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A Comparison of Geomorphic Settings, Sediment Facies and Benthic Habitats of Two Carbonate Systems of Western Mediterranean Sea and South Western Australia: Implications for Coastal Management

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ABSTRACT

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A similarity exists between the coastal areas of South Western Australia and South Sardinia (Italy-Western Mediterranean Sea), as temperate water carbonate sedimentation dominates the inner shelf at these locations. The seagrass carbonate factory regulates the deposition of modern bioclasts, and the distribution of seagrass meadows and accumulation of bioclasts is controlled by similar processes at the study sites. These biogenic components are mixed to quartz-feldspar sands producing significantly comparable sediment facies, which have been previously documented for Esperance Bay (South Western Australia) and off Porto Pino beaches (Sardinia). Whilst the geological settings of these areas show similar outcropping lithologies, the clastic component of these mixed biogenic and quartz-feldpar sand facies is transported by different agents in the Australian and Sardinian site. In this paper, the similarity between sediment facies is highlighted and their comparison has produced new insights into the processes regulating sediment accumulation in two hydrodynamically different embayments. The characteristics of seagrass beds and their link to the beach system are also compared and set within the context of Mediterranean and South Australian bioregions. These outcomes are relevant for beach management, as European and Australian environmental regulations are compared herein.

ADDITIONAL INDEX WORDS: *Temperate carbonate factory, beach management, geomorphology, seagrass meadows, Esperance (Australia), Porto Pino (Sardinia).*

INTRODUCTION

The carbonate sediment factory in temperate water environments is commonly associated with seagrass meadows (James and Bone, 2011). Seagrass meadows support abundant benthic biota, including numerous calcareous epiphytic organisms that contribute to the production of carbonate sediments. This modern biogenic sedimentation of temperate water carbonates has been previously documented for various sites in the western Mediterrenean (De Falco *et al.*, 2011; De Muro *et al.*, 2013) and western Australia (Collins, 1988; Tecchiato *et al.*, 2015). Two embayments located in south Western Australia and Sardinia show a similar mixed biogenic and siliciclastic sediment facies. Whilst the quartz component of these facies is derived from the erosion of similar outcropping lithologies, the modern biogenic fraction is seagrass derived. The compared areas respectively represent high-energy and low to moderate energy carbonate depositional environments. The comparison of mixed biogenic and siliciclastic sediment facies identified at the study sites have allowed an assessment of the sediment accumulation occurring in the two carbonate systems.

Both the Mediterrenean and the south western Australian coast host a mix of tropical and temperate seagrasses, however the Australian meadows are more diverse and *Posidonia* is one of the most ancient endemic seagrass genera found in these regions (Short *et al*., 2007). Seagrasses are considered to play an important role in the coastal geomorphology of Mediterranean and Australian inner shelf (De Falco *et al.*, 2011; Short, 2010). Waves are attenuated by greater friction across seagrass meadows, which have the capacity to reduce water flow and therefore increase sediment deposition and accumulation as well as beach stability (De Muro *et al.*, 2008, 2010, 2013; Fonseca, 1989; Madsen *et al*., 2001). The accumulation of beach wrack or “banquettes” also supports the prevention of coastal erosion (Carruthers *et al.*, 2007; De Muro and De Falco, 2015; Simeone *et al.*, 2013) and seagrass derived sediment often supplies the beach system contributing to beach stability (Carruthers *et al.*, 2007; Short, 2010; Tecchiato *et al.*, 2015). Some of the processes driving the distribution of this benthic habitat is relevant to coastal management because the preservation of seagrass beds enhances beach stability.

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European (Habitat Directive – EC., 1992) and Australian legislations protect these key ecosystems. In the Mediterrenean, the reason for the protection of this habitat is linked to a widespread decline of the extent of *P. oceanica* beds, particularly around urban centres and ports. Loss of seagrasses caused by mooring damage is common in the Mediterranean and was also described in Western Australia. However this practice is not forbidden neither in Australia nor in Europe. Removal of seagrass “banquettes” also damages the beach environment, but in the Mediterranean only regional regulations exist for this matter. Whilst in Australia beach wrack is not commonly removed from the beach, in Sardinia the impact of trucks used to remove seagrass “banquettes” is significant. This traffic flattens the berm, modifies sand permeability and reduces organic sediment input to the shore (De Muro and De Falco, 2015; Simeone *et al.*, 2013).

The aims of this paper include the comparison of (i) geomorphic settings and underlying geology; (ii) mixed biogenic and siliciclastic sediment facies; (iii) distribution of benthic habitats. Finally, this publication also aims to (iv) identify the processes driving the distribution of seagrass meadows and (v) sediment accumulation. Subsequently, the implications of sedimentary processes for coastal management in similar environments is discussed.

Regional settings

The comparison of geomorphic settings, temperate water carbonate sedimentation and distribution of benthic habitats carried out in this research is based on data collected at the following sites: Porto Pino (south-western Sardinia, central-southern Mediterranean Sea, Figure 1) and Esperance Bay (South Western Australia, Figure 2). The selection of these sites was based on environmental similarity and on data availability including previously published literature (De Muro *et al.*, 2015a; Ryan *et al.*, 2007).

Physical environment – Porto Pino (IT)

Porto Pino beach is a NW–SE oriented embayment located in south western Sardinia (Figure 1). The coastal area extends for a total length of 5 km and is mainly exposed to winds and waves from the SW and NW (De Muro *et al.*, 2015a). A seasonal stream in the central sector of Porto Pino beach supplies quartz-rich sand to the bay.

In this area the continental shelf is relatively wide for the Sardinia region (over 20 km), as it is part of a passive margin. Paleozoic deposits (rhyolitic and dacitic volcanites, and leucogranites) outcrop in the SE and E sectors of the study site. Mesozoic outcropping (fossiliferous dolostones and bioclastic limestones) and Quaternary deposits are also locally present outcropping at Punta Tonnara in the NW sector of the embayment.

Physical environment – Esperance (AU)

Esperance Bay is a ~20 km long southwest facing embayment in southern Western Australia (Figure 2), located along a stable passive continental margin. A couple of island groups from the Recherche Archipelago are in the bay, and represent outcrops of Middle Proterozoic granites, gneisses and migmatites (Ryan *et al.*, 2007). The embayment consists of flat lying Cenozoic limestones and is bordered by sand barriers and granitic rocky headlands (Sanderson *et al.*, 2000).

Climate and hydrodynamics – Porto Pino (IT)

Sardinia is characterized by a mediterranean climate with warm to hot, dry summers and mild to cool, wet winters. The temperature of Porto Pino beach varies from 10.5°C in winter

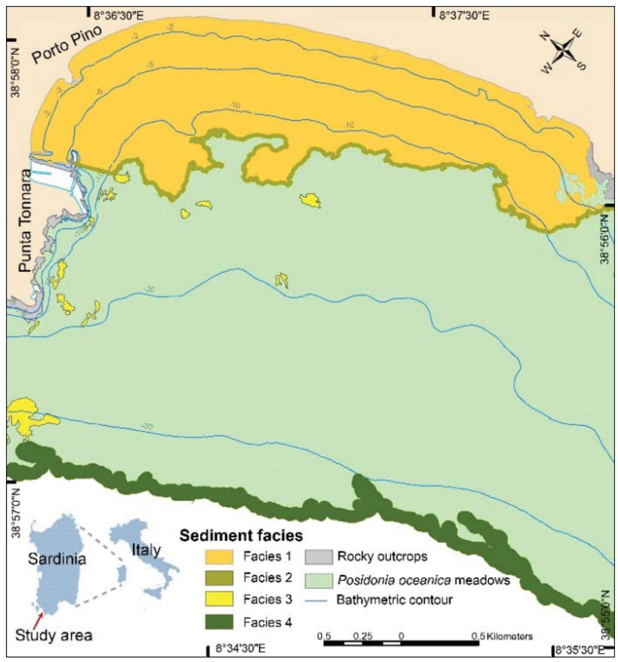

Figure 1. Location of study area and distribution of sediment facies off Porto Pino beach (south-western Sardinia).

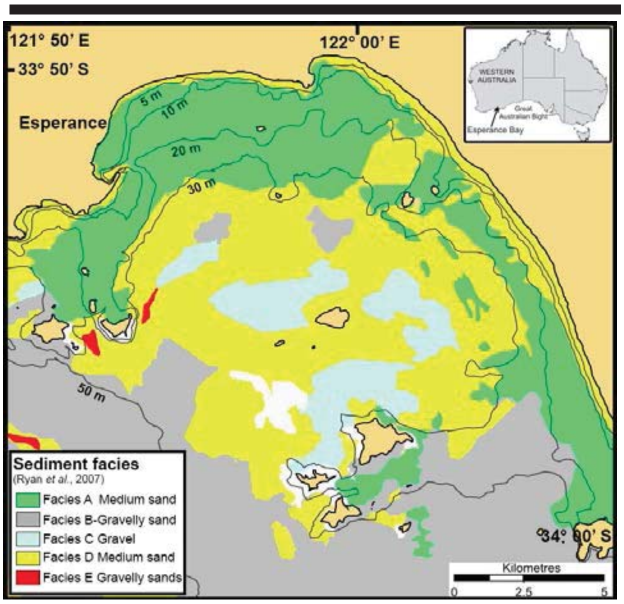

Figure 2. Location of study area and distribution of sediment facies off Esperance Bay (South-western Australia).

and 24.5°C in summer with rainfull concentrated in the winter season with an annual average of 85 mm.

The Porto Pino embayment is microtidal and wave-dominated. The prevailing winds are NNW and NW, the latter more intense than the former. The winds from SW, SSW and S affect the dynamics of the surf zone and are intense in winter. The W winds are directly related to storms from the NW and occasionally reach high intensity, also modifying the surf zone. The southern continental shelf of Sardinia is subject to extreme wave energy compared to the surrounding regions of the Mediterranean Sea, with >3.0 m wave heights and > 7 s swell waves. De Muro *et al.* (2015a) described three main coastal currents (longshore and rip) which control sediment transport along a SE-NW axis. These currents regulate the beach morphology which varies from longshore bar and trough to transverse bar and rip.

Climate and hydrodynamics – Esperance (AU)

Southwestern Australia is characterised by a semi-arid Mediterranean climate with temperatures averaging 8 to 26°C seasonally. Rainfall is limited to the winter season and fluvial discharge to the ocean is very low. Whilst in summer winds from SE prevail, in winter storms from SW dominate (Sanderson *et al.*, 2000). The southern continental shelf region is subject to extreme wave energy with >2.5 m wave heights and > 12 s swell waves. This region is storm dominated as tropical fronts meet cooler Southern Ocean waters. Esperance Bay is microtidal and is affected by strong, relatively consistent swells from the SW. These swells can be reinforced by wind generated waves, and produce a net eastward oriented littoral drift along the south coast. This current regulates the onshore coastal geomorphology (Kendrick *et al.*, 2005).

METHODS

This research is based on the analysis of unpublished data only for the Porto Pino area. The data described in this paper include: (a) geomorphology data based on multibeam and single beam bathymetry, (b) sediment data including grainsize, carbonate content and petrology, (c) benthic habitat mapping based on sidescan sonar, satellite images, scuba diving and underwater video data. Further details on the methodologies used in these analyses can be found in De Muro *et al.* (2015a), Kendrick *et al.*(2005) and Ryan *et al.* (2007).

RESULTS

The following sections highlight the nearshore geomorphology, sediment facies and benthic habitats of the selected study sites: Porto Pino (south-west Sardinia, Italy) and Esperance Bay (South Western Australia).

Geomorphology - Porto Pino (IT)

The seabed near the promontory of Punta Tonnara is rocky (sandstones and limestones) and off Porto Pino reaches 50 m depth ~6 km offshore (Figure 1). Two beach rock ridge systems parallel to the present shoreline and rocky outcrops occur at -5 m and -40 m respectively. These features are the only distinctive geomorphic element of the study area.

Geomorphology - Esperance (AU)

The seabed off Esperance Bay gradually slopes towards the southwest reaching 50 m depth ~10 km offshore (Figure 2). The seafloor shoals in areas adjacent to islands and bedrock reefs. Important geomorphic features of the bay are high profile reefs consisting of granitic outcrops, and low profile reefs which comprise northwest to southeast trending limestone outcrops (Ryan *et al.*, 2007). Bare sand areas are mostly planar, blanket like deposits which occur throughout the inner bay and on the lee side of islands. Small patches of subaqueous dunes (*sensu* Ashley, 1990) are located further offshore (Ryan *et al.*, 2007).

Benthic habitat distribution - Porto Pino (IT)

Three main benthic habitats and substrate types were identified off Porto Pino: (1) uncolonised sandy substrate, (2) rocky outcrops, and (3) *P. oceanica* meadows (De Muro *et al.*, 2015a). The distribution of these habitats is depth consistent and shore parallel. Some “intermattes” (unvegetated areas inside the meadow) were observed in the central and NW sectors of the beach, and rocky substrates are situated near the coastline in the NW and SE sectors (De Muro *et al.*, 2015a).

Benthic habitat distribution – Esperance (AU)

Seagrass beds with common *Posidonia* and *Amphibolis* species were mapped between -5 and -30 m depth within 5 km of the shoreline throughout the embayment and are particularly extensive on the western side of Esperance Bay (Kendrick *et al.*, 2005). Seagrass meadows prefer sheltered sections of Esperance bay and were also found on the lee side of islands forming rather isolated meadows compared to the more continuous mapped closer to the shoreline (Ryan *et al.*, 2007). Offshore reef systems are heavily colonised by sessile organisms. Sand waves, or subaqueous dunes (Ashley, 1990) occur in small patches in the outer section of Esperance Bay (Ryan *et al.*, 2007). Rhodolith beds were mapped between 25 and 60 m in both the inner and outer bay (Kendrick, *et al.*, 2005; Ryan *et al.*, 2007).

Sediment facies - Porto Pino (IT)

Four sand dominated sediment facies were identified at Porto Pino (Table 1, Figure 1), including two shore face facies and two offshore facies. In Sardinia, siliciclastic sands alike facies (1) are redistributed along the shoreface between the shoreline and the upper limit of *Posidonia* meadows (Pusceddu *et al.*, 2011; De Muro *et al.*, 2015b). Sediment facies (1) characterises the shallow beach system between 0 and 5 m depth and is mostly siliciclastic. A mixed bioclastic and siliciclastic sediment facies (2) is situated between the shoreface and the shallower limit of seagrass beds between 1 and 12 m depth. Facies (3) was collected in the intermattes habitat between 10 and 30 m depth and is mostly biogenic. The distribution of facies (4) is shore-parallel and this sediment is located in the deeper areas below the lower limit of *Posidonia* meadow at 30-35 m depth. Bioclastic sediment increase is depth consistent within the *Posidonia* meadows, as shown in the composition of Facies (3) and (4).

Sediment facies - Esperance (AU)

Five offshore sediment facies were identified within Esperance Bay (Table 2, Figure 2). Grainsize increases moving offshore, from fine-medium sands inshore to coarse sands in the outer bay, and gravels correspondently to rhodolith beds. Whilst quartz is the dominant component of the inshore facies, relict carbonate clasts and bioclasts are more common in the offshore facies (Ryan *et al.*, 2007). Modern bioclasts are common within offshore seagrass beds, bare sand substrates and low profile reefs. Carbonate sediment increase is depth consistent within seagrass beds. Ryan *et al.* (2007) indicated a higher carbonate percentage in the offshore seagrass beds, linked to limestone derived lithic clasts as well as modern bioclasts. Bathymetric range of the sediment facies is as per benthic habitat distribution.

Table 1. *Characteristichs of the sediment facies of Porto Pino (De Muro et al., 2015a).*

Sediment facies	$CaCO_3$ %	Gravel %	Sand %	Mud %	Depositional environments
(1) Siliciclastic sands	22.5 ±10.6	0.1 ±0.0	99.5 ±0.0	0.4 ±0.0	Shoreface sands (0-5 m)
(2) Mixed bioclastic and siliciclastic gravelly sands	27 ±10.6	9.1 ±18.0	89.6 ±17.2	1.3 ±2.0	Transition from shoreface to the upper limit of *Posidonia* meadows (1-12 m)
(3) Biogenic gravelly sands	45 ±21.2	21.1 ±19.5	78.9 ±19.5	0.0 ±0.0	Intermattes (10-30 m)
(4) Detritic gravelly sands	50 ±14.1	9.0 ±5.6	91.0 ±5.6	0.0 ±0.0	*Posidonia* meadow's lower limit (30-35 m)

Table 2. *Characteristics of the sediment facies of Esperance Bay (modified from Ryan et al. 2007).*

Sediment facies	$CaCO_3$ %	Grave l %	Sand %	Mud %	Depositional environments
(A) Medium sand	63.4 ±22.7 Inshore ~20 Offshore~80	9.7 ± 16.4	89.4 ±16.3	0.94 ±1.6	Inshore and Offshore seagrass beds (5-30 m)
(B) Gravelly sands	69.8 ±20.1	20.7 ±23.2	79.0 ±23.3	0.31 ±0.2	Low profile Reef (20-60 m)
(C) Gravel	83.6 ±5.9	40.1 ±30.1	56.3 ±30.3	3.6 ±6.6	Rhodoliths (25-60 m)
(D) Medium sand	69.7 ±16.3	5.9 ±12.4	93.2 ±13.2	0.92 ±1.5	Bare Sand (0-60 m)
(E) Gravelly sands	86.3 ±3.1	22.0 ±31.8	77.8 ±32.0	0.25 ±0.3	Subaqueous Dunes (~20 m)

DISCUSSION

The similarities found at the study sites are mainly related to processes regulating seagrass distribution and sediment accumulation. Seagrass meadows show a significant areal extent off Porto Pino and Esperance Bay, and are likely to contribute to beach stability and to control the morphology of the seabed from the shoreface to inner shelf areas. Considering that we are comparing two wave dominated environments (Australian bay - high energy, Mediterranean embayment - lower energy) characterized by different seagrass genera, it is interesting to note that the geographic distribution of these benthic habitats prefers the most sheltered regions of the studied embayments. In fact, different geomorphological features shelter the studied areas such as islands and promontories, as well as low relief palaeo-reefs and ridge systems offshore.

Facies (1 and 2) of Porto Pino and facies (A inshore) of Esperance are very similar (Tables 1 and 2), as well as Facies (3 and 4) of Porto Pino and Facies (A offshore seagrass beds) of Esperance, both mixed carbonate siliciclastic sediment with up to 90% sand and up to 60% carbonate. The quartz component of these sediment facies reaches their depositional environment through different processes: fluvial transport in Sardina and cliff erosion in Australia. The carbonate content of these sediment facies (4 and A) reflects the presence of eroded limestone material and modern bioclasts, with similar amounts in both facies. This is partly due to the capacity of seagrass meadows to physically retain siliciclastic sediments deposited at shallower depths than the meadow. The accumulation of similar relict sediment on two contrasting continental shelves regulated by different hydrodynamic regimes, suggests that limestone derived lithic clasts were chemically stable within the range of temperatures that occurred in the last Interglacial. Also the modern temperate carbonate production of these environments appears to produce similar quantities of sediment, with a trend of carbonate component increase from the inshore to the offshore sediment facies recorded at both Italian and Australian site within seagrass beds. Whilst this assessment is only preliminary, future research is planned and will support understanding of modern carbonate sedimentation for the selected sites and could be applicable to cool-water carbonate systems globally.

Implication for coastal management

The main outcomes of this paper are the implications for coastal management resulting from an international comparison. The protection of seagrasses is somehow ensured by environmental managers for the selected Mediterrenean and oceanic coasts, however the aspects outlined below are currently not included in the regulations.

The geographic distribution of seagrass meadows prefers the most sheltered regions of the studied embayments. Especially in Sardinia, sheltered bays attract boating tourism and seagrasses are highly affected by mooring damage and fishing. Considering the ecological significance of this habitat, mooring should be forbidden on seagrass meadows.

The removal of beach wrack along part of the Sardinian coasts has caused poor sediment budgets and higher exposure to storms, with subsequent coastal erosion. Further data are needed to compare the importance of beach wrack for maintaining beach stability at both sites.

CONCLUSIONS

This research uses a sedimentological approach to compare cool water carbonate sedimentation and benthic habitat distribution for two geomorphologically different embayments in terms of size and features but with similar outcropping lithologies. An important outcome is the role of seagrass meadows in maintaining beach morphodynamics of the studied Mediterranean and Australian embayments. Seagrasses favour the accumulation of terrigenous sediments within the beach and nearshore system, allowing accumulation of biogenic sediment in the deeper part of the meadows. Further research is needed to deepen our knowledge on the relationship between beach evolution and benthic habitats, as well as on the processes driving sediment accumulation.

This initial comparison of the selected Mediterranean and Australian embayments also outlined the regular removal of beach wrack on the Sardinian beaches and its impact on the adjacent beach system. In Australia these operations are not common, offering an example of environmentally sensitive management which may be used to support the development of a Mediterranean regulation for the protection of seagrass "banquettes".

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