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Changes of relative sea level during the past 5000 years in the ancient harbor of Marseilles, Southern France

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Abstract

In the ancient harbor of Marseilles, marine fauna fixed upon archaeological structures as well as bio-sedimentary units document a 1.5 m steady rise in relative sea level during the past 5000 years, followed by a near stable level at present datum from about 1500 years AD to the last century. This trend is similar to the one previously documented along the rocky coasts of the same region. Field observations inside and outside the harbor confirm that no sea level stand higher than the present ever occurred during the studied period in contradiction with the numerical model of Peltier but in agreement with the glacio-hydro-isostatic models of Lambeck and Johnston and Lambeck and Bard. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: palaeo-shorelines; sea level indicators; geo-archaeology; models; Holocene; Mediterranean

1. Introduction

Compilation of worldwide relative sea level variations for late Pleistocene and Holocene shows that from 18 000 years BP to around 6000–5000 years BP, the glacio-eustatic component of sea level rise has been around 120 m (Pirazzoli, 1991, 1996 Mörner, 1996). During the last 6000–5000 years, however, most records indicate a stabilization of relative sea level related to the decreasing melt of the major ice sheets. A few models however, tentatively suggest that some additional meltwater was still added to the ocean during the past 6000 years, inducing a sea level rise of about 2 m (Nakada and Lambeck, 1988; Lambeck, 1993). The study of the second half of the Holocene is therefore important to assess various non-eustatic dynamic factors (isostatic crustal movements, sea-surface topography) that may have triggered local changes (Mörner, 1976; Lambeck and Johnston, 1995; Peltier, 1998).

However, the relative sea level curves since the Last Glacial Maximum have been based upon a few measurements for the last 5–6 millennia (Pirazzoli, 1991; Fleming et al., 1998): for example only 2 dates from the Tahiti coral reefs (Bard et al., 1996) and 4 from the Barbados coral reefs (Fairbanks, 1989). In addition, many of these dates are not based upon reef flat bioconstructions, such as Poritid or Favid micro-atolls, which yield very precise sea level data (Chappell, 1983 for example), but upon reef-crest corals such as *Acropora palmata* and

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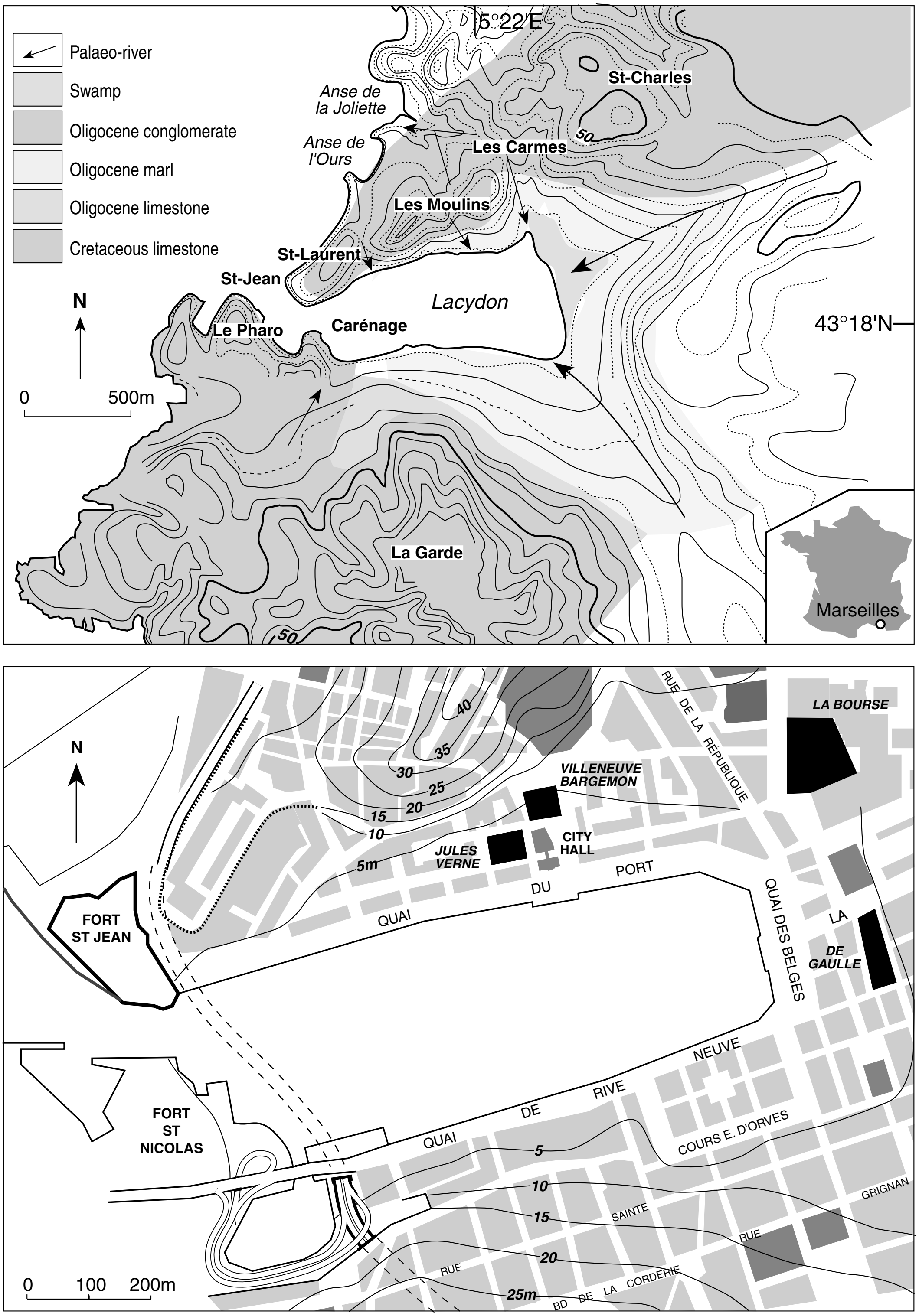


Palaeo-river
Swamp
Oligocene conglomerate
Oligocene marl
Oligocene limestone
Cretaceous limestone
5°22'E
43°18'N
N
0 500m
Anse de la Joliette
Anse de l'Ours
St-Charles
Les Carmes
Les Moulins
St-Laurent
St-Jean
Le Pharo
Carénage
Lacydon
La Garde
50
Marseilles
N
LA BOURSE
VILLENEUVE BARGEMON
CITY HALL
JULES VERNE
RUE DE LA RÉPUBLIQUE
QUAI DU PORT
QUAI DES BELGES
LA
DE GAULLE
FORT ST JEAN
FORT ST NICOLAS
QUAI DE RIVE NEUVE
COURS E. D'ORVES
SAINTE
RUE
GRIGNAN
RUE
BD DE LA CORDERIE
40
35
30
25
20
15
10
5m
5
10
15
20
25m
0 100 200m

Acropora-Hydrolithon assemblages (Fairbanks, 1989; Montaggioni et al., 1997), which are less precise indicators (Laborel and Laborel-Deguen, 1996) since their vertical range of repartition on modern reefs is the same order of magnitude as relative sea level variation during the last 5000 years.

Archaeological excavations of the ancient harbor of Marseilles, in 1993–1994 (Jules Verne and Charles de Gaulle excavations; Morhange et al., 1996) and 1995–1996 (Villeneuve Bargemon and La Bourse excavations; Hermary et al., 1999), have provided a new set of high precision data for the past 4000 years which fit those we obtained on the same coasts, from *Lithophyllum lichenoides* build-ups, also with a precision of ±10 cm (Laborel et al., 1994; Morhange, 1994). This allows us to compare our field results to two different isostatic predictive models for the northwestern Mediterranean (Lambeck and Johnston, 1995; Lambeck and Bard, 2000; Peltier, 1994, 1996).

2. Environmental conditions in the study area

The ancient harbor of Marseilles is a deep and narrow sheltered embayment in Oligocene conglomerates and sandy marls (Nury, 1977) surrounded by steep hills (Fig. 1). Tide range is only about 0.1 m, but atmospheric pressure variations may trigger occasional surges with a maximal amplitude of 1.5 m (Service des Phares et Balises, Marseilles Harbor Authority, personal communication). The region of Marseilles is considered to have been tectonically stable during the late Pleistocene (Guieu, 1977; Bonifay, 1980; Bonifay and Courtin, 1980; Collina-Girard, 1992).

3. Methodology

The French datum (zero NGF) was fixed in Marseilles at the end of the 19th century by averaging local mareographic records between 1885 and 1897 (Guéry et al., 1981).

Among the various biological sea level indicators used in the Mediterranean area, the upper limit of the barnacle *Balanus* cf. *amphitrite* (Darwin), which thrives in polluted and confined environments, is particularly well adapted in harbor areas (Laborel and Laborel-Deguen, 1994). Several authors (Stephenson and Stephenson, 1949; Pérès and Picard, 1964; Leung Tack Kit, 1972; Patriti, 1976; Specchi et al., 1976) showed that *Balanus* populations commonly develop upon quay walls and wharf pilings, stopping abruptly at mean sea level. Our own topographic precision levelings (Morhange, 1994) accordingly demonstrated that the upper limit of living barnacles in Marseilles is presently 10 cm above French geodetic (zero NGF, baseline of our archaeological excavations), a datum established at the end of the 19th century when the mean sea level measured was about 11 cm lower than today (Guéry et al., 1981). Sub-fossil *Balanus* has already been used as sea level marker for geo-archaeological studies in Marseilles (Pirazzoli and Thommeret, 1973).

Precision obtained from Barnacles ranges from plus or minus a few centimeters when the upper population limit is continuous, down to about 10 cm when it is scattered or less preserved (Laborel and Laborel-Deguen, 1994).

Wherever no *Balanus*-bearing hard substrate was available, the summit of the onlap layers of sub-tidal beaches (precision: ±0.2 m) was used as a sea level indicator (Morhange et al., 1996).

Archaeological dates obtained from the study of excavated ceramics are reported in calendar (BC/AD) years. Radiocarbon dates from marine specimens were corrected for $\delta\ ^{13}C$ (±2 standard deviations) and calibrated (Stuiver and Braziunas, 1993; Table 1).

4. Results

The oldest marine sedimentary unit is a sub-littoral pebble beach overlying the Oligocene substratum (Fig. 2) and reaching −1.64 m NGF on the northern border of the Villeneuve Bargemon archaeological excavation. It tapers off from 20 cm in its lowest part to 7 cm in its upper part. The pebbles have a littoral morphology and bear fixed marine shells and

Fig. 1. Present time topographic and geological features of Lacydon creek. The details of the coastline are not accurately defined. Localization of the archaeological excavations.

Table 1
Height under present sea level and dates obtained in Marseilles

Lab. code	Excavation	Material	Depth (cm)	δ ^{13}C (0/00)	^{14}C years BP	Calendar years	Reference
Ditch	de Gaulle	*Balanus* sp.	12 ± 5			1660 AD	Morhange (1994)
LGQ 906	de Gaulle	*Balanus* sp.	12 ± 5	est. 0	650 ± 130	1440–1950 AD	Morhange (1994)
MC 697 A	La Bourse	*Balanus* sp.	25 ± 5	est. 0	2220 ± 80	35 BC–344 AD	Pirazzoli and Thommeret (1973)
MC 697 B	La Bourse	*Balanus* sp.	25 ± 5	est. 0	2290 ± 80	132 BC–252 AD	Pirazzoli and Thommeret (1973)
Roman quay	La Bourse	*Balanus* sp.	25 ± 5			400–500 AD	Jourdan (1976)
Archaic quay	Villeneuve–Bargemon	*Balanus* sp.	63 ± 5			510–500 BC	
Wooden posts	La Bourse	*Balanus* sp.	67 ± 5			510–500 BC	
Ly 9008	Villeneuve–Bargemon	*Balanus* sp.	63 ± 10	0.15	2965 ± 40	835–735 BC	
Roman quay	Jules Verne	*Balanus* sp.	65 ± 10			150 AD	Morhange (1994)
Hellenistic quay	Jules Verne	*Balanus* sp.	68 ± 10			50 AD	Morhange (1994)
Ly 8374	Villeneuve–Bargemon	Marine shells	148 ± 20	1.45	3705 ± 45	1759–1521 BC	
Ly 8423	Villeneuve–Bargemon	Marine shells	164 ± 20	1.5	4420 ± 45	2463–2215 BC	

frail tubeworms (*Ostrea* sp., *Chama* sp., *Serpula concharum* and *Pomatoceros lamarckii*). They indicate sheltered waters with a precision of +20 cm (Table 1). The upper limit of the unit was unfortunately destroyed by the excavation wall, but its upper taper as well as the exoscopic morphology of quartz grains both indicate the very close proximity of the shoreline. Contemporary sea level was therefore −1.64 m, with a precision of ±20 cm. Marine shells fixed on the pebbles were dated 4420 ± 45 years BP (Ly 8423), 2463–2215 years cal. BC.

A layer of free-living calcareous algae (maërl) undisturbed thalli, whose upper limit is at −1.48 m NGF, overlies the pebbles (Morhange, 1994). Maërl is a biological accumulation of the coralline Rhodophyte *Mesophyllum coralloides* (Jacquotte, 1962; Steneck, 1986), a sublittoral species which may develop upwards to mean sea level in calm marine embayments (de Gaillande, 1968) and thus may be used as a sea level indicator with a precision of +20 cm. Radiocarbon dating of thalli yielded an age of 3705 ± 45 years BP (Ly 8374, 1759–1521 years cal. BC). Contemporary mean sea level was then −1.48 m NGF at 3705 ± 45 years BP, with a precision of ±20 cm.

A Greek quay, 8 m long and 7 m wide, built around 600–575 years BC, was unearthed on the northeastern corner of the Villeneuve Bargemon excavation zone (Figs. 3 and 4). Its upper surface lies between −0.3 and −0.5 m NGF and is covered by fixed marine organisms. The upper limit of *Balanus* cf *amphitrite* is well preserved along more than 20 m at −0.63 m ± 5 cm NGF marking mean sea level. The quay was silted up in 510–500 years BC and shells killed by sands from a nearby rivulet. The same sea level stand (−0.67 m ± 5 cm NGF at 510–500 years BC) was also observed on *Balanus*-bearing wooden posts from a nearby excavation (La Bourse).

On the Jules Verne site, a Hellenistic boulder quay built around 100 years BC was lined by a wooden planking driven into the Oligocene sediments. The planking bore scattered barnacles with an upper limit at −0.68 m ± 10 cm NGF. They were killed in 50 BC when the quay was silted up and abandoned. Contemporary sea level was therefore −0.68 m, with a precision of ±10 cm.

On the Jules Verne site, we found a Roman quay

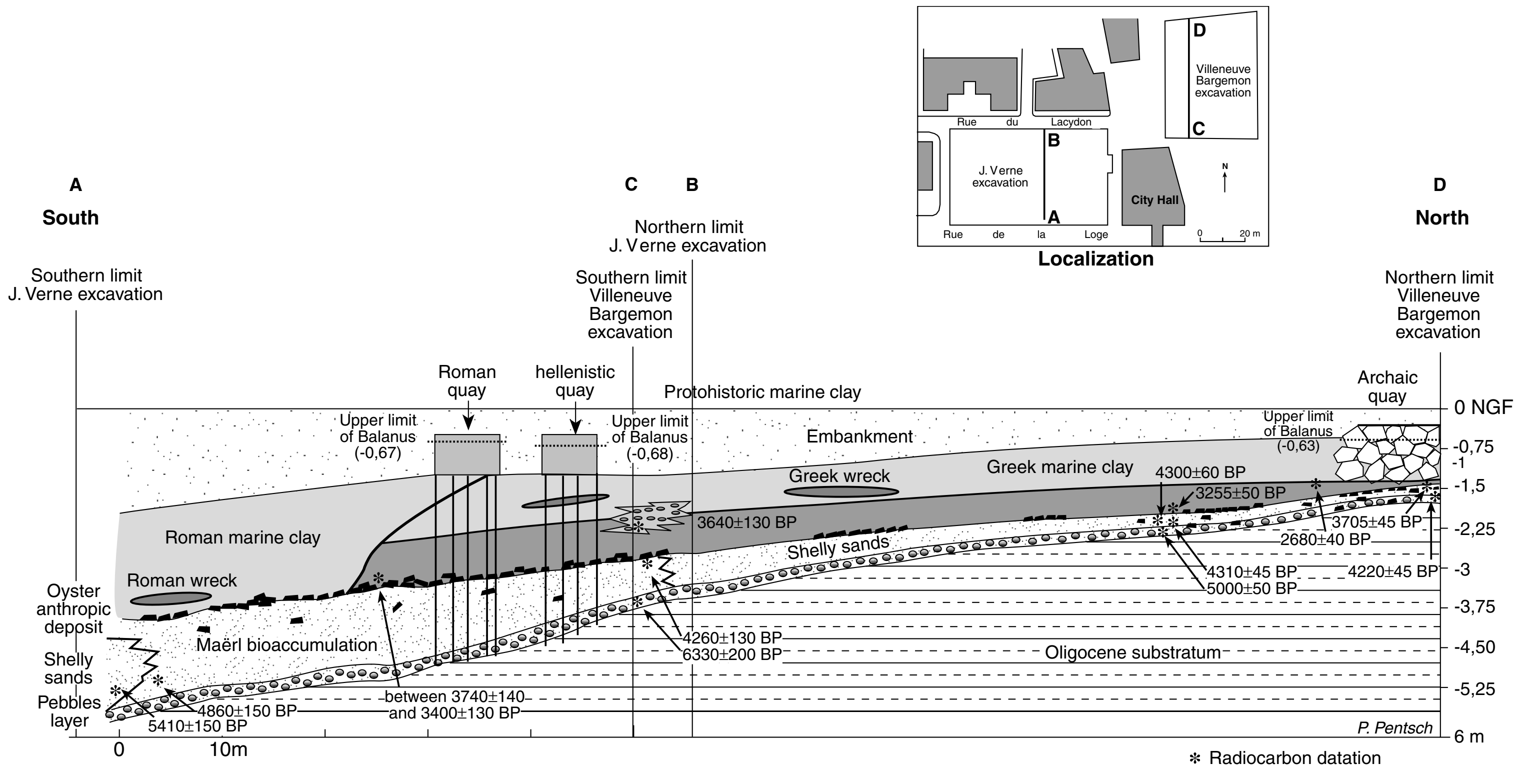


Fig. 2. Summarized stratigraphic section of the North shore of Lacydon, Marseilles.

Fig. 3. A well-preserved ancient Greek quay, with contemporary sea floor and presenting an intact and continuous upper limit of its barnacle cover, Villeneuve Bargemon excavation. Photograph: C. Morhange.

(built about 20 years AD). Its wooden posts bore scattered barnacles with an upper limit −0.65 m NGF (±10 cm). Barnacles were killed about year 150 AD when the quay was silted up. Contemporary sea level was therefore −0.65 m, with a precision of ±10 cm.

At La Bourse, Pirazzoli and Thommeret (1973) unearthed a roman quay built during the second part

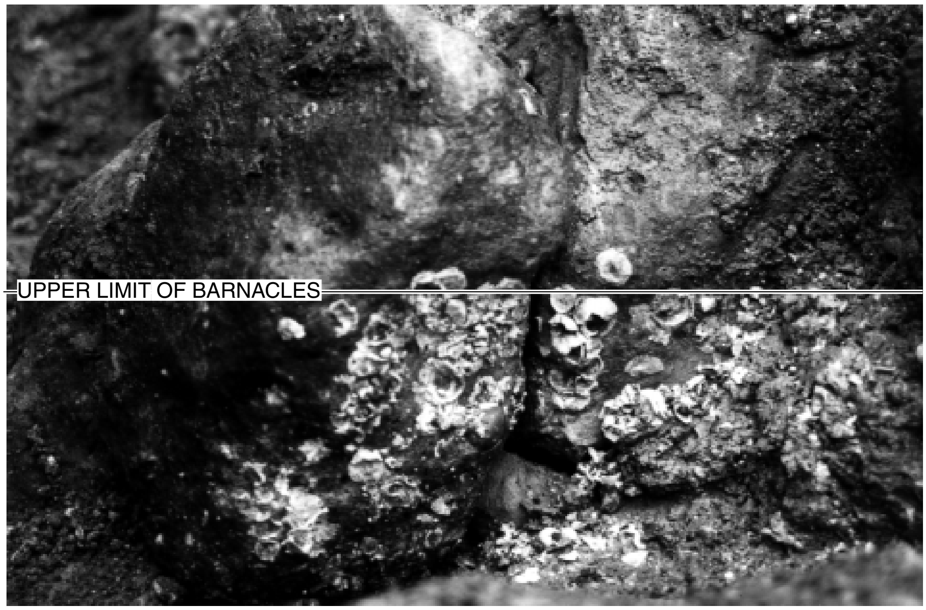


Fig. 4. Detail of the intact upper limit of barnacles on the ancient Greek quay, Villeneuve–Bargemon excavation. Photograph: C. Morhange.

Fig. 5. A well-preserved Roman quay, presenting a continuous upper limit of its barnacle cover. The horizontal limit of the corresponding sub-littoral zone is determined by the intact upper limit of barnacles, La Bourse excavation. Photograph: CCJ, MMSH, CNRS.

of the first century AD (Guéry, 1992). It bore a continuous line of barnacles (upper limit at −0.25 m ± 5 cm NGF), (Fig. 5) which were killed by siltation between 400 and 500 years AD (Jourdan, 1976). Two radiometric dates gave ages of 2220 ± 80 years BP (MC 697A), 35 years cal. BC–344 years cal. AD and 2290 ± 80 years BP (MC 697B), 132 years cal. BC–252 years cal. AD. At the time of *Balanus* killing by siltation (450 AD) sea level was −0.25 m, with a precision of ±5 cm.

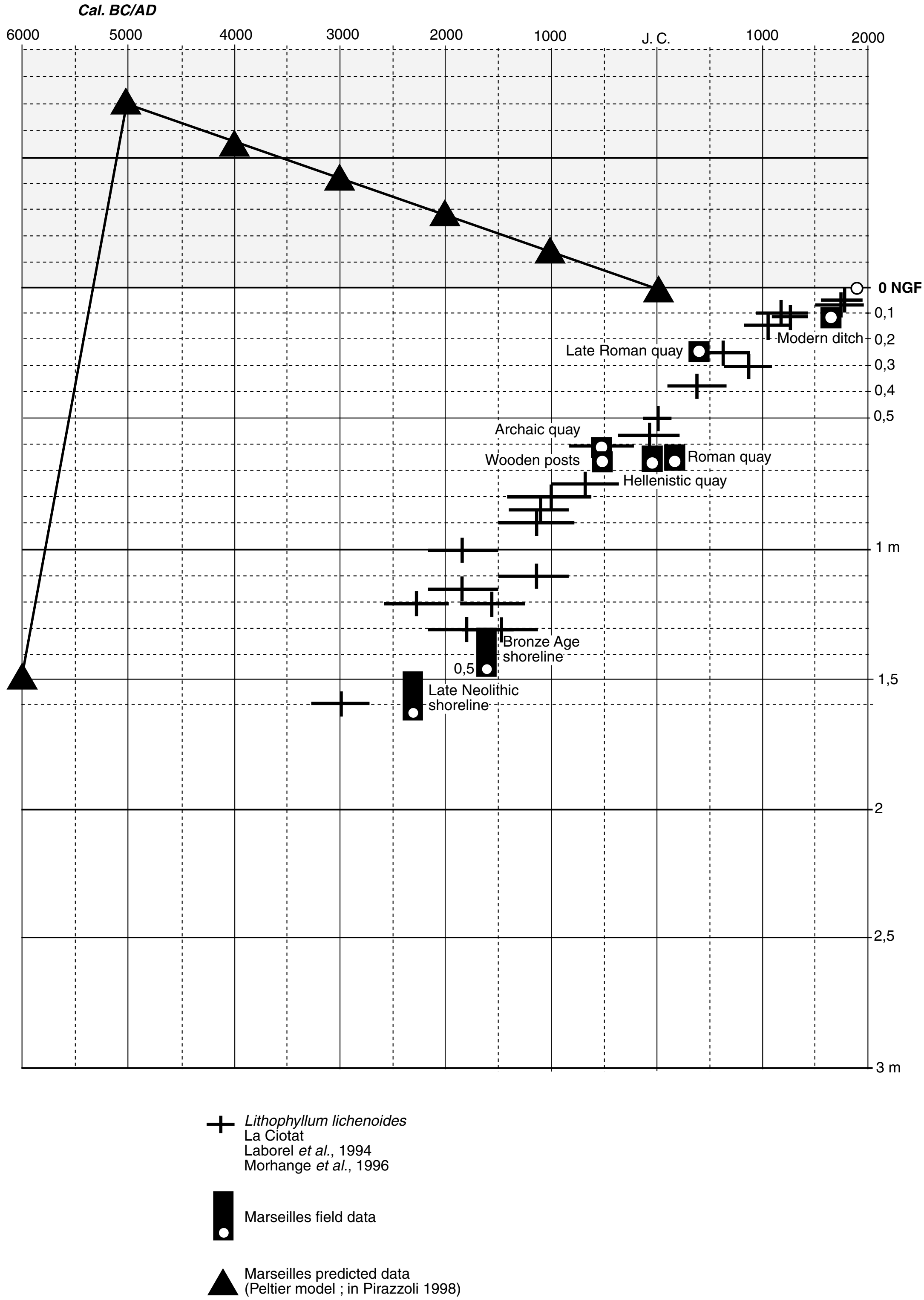
On the Charles de Gaulle site (Marc Bouiron dir.), a 15 m long wall belonging to a medieval ditch connected to the sea was excavated. This wall bore a continuous and straight upper limit of barnacles at −0.12 m ± 5 cm NGF. The date of the barnacles is 250 ± 130 years BP (LGQ 906) or younger than 1440 years cal. AD. This date is consistent with the recorded filling up of the ditch in 1660 years AD, under the reign of Louis XIV. Contemporary sea level was therefore −0.12 m, with a precision of ±5 cm.

5. Discussion

Comparing sea level data obtained in sheltered water from biological indicators (upper limit of *Balanus* or of "maerl" bioaccumulation) with those coming from surf beaten rocky coast indicators such as *Lithophyllum lichenoides* rims is not easy. On the one hand, precision is generally better in harbors than in high energy sites, and on the other, archeological structures, even when rooted in hard substratum are more prone to slight displacements due to slumping or later reworking by man. It is therefore not surprising that coincidence of the two sets of data is not perfect (Fig. 6).

The age–depth diagram (Fig. 6) shows a regular rise in relative sea level up to about 500 years AD followed by a period of stability until sea level began rising again at the beginning of the 20th century. Total rise has been less than 1.5 m since 4400 years BP. Linear regression ($n = 7$, $R^2 = 94\%$) leads to a mean velocity for sea level rise of 0.7 mm/year between 4413 years cal. BP and 450 years AD ($n = 7$, $R^2 = 94\%$) and 0.2 mm/year since 450 years AD ($n = 3$, $R^2 = 89\%$).

Our former diagram drawn using *Lithophyllum lichenoides* rims at La Ciotat, 35 km east (Laborel et al., 1994) is similar to the one obtained at Marseilles. In both cases, sea level rose from 4500 to about 1500


Cal. BC/AD
6000
5000
4000
3000
2000
1000
J. C.
1000
2000
0 NGF
0,1
0,2
0,3
0,4
0,5
1 m
1,5
2
2,5
3 m
Modern ditch
Late Roman quay
Archaic quay
Wooden posts
Roman quay
Hellenistic quay
Bronze Age
shoreline
0,5
Late Neolithic
shoreline
Lithophyllum lichenoides
La Ciotat
Laborel et al., 1994
Morhange et al., 1996
Marseilles field data
Marseilles predicted data
(Peltier model ; in Pirazzoli 1998)

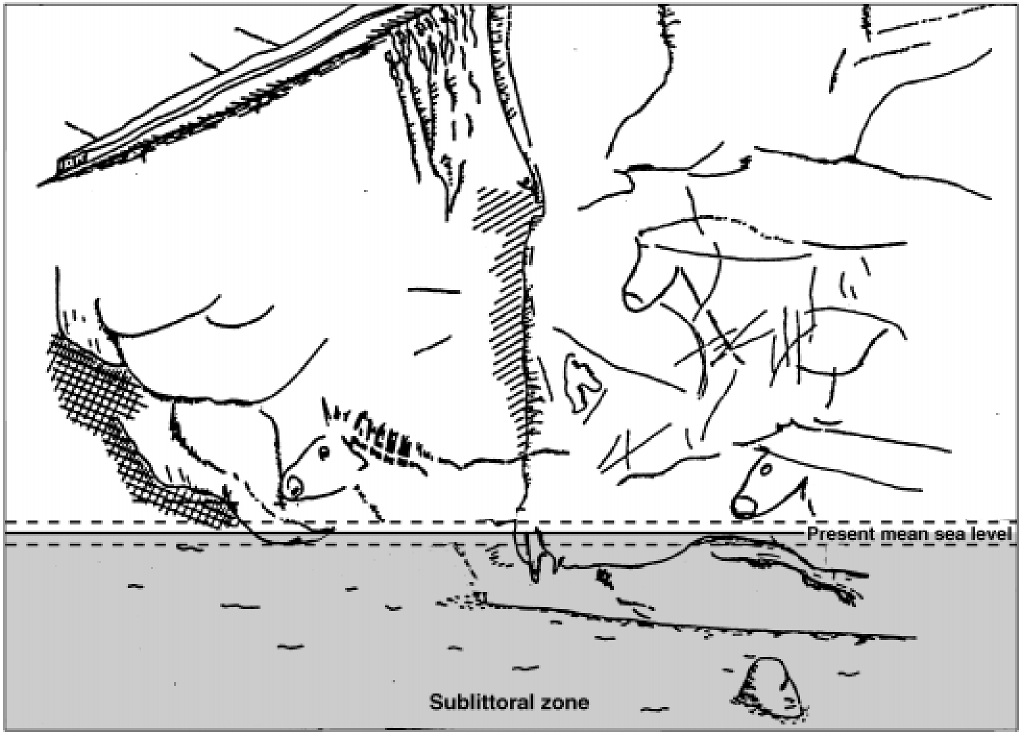


Fig. 7. The negative proof of the absence of a Holocene relative sea level above present datum supported by the painted horses on a wall of a half-submerged paleolithic cave near Marseilles (modified from Vouvet et al., 1996).

years BP with a mean velocity slowing off from 0.4 mm/year (before 1500 BP) to 0.2 mm/year (before the 20th century). The rate of sea level rise later increased to around 1.5 mm/year during the 20th century (Blanc and Faure, 1990). In a previous paper (Morhange et al., 1996), data from archaeological indicators, such as slipways and sewers, had led us to conclude that the sea level curve in Marseilles was somewhat different from the one in La Ciotat. The later discovery of a well-preserved Greek quay in the Villeneuve–Bargemon excavation allowed us to correct this first interpretation.

A recent work, using radiometric dating of the base of peat formations (Vella et al., 1998; Vella, 1999), to study relative sea level variations in Fos near the Rhone delta, suggested a minor period of stabilization between 4000 and 3500 years cal. BP, around −2.15 m NGF. This meant a discrepancy of about 1 m with our own data. This may be an artifact due either to the lower precision of the sea level indicator used or to peat compaction. We think, indeed, along with many authors, that there is no evidence of any sea level oscillation for the last 5000 years at least. (Aloisi et al., 1978; Dubar and Anthony, 1995).

Recent glacio-isostatic and hydro-isostatic rebound far away from glaciated regions can be calculated using global isostatic modeling. Our field data can thus be compared with local predictions elaborated from two different isostatic earth models based upon similar mathematical developments (Pirazzoli, 1998).

Like most models of this kind, ICE-4G model (Peltier, 1994, 1996, 1998) is based upon deglacial history and mantle-viscosity parameters. Predictions for the Marseilles area (in Pirazzoli, 1998) indicate

Fig. 6. Age–depth diagram: data from archaeological excavations compared with data gained from ^{14}C dated algal rims from rocky cliffs at La Ciotat (Laborel et al., 1994; Morhange et al., 1996) and with predictions of relative sea level changes by Peltier in Pirazzoli (1998).

that relative sea level should have varied between 1 and 0.5 m above the present sea level between 5000 and 3000 years cal. BP. Such predictions clearly do not fit archaeological, geological and biological field evidence. Indisputable traces of a Holocene vertical oscillation above present sea level have never been found in Provence. This is proved, for example, by the preservation above present sea level of some half-submerged palaeolithic horses (Fig. 7; Vouvet et al., 1996), painted on a wall of the Cosquer cave near Marseilles. The lower part of the painting only has been blotted out by sea water, whereas any recent positive level oscillation would have also destroyed the upper part of the painting.

In Southern France, alias, with the exception of the tectonically active region of Nice (Dubar, 1987), field observations never indicate any high Holocene level between 5000 and 3000 years cal. BP as predicted by Peltier's curve. The only occurrence in the literature of a higher than present Holocene sea level in southern France, at Cape Romarin (Aloisi et al., 1978) was recently found to be of Pleistocene age (Laborel et al., 1998).

The second model (Lambeck and Johnston, 1995), based upon different deglacial history and mantle-viscosity parameters, indicates instead a relative sea level rise of 2 m between 6000 and 2000 years BP and of 0.5 m between 2000 years BP and present, in agreement with our field data (Lambeck and Bard, 2000).

We therefore think that further precise field work on sea level indicators in ancient harbors, which are sheltered places where accurate data may be recorded, is needed (Pirazzoli, 1976).

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