characteristic of 'East Nilemah' is the occurrence of welded swash bars, as interpreted in the GPR lines, which were not observed in the transects at the western shore of Hamelin Pool.

Fishermen's Point, located on the western coast of Hamelin Pool, has shores facing north and east. Its north-facing shore displays spit-ridge growth to the east

suggesting longshore currents operating from west to east (Figure 32C). These currents are either induced by storms approaching from north/northwest or result from the deflection of flood tidal currents. In the east-facing shore the sediment transport is overall from north to south also resulting either from flood tidal currents that are dominant in the western shore of Hamelin Pool or from longshore currents induced by north/northwest approaching storms. Moreover, isolated lagoons are additional elements that were not observed in 'East Nilemah' and occur associated with spit ridges in Fishermen's Point. These isolated lagoons are particularly detectable in GPR transect FP-B (Figure 26) which is located in the east-facing shore, more protected from storm impacts. The indication of south to north spit growth in the east-facing shore, although small, results from the wind drift.

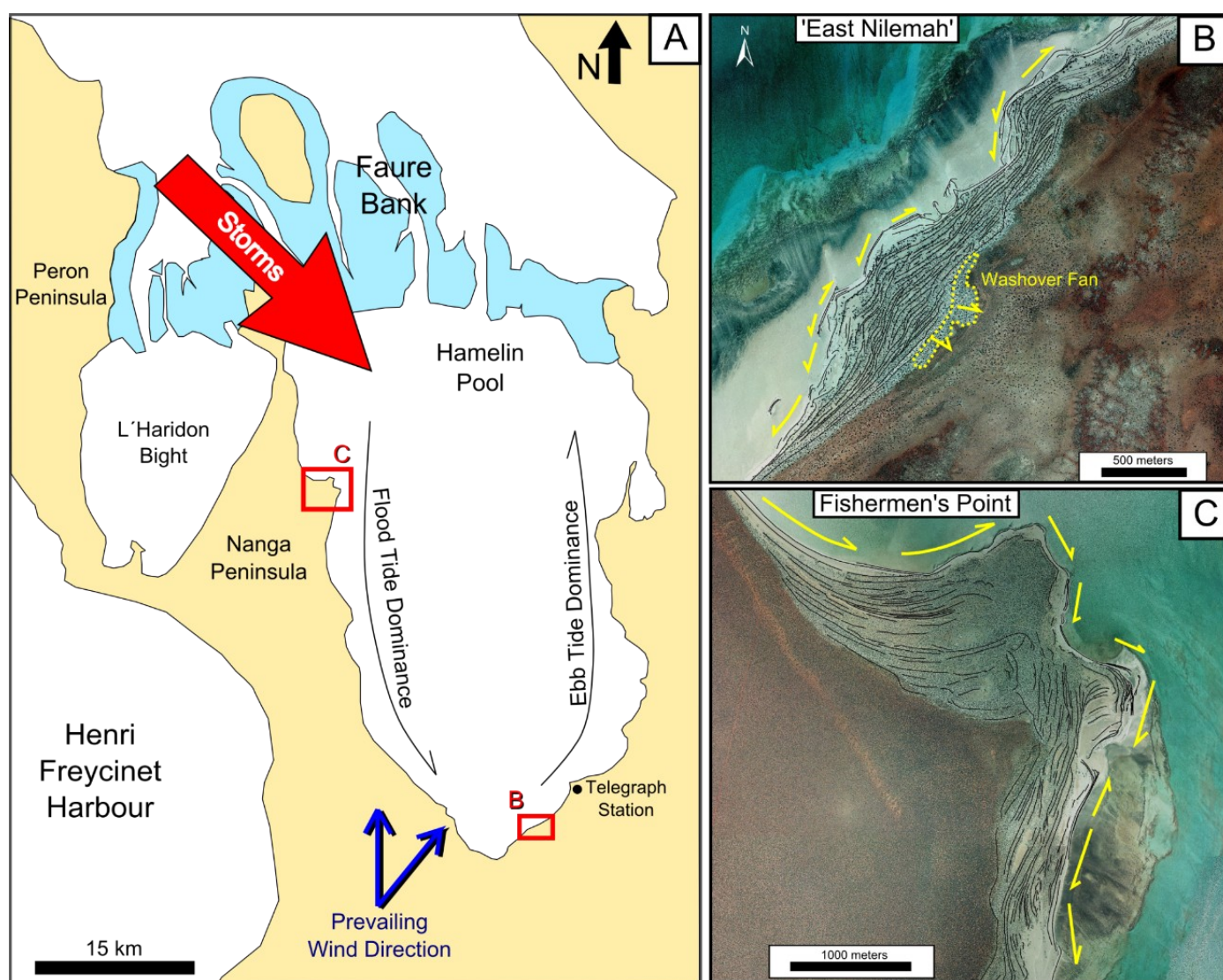


Figure 32. A. Map with the directions of main energetic coastal processes at Hamelin Pool. Prevailing winds are southerly and south-westerly which favors flood tide dominance in east-facing coasts and ebb tide dominance in west-facing shores. Storms and tropical cyclones usually approach Hamelin Pool from the northwest. B. Interpreted directions of energetic processes responsible for coastal morphology in 'East Nilemah'. C. Interpreted directions of energetic processes responsible for coastal morphology in Fishermen's Point.

Although depositional domains may endure and overlap in time, Figure 33 is an attempt to constrain their chronologies and expose their rough stratigraphic significance. Depositional domains do not display well-defined chronological boundaries except for the washover domain in 'East Nilemah' which relates to the onset of the system in the eastern shore, and the spit domain which tends to be well developed after 1450 ^{14}C years BP in both sites studied (Figure 33B). However, the spit domain develops earlier (or is better preserved) in Fishermen's Point eastern coast, which is more protected from storm attacks, starting to develop at about 2450 ^{14}C years BP. On the other hand, ridge sets on both sites show a relatively good chronological correlation (Figure 33C) indicating that the beach-ridge system growth is controlled by periods of high sediment availability and adequate storminess which in conjunction with operating marine processes will favor the system's progradation.

In summary the beach-ridge system development can be divided into three main stages responsible for the deposition of the washover, beach and spit depositional domains which are modified by sporadic events responsible for the deposition of a diachronous blanket. The first stage (3700–5000 ^{14}C years BP) is represented by an early washover domain characterized by higher than present sea level, possibly higher storm intensities and higher storm-surge water levels. In the second stage (1640–3700 ^{14}C years BP), the beach depositional domain develops by beachface progradation under falling sea-level conditions, although the beachface is active only during elevated water levels in either the waning phase or the passage of distant storms, when swash and backwash processes predominate. The third stage (1640 ^{14}C years BP – present), when the deposition of the spit domain takes place, is characterized by even lower sea-level and lower storm intensities which now are unable to overcome beach-ridges thus inducing longshore currents that predominate during spit ridge growth. Indications of changes in coastal dynamics correlative to this third stage were also described by Jahnert et al. (2012), who observed remobilization of shells followed by a marked decrease in layer dip angles that occurred since 2000 years ago in a unit geometrically similar to the beach depositional element, as spit ridge development was limited in their

study area. A diachronous blanket that caps the domains originated in these three stages is composed of mixed-origin deposits: (1) storm-surge ridges deposited by multiple episodes of inundation overwash and sub-aerial exposure when windblown clay and silt infiltrate the upper parts of exposed coquina deposits; (2) eolian deposits that occur during sub-aerial exposure of beach ridges and result from eolian sedimentation and reworking; and (3) incipient soil which develops between major inundations caused by storm events.

6. CONCLUSIONS

This study documented a Holocene coquina beach-ridge system that developed during episodes of elevated water levels (storm surges) under overall falling sea level conditions. GPR profiles and sedimentological data support the construction of a depositional model for the coquina deposits, in which overwash promotes the deposition of washovers and storm-surge ridges at the peak of major storms while berm construction and beachface accretion takes place during the waning phase of storms (or the passage of distant storms) by high waves and related swash, backwash, overtopping and minor overwashing processes. Radiocarbon chronology indicates that the onset of the system took place at about 5000 ^{14}C years ago. After about 2000 ^{14}C years BP marked environmental changes have occurred within Hamelin Pool, as indicated by a number of observations such as change in the depositional style of beach-ridge deposits (spit ridges start to predominate and ridges have overall lower elevations) and the occurrence of an important erosive period after 1450 ^{14}C years BP in Fishermen's Point. Finally, the contrasts observed between the beach ridges in the western and eastern shores result from the different degrees of exposure to storms that usually approach Hamelin Pool from the northwest and north resulting in distinct external and internal beach-ridge morphologies. Marine processes such as longshore drift and tidal currents have a secondary role in the architecture and depositional style of the beach-ridge system during fair-weather periods.

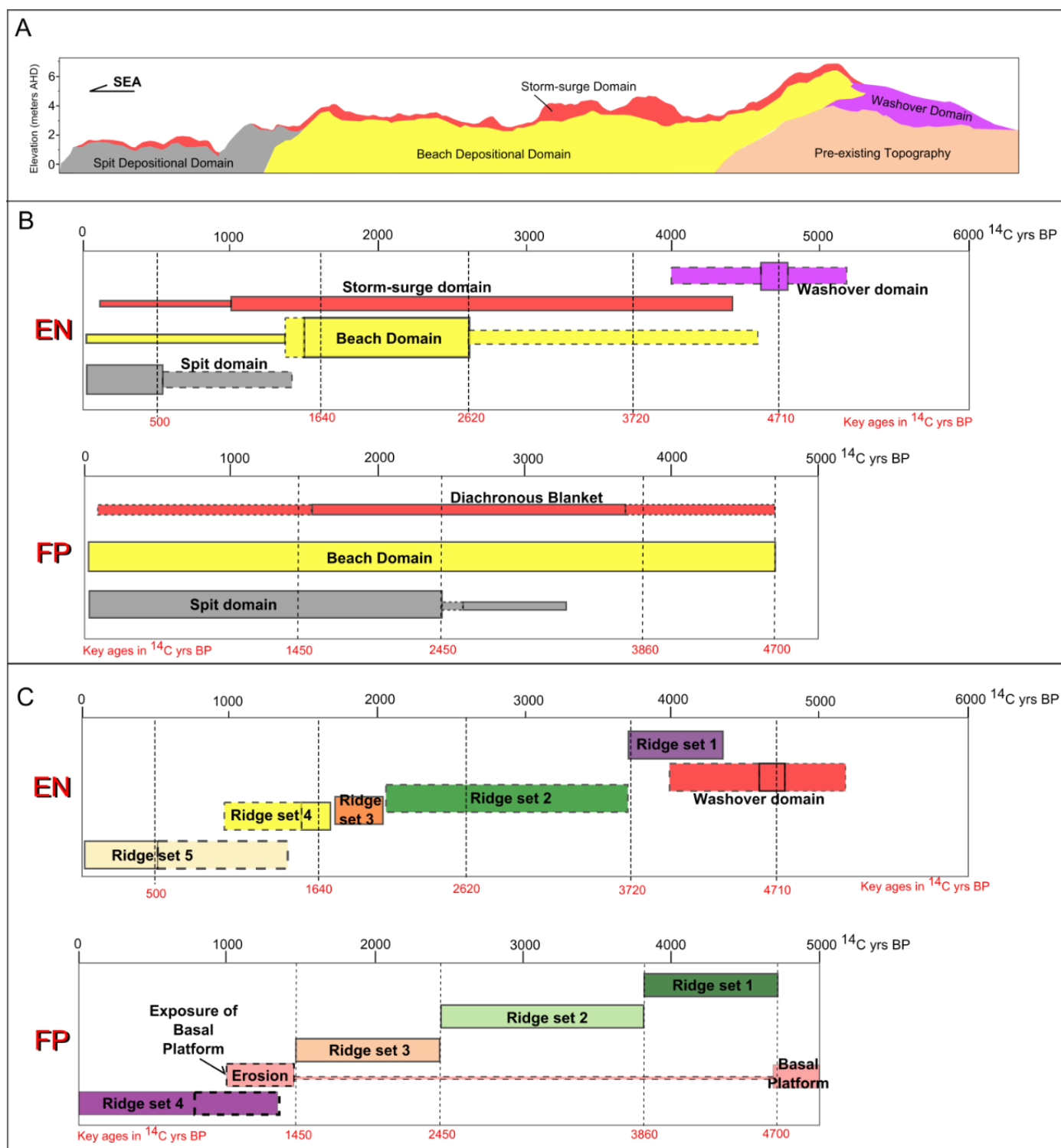


Figure 33. Depositional domain and ridge set chronology. **A.** Sketch of typical depositional domain arrangement. **B.** Depositional domain chronology in 'East Nilemah' (top) and Fishermen's Point (bottom). Thickness of the bars indicates relative abundance and dashed line in the bar contour indicate inference of the occurrence of depositional domains. **C.** Ridge set chronology in 'East Nilemah' (top) and Fishermen's Point (bottom). Dashed lines in the bar contour indicate inference of the occurrence of ridge sets.

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AUTHORSHIP CONTRIBUTION STATEMENT

Rodrigo Silva: Conceptualization, Methodology, Formal analysis, Investigation and Writing – original draft; Lindsay Collins: Conceptualization, Methodology, Resources, Project administration, Supervision, Writing – review & editing; Elmar Strobach: Formal analysis, Investigation, Writing – review & editing; Roman Pevzner: Formal analysis, Resources, Investigation, Writing – review & editing

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