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Typology of the reef formations of the Mediterranean seagrass *Posidonia oceanica*, and the discovery of extensive reefs in the Gulf of Hyères (Provence, Mediterranean)

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***Résumé.* Typologie des formations récifales édifiées par la magnoliophyte marine *Posidonia oceanica* et découverte de vastes récifs dans le golfe de Hyères (Provence, Méditerranée)**. L'édification de formations récifales par la magnoliophyte marine méditerranéenne *Posidonia oceanica* est due à la montée de la matte, ensemble constitué par les rhizomes et les racines et dont les interstices sont colmatés par le sédiment piégé par la canopée de feuilles. En mode calme, la matte peut s'approcher suffisamment de la surface pour que, à marée basse, l'extrémité des feuilles émerge : on parle alors de formation récifale (récif). Ce processus, avec la formation d'un récif barrière isolant un lagon, a été découvert au début des années 1950s dans la baie de Port-Cros (Provence, France) par Roger Molinier et Jacques Picard. Ils ont également décrit les stades initiaux de cette édification, les récifs frangeants. Depuis lors, la formation récifale de Port-Cros a été considérée comme le type, le modèle des récifs barrières de *P. oceanica*. D'autres formations récifales à *P. oceanica* ont été décrites : plateau récifal et micro-atolls.

En fait, il existe une relative diversité des formations récifales à *P. oceanica*, diversité jusqu'ici mal répertoriée. Ici, les différents types de formations récifales sont définis et décrits ou redécrits : récifs frangeants (FR), récifs barrières avec lagon de matte (BRML), récifs barrières avec lagon de matte érodée (BREML), récifs barrières avec lagon géomorphologique (BRGL), c'est à dire où le lagon n'est pas occupé par de la matte morte, récifs barrières fossiles (FOBR), c'est à dire où les *P. oceanica* qui constituaient le front d'émersion sont mortes, faux récifs barrières (FABR), lorsque le front d'émersion qui limite le lagon s'appuie sur une barre rocheuse et est donc en fait référable à un récif frangeant, plateaux récifaux (PR), récifs perpendiculaires à la côte (PER), qui correspondent peut-être à des stades initiaux de PR, et micro-atolls (MA). En fonction de cette typologie, qui prend en compte des types de formations récifales plus ou moins différents du paradigme du récif barrière de Port-Cros, les formations récifales à *P. oceanica* sont peut-être un peu moins rares qu'on ne le pensait.

Dans le golfe de Hyères, un certain nombre de formations récifales à *P. oceanica*, qui n'avaient pas jusqu'à présent attiré l'attention des chercheurs, sont décrites et cartographiées à La Badine (Nord-Est de la presqu'île de Giens) et sur la côte Nord du golfe devant les Vieux

Salins (Hyères), à L'Argentière (La Londe-les-Maures) et entre la côte et l'îlot de Léoube (Bormes-les-Mimosas). L'une d'elles, celle des Vieux Salins, constitue l'un des plus grands BRMLs connus à ce jour des côtes françaises et de l'ensemble de la Méditerranée, après ceux de la Madrague de Giens (Provence) et du Stagnone de Marsala (Sicile).
La prise en compte de la diversité des formations récifales à *P. oceanica* revêt une importance capitale dans la gestion de la zone côtière. En effet, ces formations ont une grande valeur patrimoniale, et certains types de récifs sont plus rares que les autres. De plus, ces formations contribuent aux remarquables services écosystémiques rendus par les herbiers à *P. oceanica*, plus particulièrement en ce qui concerne la protection des plages contre l'érosion et leur rôle de nurserie pour des "poissons" d'intérêt commercial. L'édification d'une formation récifale est un processus qui nécessite des siècles et même des millénaires ; sa destruction est donc irréversible à l'échelle humaine. Malheureusement, un certain nombre de récifs à *P. oceanica* ont été détruits, dans un passé lointain ou récent, du fait des activités humaines, et beaucoup de ceux qui subsistent sont dans un mauvais état de conservation.

Mots-clés : *Posidonia oceanica*, récifs-barrières, formations récifales, patrimoine naturel, services écosystémiques, gestion de la zone littorale.

Abstract. Reef formations of the Mediterranean seagrass *Posidonia oceanica* result from the rise of the *matte* towards the sea surface, when the meadow reaches the sea surface, and the tips of the leaves emerge. The process of reef formation was first described in the Bay of Port-Cros (Provence, France). Since then, the Port-Cros barrier reef has been considered as the type, or the model, of *P. oceanica* reefs. In fact, there is a wide variety of *P. oceanica* reefs, and this diversity has yet to be described. Here, we outline a typology of these reef formations: fringing reefs (FR), barrier reefs with matte lagoon (BRML), barrier reefs with eroded matte lagoon (BREML), barrier reefs with a geomorphological lagoon (BRGL), fossil barrier reefs (FOBR), false barrier reefs (FABR), plateau reefs (PR), perpendicular reefs (PER) and micro-atolls (MA). Taking into account this typology, which encompasses reefs that differ to a greater or lesser extent from the paradigmatic Port-Cros barrier reef, *P. oceanica* reefs are a little less rare than previously thought. In addition, a number of reefs, hitherto unnoticed, were discovered in the Gulf of Hyères; one of them, the Vieux Salins BRML, is among the longest barrier reefs of the French coast and one of the largest in the whole Mediterranean Sea. It is of paramount importance, for the management of the coastal zone, to take into consideration the diversity of the *P. oceanica* reefs, as these reefs have a high heritage value, and some types of reefs are rarer than others. In addition, these reefs contribute greatly to ecosystem services, such as beach protection from erosion and fish nursery. The reef building process lasts centuries, or even millennia, so that their destruction is irreversible at human scale. Unfortunately, many *P. oceanica* reefs have already been destroyed by human impact, while many others are in a poor state of preservation.

Keywords: *Posidonia oceanica*, barrier reefs, reef formations, natural heritage, ecosystem services, coastal zone management.

Introduction

Posidonia oceanica (Linnaeus) Delile is a seagrass (Magnoliophyta, Viridiplantae, kingdom Archaeplastida) endemic to the Mediterranean Sea (Molinier and Picard, 1952; den Hartog, 1970; Boudouresque and Meinesz, 1982; den Hartog and Kuo, 2006; Boudouresque and Verlaque, 2008; Boudouresque *et al.,* 2012). It thrives between the sea level and 20-45 m depth, depending upon the water transparency (Molinier and Picard, 1952; Augier and Boudouresque, 1979; Orfanidis *et al*., 2005; Boudouresque *et al.,* 2009, 2012; Pergent *et al.,* 2012).

P. oceanica constitutes extensive meadows which play a paramount role in the functioning of the Mediterranean coastal ecosystems (Boudouresque *et al.,* 2006; Personnic *et al.,* 2014).

Rhizomes and leaf shoots can grow horizontally, to colonize the substrate (plagiotropic rhizomes). The leaf canopy traps autochthonous sediment, e.g. remains of calcareous organisms living within the meadow (sea urchins, foraminiferans, Corallinaceae, etc.), and allochthonous sediment, e.g. mineral particles transported by currents and biogenic particles from the pelagic ecosystem. To resist being buried, rhizomes can also grow vertically (orthotropic rhizomes) (Molinier and Picard, 1951, 1952; Boudouresque and Meinesz, 1982). The growth rate of orthotropic rhizome ranges from a few millimetres to 77 mm/a (Boudouresque *et al.,* 1984). The structure constituted by live and dead parts of rhizomes and roots, together with the sediment that fills the interstices, is called "*matte*". Sediment trapping and orthotropic rhizome growth result in the rising of the *matte* and therefore of the sea bottom over time; the average rise ranges from 10 cm to 100 cm per century (Molinier and Picard, 1952; Picard, 1953; Boudouresque and Jeudy de Grissac, 1983; Mateo *et al.,* 1997; López-Sáez *et al.,* 2006; Lo Iacono *et al.,* 2008; López-Sáez *et al.,* 2008, 2009; Rovere *et al.,* 2010; Boudouresque *et al.,* 2012).

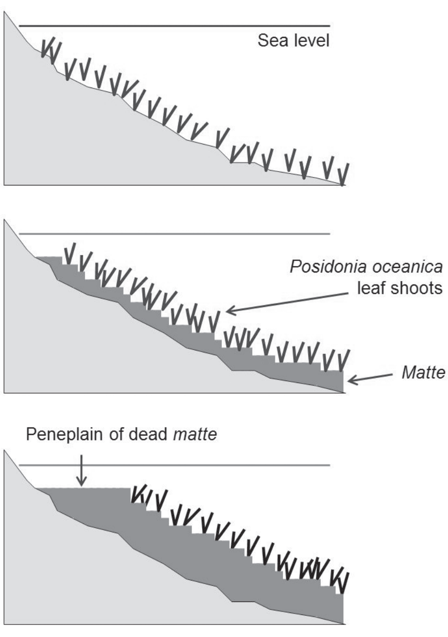

Figure 1. Dynamics of the *Posidonia oceanica* meadow under exposed conditions. The rise of the *matte*, over time, stops at 1 to 2 m deep. The erosion by sea surface hydrodynamism determines the formation of a peneplain of dead matte (PDM). Light grey: initial substrate; dark grey: the *matte*, either dead or alive. From C.F. Boudouresque *in* Boudouresque *et al.* (2012), modified.

The rising of the *matte* can bring the meadow close to the sea surface. Under exposed conditions, the rising stops 1 to 2 metres below the sea surface. Hydrodynamism prevents the rise continuing by breaking the rhizomes and their leaf bundles (shoots). This results in the formation of a **peneplain of dead matte** (PDM), as observed in La Palud Bay, Port-Cros Island, eastern Provence (Molinier and Picard, 1952; Augier and Boudouresque, 1967; Boudouresque *et al.,* 2012) (Fig. 1). Under sheltered conditions, especially in the innermost part of bays, the rise of the *matte* can continue right up to the sea surface. At low tide, the *P. oceanica* leaves spread out on the surface. In the first stage, the emersion of the tips of the leaves happens very close to and parallel to the coast. This formation is known as a **fringing reef** (FR) (Fig. 2b) (Boudouresque and Meinesz, 1982; Boudouresque *et al.,* 2012). Then, the continuing rise of the *matte* widens the fringing reef. Within the fringing reef, the leaf canopy and the shallowness hamper water circulation. The water temperature may go below (in winter) and above (in summer) the limits of *P. oceanica* tolerance, respectively 10 °C and 28-30 °C (Ben Alaya, 1972; Augier *et al.,* 1980; Tomasello *et al.,* 2009). The case is similar with salinity, which may go below, in times of rain, and above, due to summer evaporation, the normal limits of *P. oceanica* tolerance, 33 and 39-41 respectively (Ben Alaya, 1972; Fernández-Torquemada and Sánchez-Lizaso, 2003; Sánchez-Lizaso, 2004a; Fernández-Torquemada and Sánchez-Lizaso, 2005; but see Meinesz *et al.,* 2009 for a Marmara Sea strain). As a result, between the coast and the *P. oceanica* emersion front, the leaf shoots die, and a **lagoon** is formed (Fig. 2c) (Molinier and Picard, 1952; Boudouresque *et al.,* 1980; Boudouresque and Meinesz, 1982; Boudouresque *et al.,* 2012). The *P. oceanica* emersion front thus constitutes a **barrier reef** (BR). With time, the barrier reef moves seawards and the lagoon grows (Fig. 2d-e) (Molinier and Picard, 1952; Augier and Boudouresque, 1970). In the Bay of Port-Cros (eastern Provence), the seaward shifting of the barrier reef has been estimated to be 8-10 meters a century (C.F. Boudouresque, *in* Boudouresque *et al.,* 2012). In the lagoon, the bottom of which is muddy, two other species of seagrasses can establish, *Zostera noltei* Hornemann and *Cymodocea nodosa* (Ucria) Ascherson. The process of building of *P. oceanica* fringing and barrier reefs was initially elucidated and described by Molinier and Picard (1951, 1952), from the barrier reef of the Bay of Port-Cros (Port-Cros Island, eastern Provence, northwestern Mediterranean). For this reason, the Port-Cros reef was considered as the type, a sort of paradigm, of this kind of formation, despite its poor state of conservation (Augier and Boudouresque, 1970; Boudouresque *et al.,* 1975; Augier and Nieri, 1988; Bonhomme *et al.,* 2001; Goujard *et al.,* 2010), and little attention was paid to the diversity of the *P. oceanica* reefs. In addition, *P. oceanica* reefs were regarded as a rare formation, most of the reefs, due their localization in bays, having been destroyed by ancient and recent port facilities and coastal development (Boudouresque and Meinesz, 1982; Boudouresque *et al.,* 1985; Meinesz *et al.,* 1991; Boudouresque *et al.,* 2012; Meinesz *et al.,* 2013).

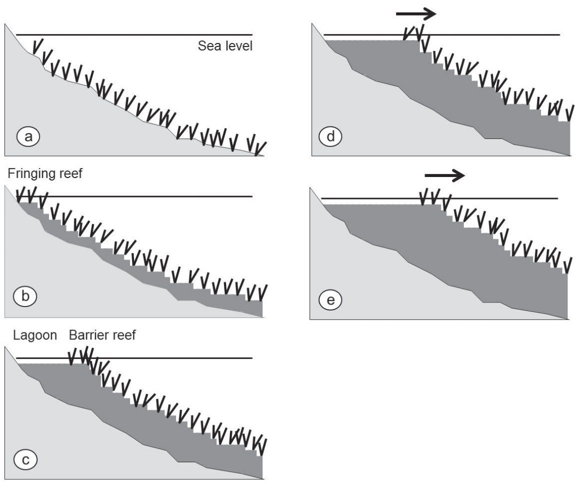

Figure 2. Dynamics of the *P. oceanica* meadow under sheltered conditions: process of building and evolution of a fringing reef and a barrier reef (a through e). The *matte* rises and reaches the sea surface. It first forms a fringing reef (b), then a barrier reef separated from the coast by a lagoon (c). Over time, dead or alive. From C.F. Boudouresque *in* Boudouresque *et al.* (2012), modified.

Here, we propose a typology of *P. oceanica* reef formations, which accounts for their real diversity, we describe a number of *P. oceanica* reefs, until now unnoticed, in the Gulf of Hyères (eastern Provence, France), we discuss the validity of the belief in the rarity of *P. oceanica* reef formations and we emphasize the role of these reefs in ecosystem services and their importance in the management of the coastal zone.

Material and methods

Typology of *Posidonia oceanica* reef formations

The authors have developed the proposed typology on the basis of a comprehensive review of the available literature (including grey literature) and of their own experience, including exploration (SCUBA diving and snorkelling) of a number of Mediterranean regions and countries (Balearic Islands, Spanish Catalonia, French Catalonia, Provence, French Riviera, Corsica, Sardinia, Sicily, continental Italy, Croatia, Albania, Turkey, Egypt, Tunisia and Algeria).

The extensive exploration of the Gulf of Hyères (eastern Provence, France) (see below) also provided basis for improving, checking and validating the typology.

Posidonia oceanica **reefs of the Gulf of Hyères**

The study area is localized in the Gulf of Hyères (eastern Provence, France): La Badine (NE of the Giens Peninsula; study zones 1, 2 and 3) and between the mouth of Gapeau River and Pointe de la Mère Dieu: Les Vieux Salins (Hyères; study zones 4, 5 and 6), L'Argentière Beach (La Londe-les-Maures: study zone 7) and Bormes-les-Mimosa (Léoube Islet: study zone 8) (Fig. 3).

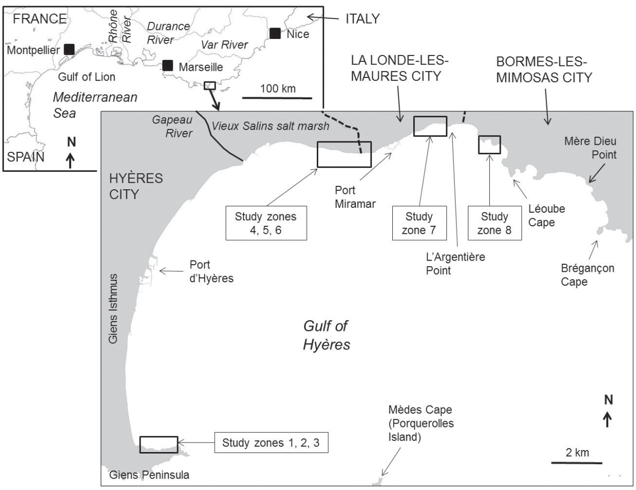

Figure 3. The Gulf of Hyères (eastern Provence, France) and localization of the study sites. Dashed lines: administrative limits of the cities.

Photographic sources were: **(i)** an orthophoto of IGN (Institut national de l'Information Géographique et Forestière; French national institute of geographical and forest information) dated from 2009; **(ii)** a Google Earth photo for La Badine (date on image: July 30, 2007; accessed March 15, 2014); **(iii)** a Google Earth photo for Vieux Salins, L'Argentière Beach and Léoube Islet (date on image: July 13, 2007; accessed March 15, 2014). The choice of these photos was based on the absence of waves, swell and iridescence of the sea surface.

The depth was established on the basis of the IGN and SHOM (Service Hydrographique et Océanographique de la Marine; Hydrographic and oceanographic agency of the French Navy) database Litto3D®, which produces a tri-dimensional image. The marine part of the area was acquired by bathymetric lidar technologies (Zavalas *et al.,* 2014) or multibeam sounder. The vertical datum is the NGF69, with zero defined by the Marseille tide gauge (western Provence, France). Digital Elevation Models (DEM) were produced from the shore down to 10 m depth. On the basis of the DEM, and using the ArcGIS 3D Analyst extension, images of the bottom in a three-dimensional context were provided, together with depth transects.

The coupling of the aerial and satellite imagery with DEM data resulted in the identification of three zones at La Badine (zones 1, 2 and 3), three at Vieux Salins (zones 4, 5 and 6), one at L'Argentière Beach (zone 7) and one at Léoube Islet (zone 8) where the presence of fringing reefs, barrier reefs and lagoons was suspected. Ground-truthing was then undertaken by means of snorkelling and a GPS (Global Positioning System) receiver, in order to check the presence of reef formations and, where present, to identify the reef type. It is worth noting that only the zones where reef formations were suspected, through the coupling of DEM and aerial imagery, were explored, so that the presence of undetected reefs in between cannot be excluded.

Results and discussion

Typology of *Posidonia oceanica* reefs

We define a *P. oceanica* reef as a formation built by the seagrass with leaf tips emerging from the sea surface and/or spreading at the sea surface, at least at low tide and in spring and early summer, when leaf length is at its maximum. In contrast with leaf tips, rhizomes and the base of the leaf bundles, where the basal meristems of the leaves are located, never emerge. Such an emersion would result in their death. The top of the *matte*, with living rhizomes, is therefore at least 10 cm below the low tide level.

Fringing reefs (FR) are described above (Fig. 2b). Fringing reefs are thought to have been the most common *P. oceanica* reef formation during the post-LGM (Last Glacial Maximum) phase of rapid sea level rise, from ~21 000 to ~6 000 years BP (before present); subsequently, the sea level rise conspicuously slowed down, with even short stops during the "little ice ages", cold episodes which occur every 1 500 years, the last one between the 13th and the 19th century (Laborel *et al.,* 1983, 1994; Morhange *et al.,* 1996; Lambeck and Chappell, 2001; Braun *et al.,* 2005; Springer *et al.,* 2008; Faivre *et al.,* 2013). The slow rise or stationary state of the sea level over the 6 last millennia probably allowed most fringing reefs to evolve into barrier reefs. The persistence of fringing reefs in the current Mediterranean landscape probably corresponds to particular local conditions, such as the scarcity of terrigenous and biotic particles and/or hydrodynamism preserving them from sedimentation and rhizome burial.

The barrier reef described by Molinier and Picard (1951, 1952) (Fig. 2c-e) in the Bay of Port-Cros (Provence, France) is referred to here as a **barrier reef with matte lagoon** (BRML). The lagoon is shallow (rarely more than 1 m depth) and carpeted with fine sediment. Beneath a thin layer of sediment, the dead *matte* (i.e. rhizomes devoid of leaf shoots, together with roots and the sediment filling the interstices) is present. The depth of the lagoon, slightly greater than that of the emerging reef, can be due to the partial decomposition of the *P. oceanica* remains and the resulting packing down of the dead *matte*. Within the lagoon, the seagrasses *Cymodocea nodosa* and *Zostera noltei* and a number of Phaeophyceae (e.g. *Cystoseira, Padina*) and Rhodobionta may be present. In Addaia Bay (Menorca) sea-balls of free-living Chlorobionta and Rhodobionta were observed (*Valonia aegagropila* C. Agardh and *Rytiphlaea tinctoria* (Clemente) C. Agardh) (Ribera *et al.,* 1997).

A **barrier reef with eroded matte lagoon** (BREML) is similar to the above described reef type. The difference is that the dead *matte* of the lagoon has been eroded and that the depth of the lagoon can be greater (several meters) (Fig. 4c). This erosion can be natural (hydrodynamism) or due to human dredging, in order to allow the mooring of small boats. The barrier reef of La Madrague de Giens (Gulf of Giens, eastern Provence, France) belongs to this type of *P. oceanica* reef formation (Charbonnel *et al.,* 2002). The barrier reef of Santa Liberata (Tuscany, Italy) may also belong to this type, according to the figure provided by Mauro *et al.* (2013).

A **barrier reef with a geomorphological lagoon** (BRGL) is a barrier reef whose lagoon is not only relatively deep but is also devoid of dead *matte*. It results from the rise of the relative sea level (RSL), either due the actual rise of the sea level, or to the subsidence of the shelf. An initial fringing reef (Fig. 4d), instead of progressing landward, rose on the spot and turned into a barrier reef (Fig. 4e-f). Within the lagoon, *P. oceanica* was never present. If erosion of the dead *matte* within the lagoon of a BREML is total, it can be misinterpreted as a BRGL. The presence of BRGL is unlikely in areas where recent subsidence of the shelf is absent or non-conspicuous, such as in western and eastern Provence.

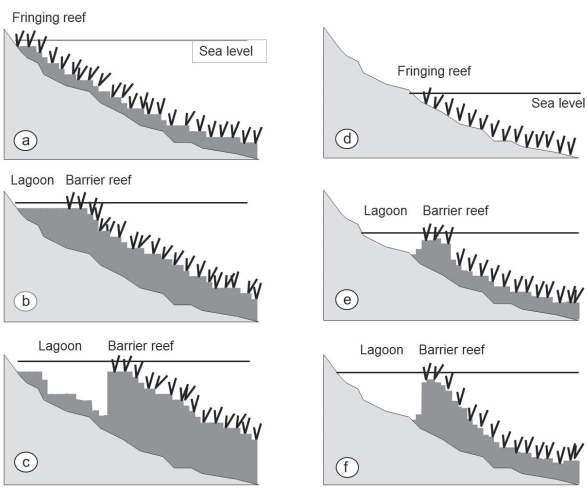

Figure 4. a-c. Building of a barrier reef with eroded matte lagoon (BREML). d-f. Building of a barrier reef with geomorphological lagoon (BRGL). Note the relative sea level (RSL) rise over time. Light grey: initial substrate; dark grey: the *matte*, either dead or alive.

A **fossil barrier reef** (FOBR) is a former barrier reef (BRML) whose leaf bundles at the emersion front subsequently withered and died. However, the profile, with a shallow emersion front and a slightly deeper lagoon, has been preserved (Fig. 5c). Of course, the seaward progression of the emersion is stopped. Over time, the emersion front, which is no longer protected by leaves and no longer traps particles, will be eroded by hydrodynamism, so that the formation will resemble a peneplain of dead matte (PDM).

A **false barrier reef** (FABR) corresponds to a lagoon of geomorphological origin, separated from the open sea by a shallow rocky ridge. *P. oceanica* established on the seaward side of the rocky ridge, mimicking a *P. oceanica* barrier reef (BR) (Fig. 5d-e). Although FABR and BR are of quite distinct origin, they can play a similar role with regard to ecosystem services (beach protection, nursery).

In the San-Fiurenzu Gulf (Saint-Florent; northern Corsica), a unique *P. oceanica* formation has been described, the **plateau reef** (PR) (Boudouresque *et al.,* 1985; Pasqualini *et al.,* 1997, 2001). It consists in a triangle of shallow dead *matte,* more or less colonized by photophilous "macroalgae" and *Cymodocea nodosa*, fringed with living *P. oceanica* (Fig. 6). Its genesis probably resulted from alternate and/ or opposite currents running to the two external sides of the triangle; two barrier reefs, back to back, progressed seaward and generated a kind of lagoon in the form of a triangle (Boudouresque *et al.,* 1985). PRs may also be present in Agay Bay (eastern Provence, France) and north of Marsala (Sicily) (Table I).

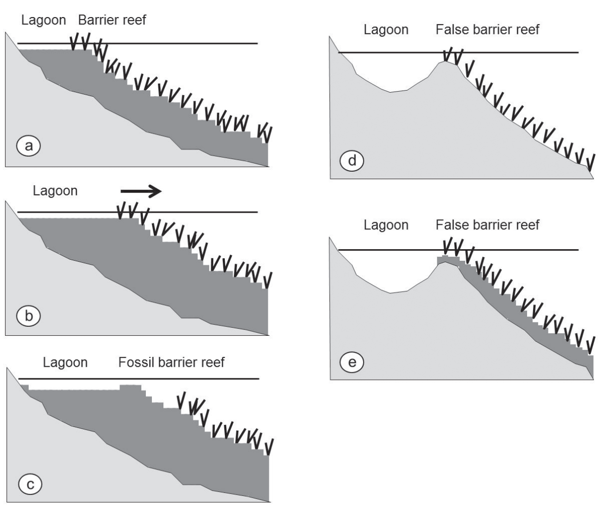

Figure 5. a-c. Origin of a fossil barrier reef (FOBR). d-e: False barrier reef (FABR). Light grey: initial substrate; dark grey: the *matte*, either dead or alive.

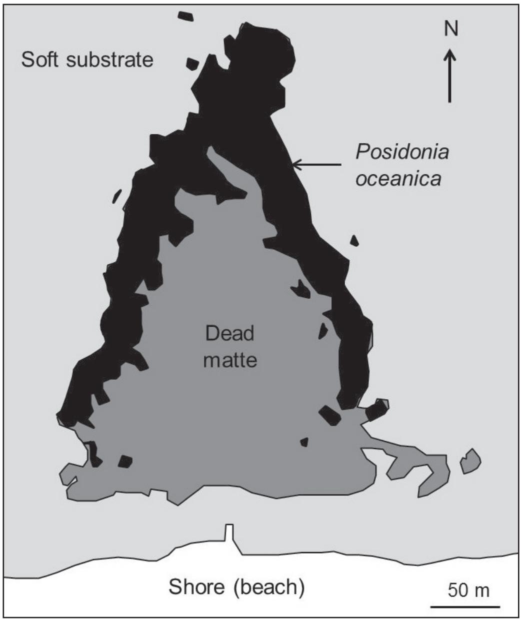

Figure 6. A map of the plateau reef (PR) of San-Fiurenzu (Saint-Florent), northern Corsica. Redrawn from Pasqualini *et al.* (1997).

At Gouringout beach, south of Sanary (eastern Provence, France), Blanc (1958) described a *P. oceanica* reef perpendicular to the coast (**perpendicular reef**, PER), probably due to a couple of opposite current cells (Fig. 7). Another PER is known from Sormiou Cove, Marseille (western Provence) (Molinier and Picard, 1952). In fact, PERs possibly correspond to a reduced, or an initial, form of PR.

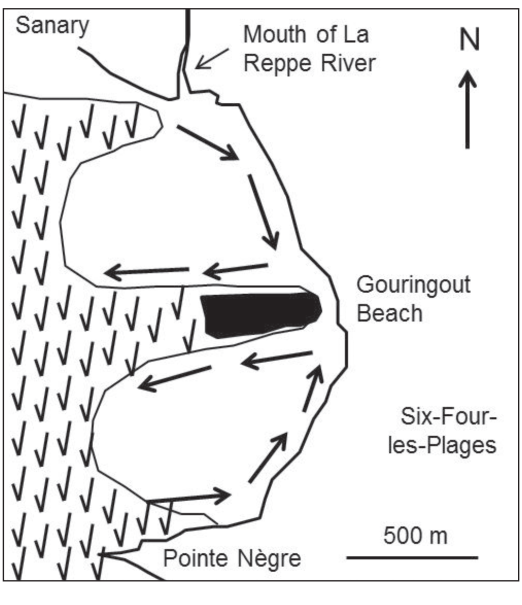

Figure 7. The *P. oceanica* perpendicular reef (PER) of Gouringout beach (eastern Provence). v: non-emergent *P. oceanica* meadow; black: PER; arrows: dominant currents. Redrawn and modified from Blanc (1958).

Finally, **micro-atolls** of *P. oceanica* (MA), where leaves are emergent at low tide, could be considered as belonging to the family of the *P. oceanica* reef formations (Fig. 8). MAs have been mentioned from San-Fiurenzu Gulf (Pasqualini *et al.,* 2001), Turkey (S. Cirik *in* Boudouresque *et al.,* 1990) and El Bibane Lagoon (southern Tunisia) (Riveill *et al.,* 2006; Vela *et al.,* 2008). The San Fiurenzu MA is a circle of living *P. oceanica*, 10-12 m in diameter, the centre of which is occupied by dead *matte*; plagiotropic (i.e. horizontal) rhizomes develop at the edge of the MA, in a centrifugal manner, whereas the shoots die in the central part of the MA (Pasqualini *et al.,* 2001). Near the mouth of the Ain Al-Ghazala Lagoon (Libya), unusually large atolls of *P. oceanica*, 20-70 m in diameter, called "macro-atolls", have been described by Pergent *et al.* (2007); the crown that forms these macro-atolls can itself be made of a suite of MAs.

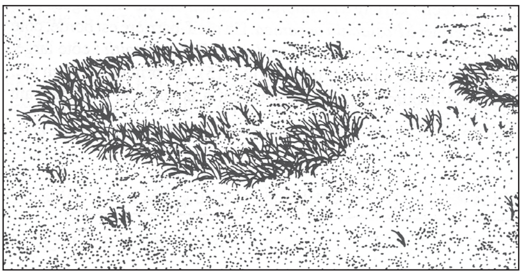

Figure 8. A micro-atoll of *P. oceanica* (MA) in Turkey. From S. Cirik *in* Boudouresque *et al.* (1990).

Posidonia oceanica reef formations of the Gulf of Hyères

Zone 1 (La Badine). A typical barrier reef with matte lagoon (BRML) is present (Fig. 9, 10 and 19). It has the shape of an arc of a circle and surrounds a 3 000 to 4 000 m² lagoon, up to 1.25 m deep, carpeted with dead *matte*. Numerous patches of *Cymodocea nodosa*, 1 to 10 m in diameter, are present in the lagoon. The BRML mentioned by Molinier and Picard (1952) at L'Estanci, but without details or map, probably corresponds to the BRML that is described here.

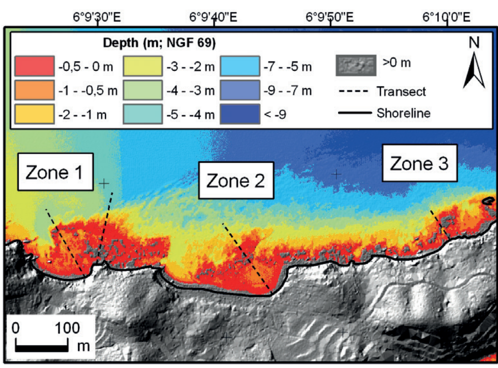

Figure 9. Study zones 1, 2 and 3 (La Badine; northern coast of the Giens Peninsula; see Fig. 3 for location). Straight lines are transects (see Fig. 10, 11 and 12). The depth map was established from the database Litto3D®. The vertical datum is the NGF69, with zero defined by the Marseille tide gauge. Offshore grey patches are not islets but emergent *P. oceanica* leaves. Reference ellipsoid: IAG GRS 198°; Lambert conformal conic projection using RGF 93 geodetic system.

Zone 2 (La Badine). A barrier reef with matte lagoon (BRML) is clearly present (Fig. 9, 11 and 19). It lines a 4 000 to 6 000 m² lagoon. Patches of *C. nodosa* are present within the lagoon, close to the reef. A clear-cut break crosses the barrier reef, with a 1.5-2.0 m high erosion scarp; this scarp continues offshore. Another erosion scarp lines the seaward side of the reef.

Zone 3 (La Badine). A small barrier reef circumscribes a very small lagoon. It is intermediate between BRML and BRGL. A fringing reef (FR) is present along a rocky ridge (Fig. 9, 12 and 19). Between the barrier reef and the FR, lies a pseudo-lagoon, i.e. a shallow area not definitely linked with *P. oceanica* reefs.

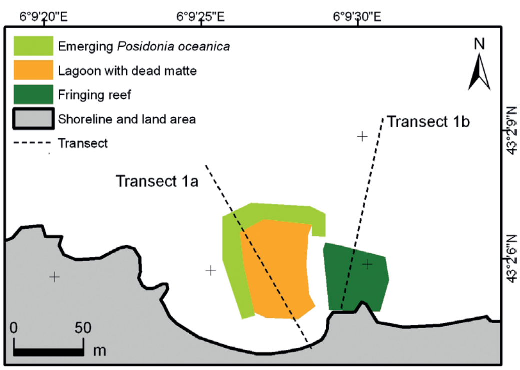

Figure 10. Study zone 1 (La Badine; northern coast of the Giens Peninsula; see Fig. 3 and Fig. 9 for location): a barrier reef with matte lagoon (BRML) and a vast area of fringing reef (FR).

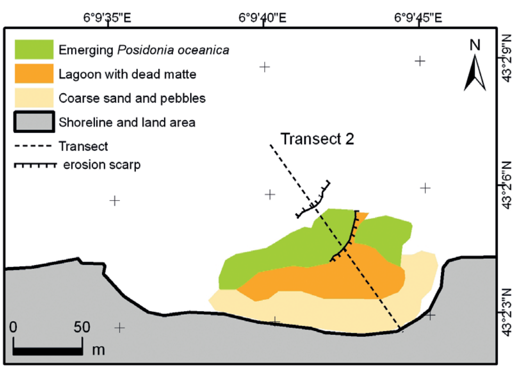

Figure 11. Study zone 2 (La Badine; northern coast of the Giens Peninsula; see Fig. 3 and 9 for location): a barrier reef with matte lagoon (BRML).

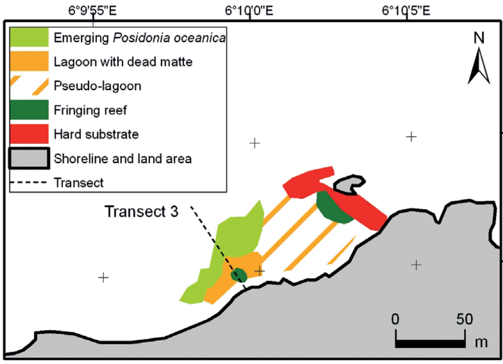

Figure 12. Study zone 3 (La Badine; northern coast of the Giens Peninsula; see Fig. 3 and 9 for location): a small barrier reef (BRML-BRGL) and fringing reefs (FR).

Zone 4 (Vieux Salins). Overall, a 700 m long BRML spreads parallel to the shoreline, with a ~3 ha lagoon (Fig. 13, 14 and 19). It consists of three segments, west to east. **(i)** A 280 m long and 40 wide reef segment delimits a 30-40 wide lagoon occupied by patches of *C. nodosa*. The presence in the lagoon of a sponge of warm affinities, *Aplysina aerophoba* Nardo 1833, is indicative of poor water exchange between the lagoon and the open sea and of the water warming in summer. **(ii)** A 150 m long discontinuous reef, with three passes 1.0-1.8 m depth interconnecting the lagoon and the open sea. The lagoon is 50-80 m wide and harbors several patches of *C. nodosa*. **(iii)** A 260 m long and 10-20 m wide reef, continuous westward and discontinuous eastward.

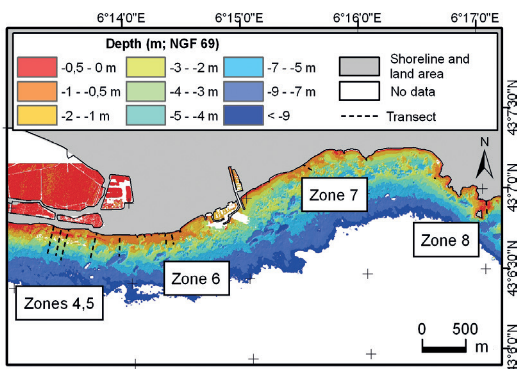

Figure 13. Study zones 4, 5 and 6 (Vieux Salins), 7 (L'Argentière) and 8 (Léoube Islet), in the northern part of the Hyères Gulf (see Fig. 3 for location). Straight dashed lines are transects (see Fig. 14, 15, 17, 18 and 19). The depth map was established from the database Litto3D®. The vertical datum is the NGF69, with zero defined by the Marseille tide gauge. Reference ellipsoid: IAG GRS 198°; Lambert conformal conic projection using RGF 93 geodetic system.

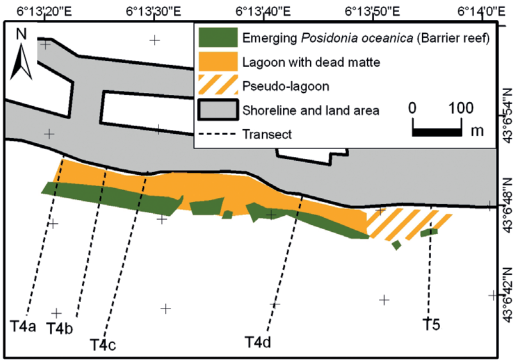

Figure 14. Study zones 4 and 5 (Vieux Salins; northern coast of the Hyères Gulf; see Fig. 3 and 13 for location): a very large barrier reef with matte lagoon (BRML) and a fossil barrier reef (FOBR).

Zone 5 (Vieux Salins). This zone is the degraded continuation of Zone 4, from which it is separated by a 20 to 40 m wide and up to 1.8 m depth pass (Fig. 13, 14 and 20). Only a few residual patches of live emergent *P. oceanica* are present. We classify it as a fossil barrier reef (FOBR).

Zone 6 (Vieux Salins). A strip of dead *matte*, (0.5) 0.7 m depth, with a very few patches of live *P. oceanica* and some potholes harboring *C. nodosa*, stretches parallel to the shoreline (Fig. 13, 15 and 20). The area located between this strip and the shore is occupied by a pseudo-lagoon with living *P. oceanica* (0.8 to 1.0 m depth) and sand with patches of *C. nodosa* (1.0 to 1.2 m depth). The seaward edge of the strip of dead *matte* presents erosion scarps and a *P. oceanica* meadow on a steep incline (Fig. 16). Two hypotheses may account for the observed structure: **(i)** The site is not sufficiently sheltered from waves and swell to allow the emersion of *P. oceanica* leaves. The strip of dead *matte* is a peneplain of dead matte (PDM). **(ii)** The strip of dead *matte* is the remains of a barrier reef. After the collapse of the barrier reef, the former lagoon was partially recolonized by *P. oceanica*.

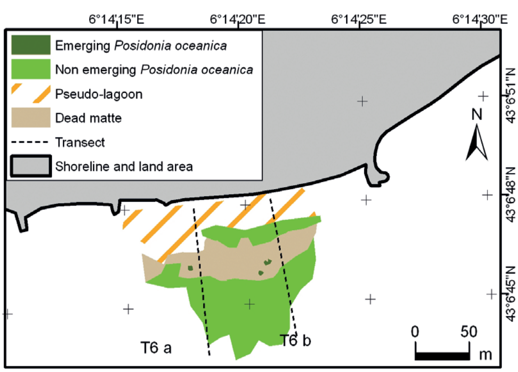

Figure 15. Study zone 6 (Vieux Salins; northern coast of the Hyères Gulf; see Fig. 3 and 13 for location): a fossil barrier reef. The former lagoon (now a pseudo-lagoon) has been partly recolonized by *P. oceanica*.

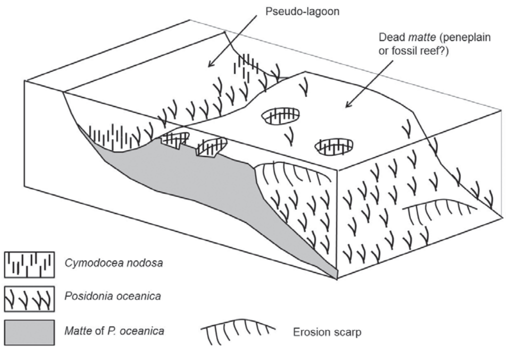

Figure 16. Diagram of the *P. oceanica* formation at zone 6 (Vieux Salins). See Fig. 13 for location and Fig. 15 for cartographical interpretation.

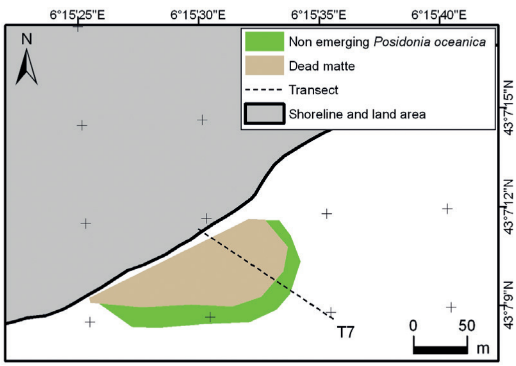

Figure 17. Study zone 7 (L'Argentière beach; northern coast of the Hyères Gulf; see Fig. 3 and 13 for location): a peneplain (PDM) or a fossil barrier reef (FOBR).

Zone 7 (L'Argentière Beach). A half-circle of dead *matte*, 60 to 90 cm depth, with potholes 1.1 to 1.2 m depth, is surrounded, on its seaward edge by a *P. oceanica* meadow with non-emergent leaves (Fig. 13, 17 and 20). Small patches of *C. nodosa* are present on the dead *matte* and at the junction between the dead *matte* and the sand of the beach. The area of dead *matte* corresponds to either a peneplain (PDM) under hydrodynamic conditions too exposed to allow the occurrence of a barrier reef, or to the lagoon of a fossil barrier reef (FOBR).

Zone 8 (Léoube Islet). Between the shore and Léoube Islet, three lines of emergent *P. oceanica* leaves are either the harbinger of a tombolo or the remains of a tombolo flooded by the Holocene rise of the sea level (Fig. 13, 18 and 20). The extent of *matte* thickness is revealed by a 2 m depth erosion hole. From the reef typology point of view, the Léoube Islet reef formation could correspond to a BREML, or to two adjacent BRMLs, or even to an undescribed type of *P. oceanica* reef formation. It therefore requires further investigation.

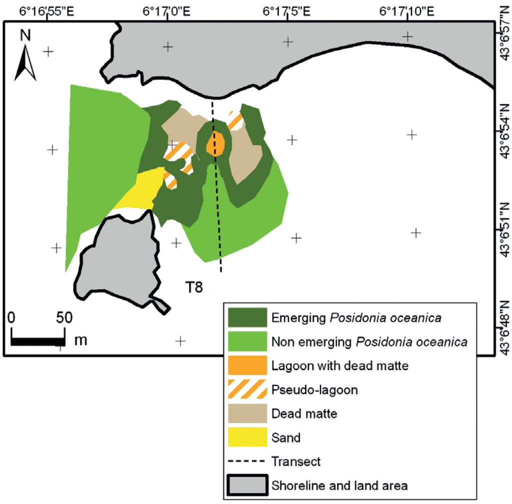

Figure 18. Study zone 8 (Léoube Islet; northern coast of the Hyères Gulf; see Fig. 3 and 13 for location). Requires further investigation for interpretation.

Overall, the newly discovered and/or described *P. oceanica* reef formations of the Gulf of Hyères encompass a wide range of the possible reef types: BREML, BRGL, BRML, FOBR and FR. In addition, some of them are in a rather good state of preservation, although not pristine, with some traces of human impact: La Badine (Fig. 10) and Vieux Salins (Fig. 14). With its ~700 m length, the Vieux Salins BRML is the second largest reef on the French coast (after the BRML of La Madrague de Giens) and undoubtedly one of the largest in the Mediterranean Sea, only exceeded by those of La Madrague de Giens (eastern Provence), Sanitja (Menorca, Balearic Islands) and Stagnone of Marsala (Sicily) (Table I).

Are *Posidonia oceanica* reef formations as rare as claimed?

A relatively small number of *P. oceanica* reef formations have been mentioned (Table I). Most of them occur in the northwestern Mediterranean (western and eastern Provence, Liguria and northern Corsica). This is congruent with the ecological requirements of the species; where the summer temperature of the surface sea water is too high, a common feature in southern and eastern Mediterranean, *P. oceanica* cannot approach the sea surface. Most of the reported reefs belong to the barrier reef with matte lagoon (BRML) type. This could be an artifact: in the absence of the formal typology of the *P. oceanica* reefs presented here, authors possibly no paid attention to reefs that were different from the Port-Cros Bay reef, of the BRML type, which was described in the seminal work of Molinier and Picard (1952).

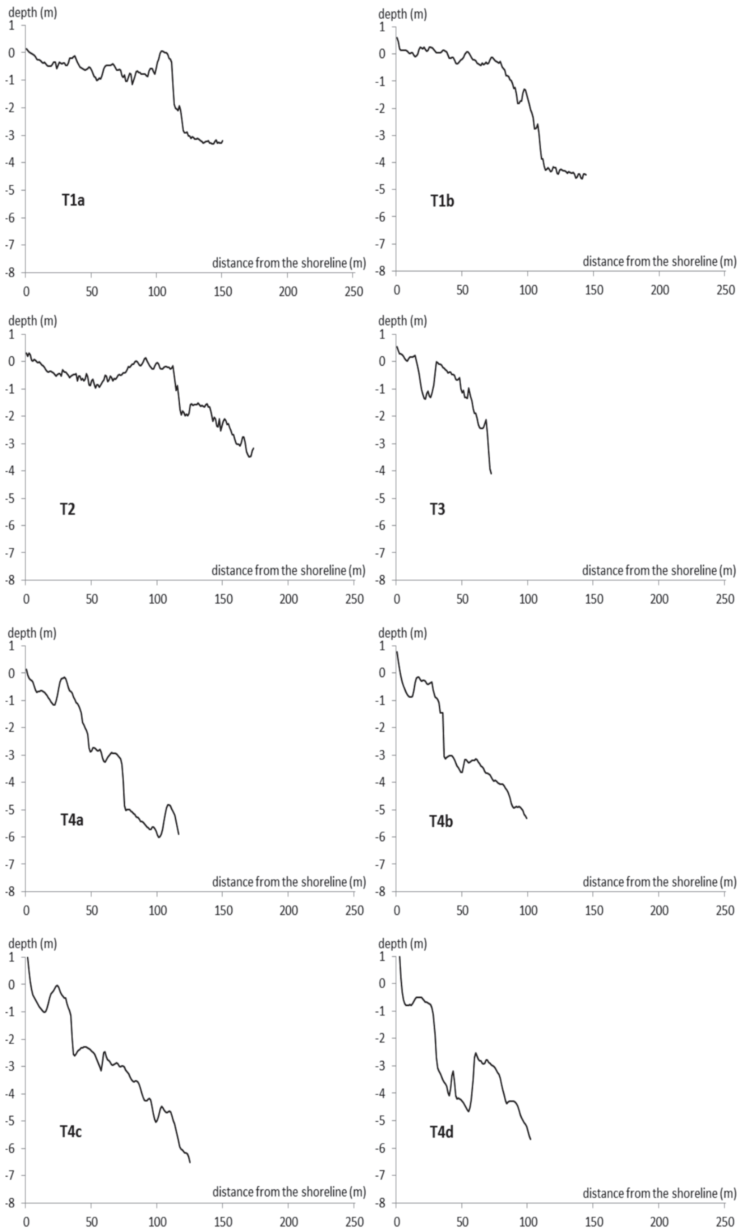

Figure 19. Depth transects T1a and T1b (zone 1, La Badine, see Fig. 10), T2 (zone 2, La Badine, see Fig. 11), T3 (zone 3, La Badine, see Fig. 12), T4a, T4b, T4c and T4d (zone 4, Vieux Salins, see Fig. 14).

However, as evidenced by the present study, *P. oceanica* reefs could be less rare than usually claimed. Modern methods of habitat mapping, *via* e.g. side scan sonar, are ineffective in shallow waters. The scale of the maps required by managers is too small (i.e. too regional, as opposed to local) to make *P. oceanica* reefs representable in a map. Finally, once the presence of such reefs is suspected from aerial or satellite imagery, snorkelling is needed for ground-truthing, a method regarded by some scientists and managers as too simple and therefore out of fashion. These biases could account for the current incomplete census of the *P. oceanica* reef formations.

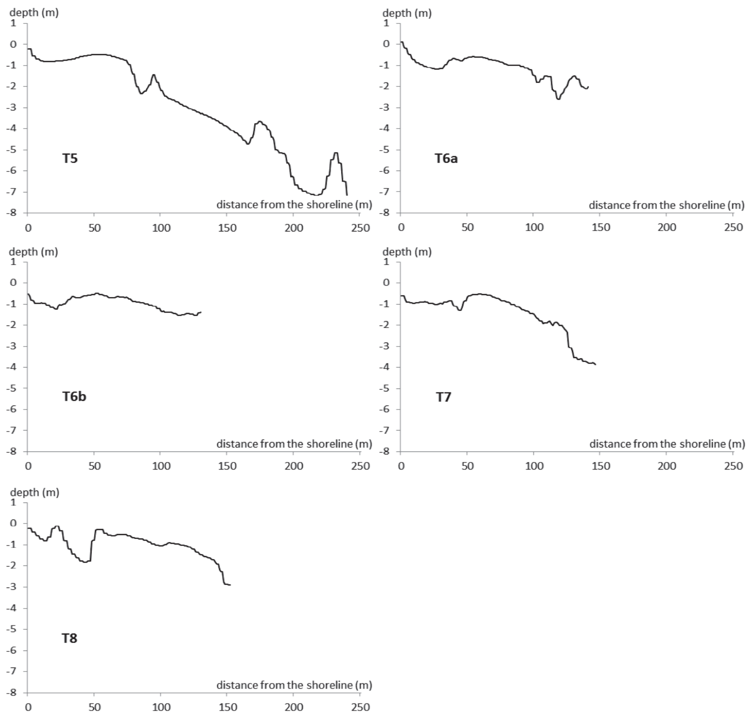

Figure 20. Depth transects T5 (zone 5, Vieux Salins, see Fig. 14), T6a and T6b (zone 6, Vieux Salins, see Fig. 15), T7 (zone 7, L'Argentière Beach, see Fig. 17) and T8 (zone 8, Léoube Islet, see Fig. 18).

Table I. A checklist of *P. oceanica* reef formations, from literature data. The allocation of a *P. oceanica* reef to a reef type was done by the authors of the present work, on the basis of the literature data and/or their own knowledge of the site. BR: barrier reef; BREML: barrier reef with eroded matte lagoon; BRML: barrier reef with matte lagoon; FABR: false barrier reef; FOBR: fossil barrier reef; FR: fringing reef; MA: micro-atoll; PER: perpendicular reef; PR: plateau reef. This list does not claim to be exhaustive. Countries and localities are ranged clockwise (whenever possible) from Spain to Algeria

Country and locality	Type of reef	Observations and comments	References
Spain			
Los Bajos (Roquetas de Mar) (Andalusia)	BRML	"Monumento natural" (Consejería de Medio Ambiente de Andalucía)	Sánchez-Lizaso, 2004b
La Cantera Islet, North (Nueva Tabarca Island)	FR?		Ramos Esplá, 1985
South to Port-Bou (Catalonia)	BRML	Small	Molinier and Picard, 1956
Sanitja port (Menorca Island)	BRML	Well preserved (T. Thibaut)	Vidal *et al.,* 1994
Addaia Bay (Menorca Island)	BRML	Well preserved	Ribera *et al.,* 1997
French Catalonia and Languedoc			
Peyrefite Cove (between Cerbère and Banyuls)	FR		Molinier and Picard, 1952
Centre Héliomarin Cove	FABR?	Possible outliers of a former reef	Pergent *et al.,* 1985
Paulilles	?	A possible mislocalization for the Centre Héliomarin Cove	Molinier and Picard, 1952
Provence			
Sormiou Cove (Marseille)	PER		Molinier and Picard, 1952
Bandol	BR	Destroyed (early 1970s): buried under a land reclamation (car park and casino)	Molinier and Picard, 1952, 1954a; Ledoyer, 1962; Pérès and Picard, 1963; Blanc, 1975; Blanc and Jeudy de Grissac, 1978
Gouringout beach (between Sanary and Six-Fours-les-Plages)	PER		Molinier and Picard, 1952; Blanc, 1958
Le Brusc (Six-Fours-les-Plages)	BRML	A unique feature: there is a connecting channel between the lagoon and the open sea, on the opposite side of the barrier reef. Degraded	Molinier and Picard, 1952, 1953a; Blanc, 1958; Pérès and Picard, 1963; Blanc and Jeudy de Grissac, 1978; Jeudy de Grissac and Tiné, 1980.
La Seyne Bay (Toulon Gulf)	BRML?	Probably present in the past	Bourcier *et al.,* 1979
Le Lazaret Bay (Toulon Gulf)	BRML?	Probably present in the past	Bourcier *et al.,* 1979
Lido Beach (Vignettes, Toulon)	BRML	Partly destroyed by artificial beaches	Astier, 1975; Nodot *et al.,* 1978

Country and locality	Type of reef	Observations and comments	References
Madrague de Giens (Gulf of Giens)	BREML	~1 150 m long. Degraded. The lagoon is partly occupied by a small harbour and numerous piers	Boudouresque, 1971; Blanc, 1975; Blanc and Jeudy de Grissac, 1978; Charbonnel *et al.,* 2002
Between La Madrague de Giens and La Redonne (Gulf of Giens)	FR	Very degraded. A few outlier mounds persist	Azzolina *et al.,* 1985
La Redonne (Gulf of Giens)	FR?	Emergent *P. oceanica* leaves along both sides of a rocky ridge between the shore of Giens Peninsula and La Redonne Island	Azzolina *et al.,* 1985
La Tour Fondue (Giens Peninsula)	BRML		Boudouresque, 1971
L'Estanci beach (Giens Peninsula)	BRML	The BR is separated from the deep meadow by a sand strip. Probably the BR referred to as "La Badine, Zone 2" in the present work	Molinier and Picard, 1952
Port-Cros Bay (Port-Cros Island)	BRML	Bad state of conservation: 50% of regression since early 20th century	Molinier and Picard, 1952, 1954a; Augier and Boudouresque, 1970; Nédélec *et al.,* 1981; Augier and Nieri, 1988; Bonhomme *et al.,* 2001; Goujard *et al.,* 2010
Le Lavandou (East to the port)	-	A future FR?	Molinier and Picard, 1952
Cavalaire port	BRML	Lagoon partly filled with excavated material of human origin	Molinier and Picard, 1952
Cove near Pointe du Breuil (between Gigaro Beach and Cap Andati)	FR		Azzolina *et al*., 1985
Le Pilon (Saint-Tropez)	BRML	~400 m long. Constitutes a kind of natural jetty for a small leisure harbour. Severely degraded, in particular by the opening of a pass	Ruitton *et al.,* 2007
Agay Bay (Saint Raphaël)	PR	This ~130 m long PR was regarded as a BRML by Astruch *et al.* (2010). Relatively well preserved but fragmented	Astruch *et al.,* 2010
French Riviera			
Sainte-Marguerite Island (NW coast), Lérins Archipelago	BRML	Degraded by leisure boating (opening of a pass through the BR)	Molinier and Picard, 1954a; Meinesz, 1973; Andromède Océanologie, 2011

Country and locality	Type of reef	Observations and comments	References
Corsica			
Marina di Malfacu (Santo-Pietro-di-Tenda, L'Agriate)	BREML?	Highly degraded	Casta, 1981; Vela and Garrido-Maestracci, 2009
South to Fornali Cove (Gulf of San Fiurenzu – Saint-Florent)	BRML	200 m long, discontinuous	Molinier, 1960; Vela and Garrido-Maestracci, 2009
La Roya, San-Fiurenzu (Saint-Florent)	BRML?		Boudouresque *et al.,* 1985 Vela and Garrido-Maestracci, 2009
Centre Nautique, San-Fiurenzu (Saint-Florent)	PR and MA	Stable state of conservation since its first description	Molinier, 1956, 1960; Boudouresque *et al.,* 1985; Pasqualini *et al.,* 1997, 2001
Centuri harbour, Capicorsu (Cap Corse)	BRML	15 m long. Protected by a small breakwater?	Molinier, 1960
Sant'Amanza (Bunifaziu – Bonifacio)	?		Vela and Garrido-Maestracci, 2009
Piantarella (Bunifaziu - Bonifacio)	?		Vela and Garrido-Maestracci, 2009
Ventilegne (Bunifaziu - Bonifacio)	?		Vela and Garrido-Maestracci, 2009
Cala di u Furnellu (Monacia d'Aullene)	?		Vela and Garrido-Maestracci, 2009
Tizzano (Sartè Sartène)	?		Vela and Garrido-Maestracci, 2009
Liguria			
Noli	FR		Bianchi and Peirano, 1995
Prelo (Genova)	FR	Mostly destroyed by a small jetty built in its central part in early 20th century	Lasagna *et al.,* 2011
Portofino	BRML?	Several sites	Issel, 1912, 1918
Framura (La Spezia)	FR		Bianchi and Peirano, 1995
Portovenere (La Spezia)	FR		Bianchi and Peirano, 1995
Tuscany			
Santa Liberata (Orbetello)	BREML?	Degraded? Or not degraded? (sources are not congruent)	Lenzi *et al.,* 2013; Mauro *et al.,* 2013
Sardinia			
Punta s'Aliga (canale di San Pietro)	BRML	Macrophytes and *C. nodosa* in the lagoon	Brambati *et al.,* 1980
Sicily			
Marsala (North: between Punta dello Stagnone and Punta Palermo)	BRML?	Emergent *P. oceanica* leaves in a channel with changing currents. The largest BRML of the Mediterranean Sea	Molinier and Picard, 1953b; Calvo and Frada Orestano, 1984

Country and locality	Type of reef	Observations and comments	References
Marsala (North: between Punta del Alga and Punta dello Stagnone)	PR? BREML?		Calvo and Frada Orestano, 1984
Augusta (North)	BRML?		Molinier and Picard, 1953b
Turkey			
Urla-I kele (Izmir Gulf)	BRML	A few patches, possible remains of a BR, 10-20 m off the shore	Pergent and Pergent, 1985
Ilıca-Mente (Çe me, Izmir Gulf)	FR?	According to the authors, recent emersion	Dural *et al.,* 2013
Izmir Gulf?	MA		Boudouresque *et al.,* 1990
Egypt			
Abu-Qir (25 km East of Alexandria)	BRML	*C. nodosa* in the lagoon	Aleem, 1955
Libya			
Ain Al-Ghazala	MA	Macro-atolls made up of micro-atolls (MA)	Pergent *et al.,* 2007
Tunisia			
El Bibane Lagoon	MA		Riveill *et al.,* 2006; Vela et al., 2008
Oued Lafrann (North of Chebba)	BR, FR		Mabrouk *et al.,* 2014
Hergla (Gulf of Hammamet)	MA		Sghaier *et al.,* 2011
Kélibia (Gulf of Hammamet)	BRML	*C. nodosa* and *Z. noltei* in the lagoon	Ben Mustapha and Hattour, 1992
Le Kram (Gulf of Tunis)	FABR		Ben Alaya, 1972
Sidi-er-Raïs (Gulf of Tunis). Also spelt Sidi-el-Reiss, Sidi Rais, Sidi Raïs and Sidi-Errais	BR	Several parallel BR, up to 1.8 km off the coast, and a vast lagoon colonized by *C. nodosa*	Molinier and Picard, 1954b; Ben Alaya, 1972; El Asmi *et al*., 2006; Djellouli, 2007
La Marsa (Gulf of Tunis)	BRML	Lagoon colonized by *C. nodosa*	Ben Alaya, 1969
Le Port (Zembra Island)	BRML, FR	15 m long. Protected by a jetty	Boudouresque *et al.,* 1986
Monastir Bay	BRML?		El Asmi Djellouli *et al.* (2006)
Algeria			
Kouali Cove (near Tipasa). Also spelt Kouâli	BRML		Molinier and Picard, 1953a; Le Gall, 1969; Boumaza, 1995
Bou Ismaïl (Castiglione)	BRML		Molinier and Picard, 1953a; Le Gall, 1969

Ecosystem services and natural heritage value of *Posidonia oceanica* reefs

The *P. oceanica* meadows are at the origin of a number of ecosystem services of major importance (Fig. 21). **(i)** Very high primary production of both the seagrass and its epibionts, which are the basis for food webs. **(ii)** A spawning ground and nursery for a number of teleosts and crustaceans of economic value. **(iii)** The exportation of a large part of the primary production, as dead leaves, towards other ecosystem (sublittoral hard substrate habitats, sublittoral soft bottoms, etc.), where they greatly contribute to local food webs. **(iv)** The stabilization of the sediments on soft bottoms, which reduces re-suspension and water turbidity. **(v)** Long term sequestration of carbon within the matte, which contributes to mitigating the consequences of carbon dioxide emissions due to human activities. **(vi)** Real production of oxygen, in relation with carbon sequestration within the *matte*. **(vii)** Reduction of the strength of waves and swell, which results in the protection of beaches from erosion. **(viii)** Protection of the beaches from erosion, by means of the *banquettes* of dead leaves. **(ix)** Stabilization of the dune and input of nitrogen to the dune and foredune vegetation, by means of dead *P. oceanica* leaves (Boudouresque and Jeudy de Grissac, 1983; Mateo *et al.,* 1997; Gacia *et al.,* 1999; Gacia and Duarte, 2001; Cardona and García, 2008; Bovina, 2009; Sánchez-González *et al.,* 2011; Boudouresque *et al.,* 2012; Infantes *et al.,* 2012; Pergent *et al.,* 2012).

In addition to the overall services provided by *P. oceanica* meadow, the reefs enhance the protection of beaches against erosion (service 7) and harbour nurseries of costal "fish" (teleosts) of economic interest (service 2).

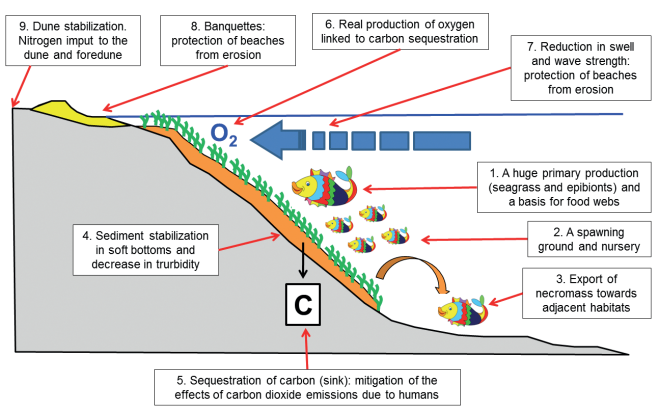

Figure 21. Ecosystem services (1 through 9) generated by the *P. oceanica* ecosystem. Reef formations, where present, enhance the protection of beaches from erosion (service 7), while lagoons play an important role as "fish" (teleosts) nurseries (service 2).

P. oceanica reef formations are highly vulnerable to human activities, e.g. coastal development, establishment of port facilities, small pleasure boats which unwittingly plough furrows, at low tide, to cross the reef, deliberate dredging of channels to allow boats to moor within the lagoon and artificial beaches (Augier and Boudouresque, 1970; Astier, 1975; Boudouresque *et al*., 1975, 2012). Many barrier reefs have probably been destroyed, millennia or centuries ago, because they were located in bays that have been made into ports, for example the Marseille' Lacydon (Greek name of the modern "Vieux Port"), the bays of Toulon (eastern Provence) and Nice (French Riviera), etc. (Boudouresque *et al.,* 1985). More recently, the Bandol BRML was buried beneath land reclamation (Blanc, 1975; Blanc and Jeudy de Grissac, 1978). Nowadays, many *P. oceanica* reef formations are in a poor state of conservation, such as the BRMLs and BREMLs of Port-Cros Bay, Le Brusc and La Madrague de Giens (eastern Provence) (Table I). Some of them are used as harbours for small leisure boats, the barrier reef acting as a natural jetty, such as La Madrague de Giens and Le Pilon reefs; passes were opened through the reef and the lagoon was deepened (Table I). Once the regression has started, stopping it proves to be very difficult, if not impossible, as illustrated by the barrier reef (BRML) of Port-Cros Bay (Augier and Boudouresque, 1970; Boudouresque *et al.,* 1975; Augier and Nieri, 1988; Bonhomme *et al.,* 2001; Goujard *et al.,* 2010). Management by a 50 year-old National Park (Barcelo and Boudouresque, 2012; Barcelo *et al.,* 2013), steady monitoring by scientific teams and the Scientific Council of the National Park (Boudouresque *et al.,* 2013a, 2013b; Farsac *et al.,* 2013), the prohibition of boating and mooring in the vicinity of the reef and within the lagoon, and well implemented regulations have not succeeded in stopping the decline. It is worth noting that the development of a reef formation requires centuries, even millennia, and that its destruction is therefore irreversible at human scale.

At the scale of the Mediterranean Sea, *P. oceanica* meadows may be more resilient to human disturbance than previously thought (Leriche *et al.,* 2006; Boudouresque *et al.,* 2009; Andromède Océanologie, 2014). However, as regards *P. oceanica* reef formations, the picture is probably worse than we usually think. Despite the general lack of knowledge and recent monitoring of most of the reef formations (Table I), most of them are, or probably are, in poor condition. All *P. oceanica* reefs, whatever their type, therefore deserve particular attention and protection.

Conclusion

More than sixty years ago, the first *P. oceanica* barrier reefs were described. Subsequently, a few other reef formations were described or simply mentioned, namely fringing reefs, plateau reefs and micro-atolls. Here, we have proposed a comprehensive typology of these formations, with their formal description, together with a number of new previously unrecorded reef types. Taking into account this typology, it may be expected that a number of *P. oceanica* reefs, that did not match the paradigmatic structure of the Port-Cros barrier reef (now: barrier reef with matte lagoon; BRML), will attract researchers' attention. In addition, several *P. oceanica* reefs, hitherto unnoticed, have been discovered in the Gulf of Hyères, which belongs to the newly established "*Aire Marine Adjacente*" (adjacent marine zone) of the recently enlarged Port-Cros National Park.

At the scale of the Mediterranean Sea, *P. oceanica* reef formations may be less uncommon than previously thought. However, their state of preservation seems to be generally poor. It is particularly worrying because reef building requires centuries or millennia and their regression or loss is irreversible at human scale. They therefore merit a high level of protection. The unexpected discovery, in the Gulf of Hyères, of several *P. oceanica* reefs, some of them in good state of preservation, is important in this regard. This is very good news.

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