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Biological evidence of sea-level rise during the last 4500 years on the rocky coasts of continental southwestern France and Corsica

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Abstract

On the rocky coasts of the northwestern Mediterranean basin, biogenic littoral rims built by the coralline rhodophyte *Lithophyllum lichenoides* develop, whose remains may be preserved for millennia when submerged in a rising sea environment. These remains can be used as biological indicators of recent sea-level variations. Our survey of the continental coasts of Var and Bouches du Rhône, west of Marseilles (southern France) and of northern Corsica shows that relative sea level rose about 1.6 m in the study area during the last 4500 years without exceeding the present datum. The rate of sea-level rise was 0.4 mm per year between 4500 and 1500 yr B.P. and slowed down to 0.2 mm per year from 1500 yr B.P. to present time. There are also morphological indications of an acceleration of the rate of sea-level rise during the last century, supporting the evidence of tide gauges. Regions at the periphery of the above zone (Alpes Maritimes, Italian border zone, and the French and Spanish Catalonia regions) were also surveyed, but a weaker development of *Lithophyllum* rims and bad preservation of algal remains led to unconvincing dates which could also be linked to regional tectonic trends.

1. Introduction

The idea of following the recent sea-level rise along the rocky coasts of the Mediterranean by sampling and dating submerged algal formations (Laborel et al., 1983) led to the elaboration of the present project in the frame of CEE (DG XII) project "Sea level" EPOCH.

1.1. Study area

Field work was done between November 1991 and January 1993 (Fig. 1) on the French continental coasts: La Ciotat, Peninsula of Giens, Port Cros, Ile du Levant, Cap Drammont, Nice, Monaco, and on the coasts of western Corsica (Marine Reserve of Scandola) and Cap Corse (Centuri and Giraglia island). Two field trips were also carried out in Spanish Catalonia and in the French eastern Pyrenees (Banyuls).

1.2. The biological basis

The spacial distribution of the littoral fauna and flora and of correlated bioerosive and bioconstructive actions follows a definite zonal pattern along rocky shores of the Western Mediterranean basin. For a detailed description of this zonation and of

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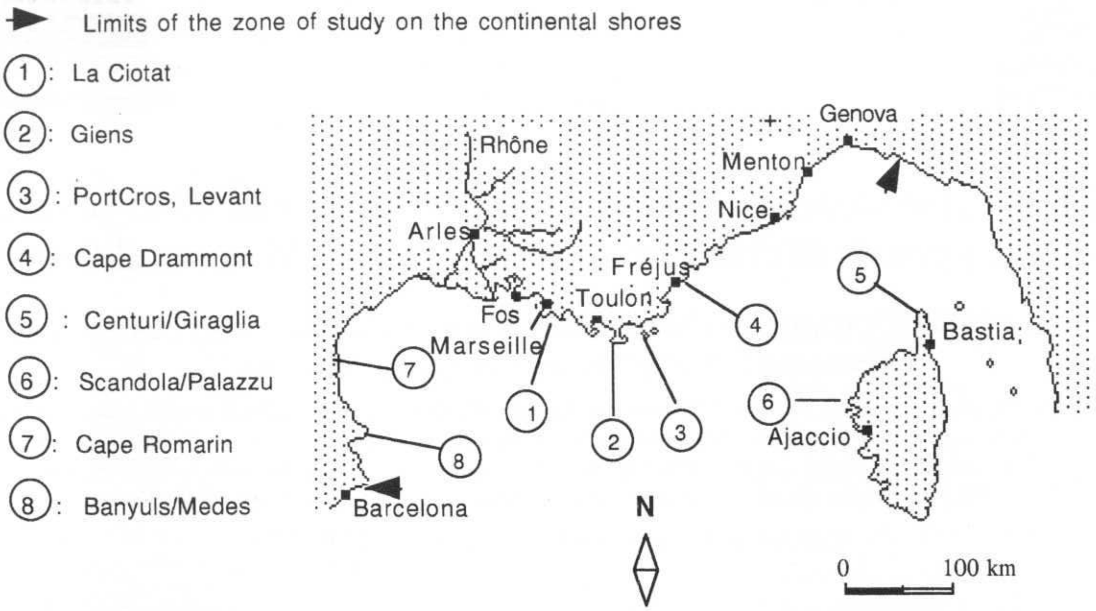

Fig. 1. General map of the region studied.

related phenomena the reader is referred to Peres and Picard (1964) and Peres (1982), as well as to the broadly similar scheme of Stephenson and Stephenson (1949). (For a detailed discussion of these problems and their implication in measuring past sea levels see Laborel, 1986.)

Zonation includes three principal zones, from land downwards:

(1) A littoral fringe wetted by surf, in which the biomass is mainly represented by endolithic Cyanobacteria (Le Campion-Alsumard, 1970).

(2) A midlittoral zone periodically submerged by waves and tides, displaying a pattern of parallel algal belts, with biomass and species diversity increasing downward. On limestone shores, Cyanobacteria and limpets shape the tidal notch and erosion bench. Rock-building elements such as the coralline rhodophyte *Lithophyllum lichenoides* may also be important (Peres and Picard, 1952).

(3) An infralittoral (sublittoral) zone ranging from mean sea-level (MSL) down to a depth of 25–35 m and densely populated by brown sea weeds (*Cystoseira* and *Sargassum*), fixed gastropods and mollusks (*Dendropoma petraeum*, *Vermetus triqueter*), cirrhipeds (*Balanus* spp.) and clionid boring sponges (Rutzler, 1975; Spencer, 1992), sea-urchins (*Paracentrotus*) and the rock-boring pelecypod *Lithophaga lithophaga* (Kleemann, 1973). Vermetid gastropods and coralline algae protect the rock against bioerosion and, under favorable conditions may build-up reef-like bioconstructions (Blanc and Molinier, 1955).

Many regional and local differences occur, linked to biogeography, tides, direction and intensity of prevailing winds, water temperature and other oceanographical factors.

On limestone shores these contrasting actions lead to different types of vertical profiles (Guilcher, 1953; Dalongeville, 1986) in which biokarsts and notches alternate with bioconstructed structures following a characteristic pattern which may be preserved for a long time when dried-up by land elevation, or resist underwater erosion when submerged and thus be used for the study of past sea levels (Pirazzoli, 1986).

1.3. The Lithophyllum lichenoides *rim*

Lithophyllum lichenoides Philippi (*Rhodophyta*, *Corallinacea*), formerly known as *Teanarea tortuosa* and *Lithophyllum tortuosum* (Woelkerling et al., 1985) is a coralline rhodophyte which develops on the rocky coasts of the northwestern Mediterranean basin (Peres and Picard, 1952), the crispate fronds of the thalli harbouring a rich and diverse infauna of mixed marine and continental origin (Delamare-Deboutteville and Bougis, 1951).

Ecology

The *Lithophyllum* rim develops slightly over MSL (lower midlittoral) in shady coves of cliffs exposed to surf action and may attain a maximum width of about 2 m and an average thickness of 30–40 cm (Fig. 10). It is the shallowest biogenic building in the Mediterranean and *Lithophyllum lichenoides* is among the Mediterranean littoral species with the narrowest depth range (not exceeding 50 cm) (Huvé, 1970).

On limestone coasts, the *Lithophyllum* rim develops at the base of the midlittoral tidal notch which it may locally fill more or less completely (Dalongeville, 1986).

The growth rate of the living thalli is relatively rapid, amounting to approximately 3 cm per year (Boudouresque et al., 1972), but the evolution from an incipient algal population to a mature rim with hardened core is a long process, the duration of which is unknown but must be over one century at least (Huvé, 1953, 1970). In warmer waters of the southwestern and eastern basins, *Lithophyllum* loses gradually its building abilities and is replaced as a constructional agent by the sublittoral fixed gastropod *Dendropoma* (*Novastoa*) *petraeum* Monterosato, generally living in association with the coralline rhodophyte *Neogoniolithon notarisisii* (Dufour) Setchell and Mason. Both species are important biological sea-level indicators (Laborel, 1986).

Repartition

Lithophyllum rims are limited to the Western Mediterranean basin but the species is also present, but not as a rim builder in the Eastern Mediterranean region (Zimmermann, 1982) as well as in the temperate North Atlantic (Palminha, 1957). In the Western Mediterranean region the best developed formations occur in Corsica (Molinier, 1960; Bianconi et al., 1987) and on the coasts of the Provence (Sicsic, 1967; Walter-Levy et al., 1959; Peres and Picard, 1964), i.e. in the zone of maximum influence of the northwestern winds rushing down the Rhône valley (the latter winds, called *Mistral* on the coast of Provence and *Tramontane* west of the Rhône delta, are powerful and cold and may blow for long periods at a time, generating strong swells; Fig. 2).

Inner structure

The inner structure of the rim (Figs. 3 and 11) consists of an outer layer of living thalli, a few centimetres deep (layer 1), resting upon an unconsolidated layer of dead thalli (layer 2) which covers a hardened multilayered zone (layer 3). This zone is the result of deposition processes filling-up the interstices between fronds with a hardened sedimentary matrix (Blanc and Molinier, 1955). The core has a multilayered structure, with a number of growth discontinuities which have been attributed tentatively to the action of aperiodical lowerings of the sea surface due to temporary anticyclonic conditions in the Western Mediterranean basin (Laborel et al., 1983). The lower surface of the rim is often made up of dead *Lithophyllum* rock strongly bioeroded by clionid sponges and *Lithophaga* and covered by shade loving weeds, corallines and invertebrates (Laborel, 1987).

1.4. Lithophyllum *rims as sea-level indicators*

Resistance to erosion

Living or dead unconsolidated thalli are easy to erode by biological or mechanical action and are presently subject to strong erosion in the whole western Mediterranean region, due to the adverse effect of ever increasing pollution of surface waters (Morhange et al., 1992). In cases of strong erosion, the subsequent lowering of the rim surface must be taken into acount for levelling operations.

Preservation

Our first surveys (Laborel et al., 1983; Laborel and Laborel-Deguen, 1994) suggest that the elaboration of a well developed rim necessitates a near-stable or slowly rising sea-level allowing a continuous superposition of new layers upon the dead core, which buttresses and strengthens the rim. Too rapid a rise would not allow the vertical development of the rim to compete with the rise

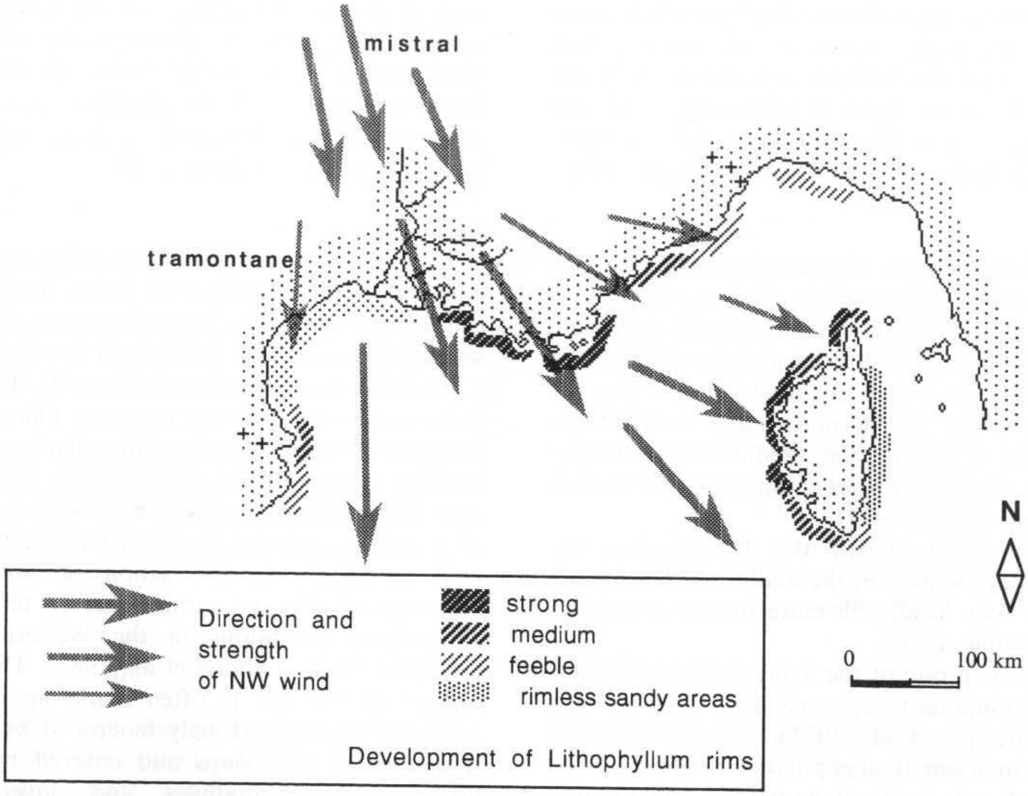

Fig. 2. General map of the northwestern winds and their influence on the development of *Lithophyllum* rims.

of sea-level, a phenomenon now widely known for coral reefs. Conversely, in places where combined movements of land and sea would cause an apparent stability of the shoreline for long periods, the rim would then develop as a thin and flat cantilever structure subject to periodical breaking off and tumbling over (Dalongeville, 1986). As for the case of a falling relative sea level, elevated thalli would be submitted to midlittoral erosion before having the opportunity of hardening and of building a true rim. So the presence of a thick and well developed *Lithophyllum* rim generally corresponds to a gentle rise of relative sea level (Fig. 4).

2. Material and methods

2.1. Selection of sites

The first step of our study was a general survey of the coasts, in all the places where important *Lithophyllum* rims had been signalled by preceding authors, such as Presqu'ile de Giens (Sicsic, 1967), Antibes (Walter-Levy et al., 1959), the island of Port Cros (Laborel et al., 1983), northern Corsica (Molinier, 1960), western Corsica south of Calvi (Bianconi et al., 1983), and the region of Banyuls (Delamare-Deboutteville and Bougis, 1951). New localities were also looked for, notably thanks to two extensive helicopter flights over the coasts of Var and Alpes Maritimes.

Promising localities were then surveyed over and underwater, measuring the thickness and width of the present rim, the vertical range of the thalli and probing for submerged remains.

2.2. Study in the field

After a preliminary survey of the selected site a vertical section was excavated with hammer and chisel or with a light pneumatic breaker through

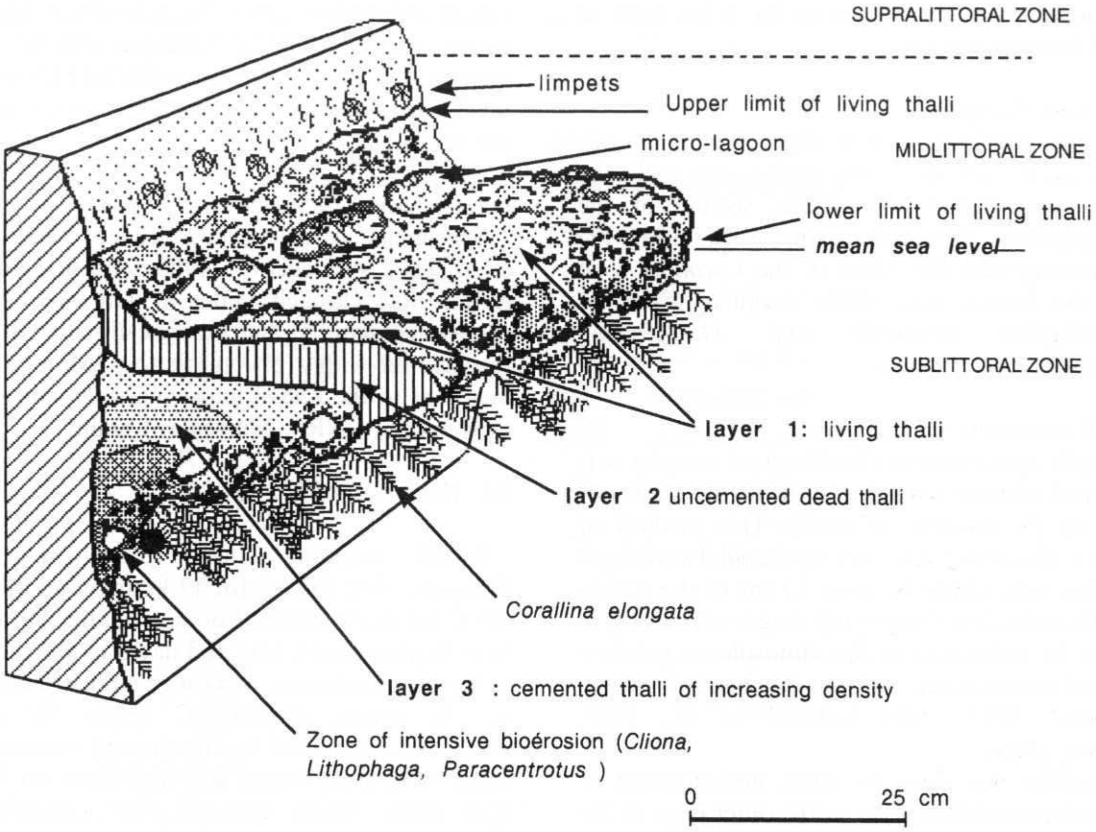

Fig. 3. Structure of a northwestern Mediterranean *Lithophyllum lichenoides* rim (from Morhange et al., 1992).

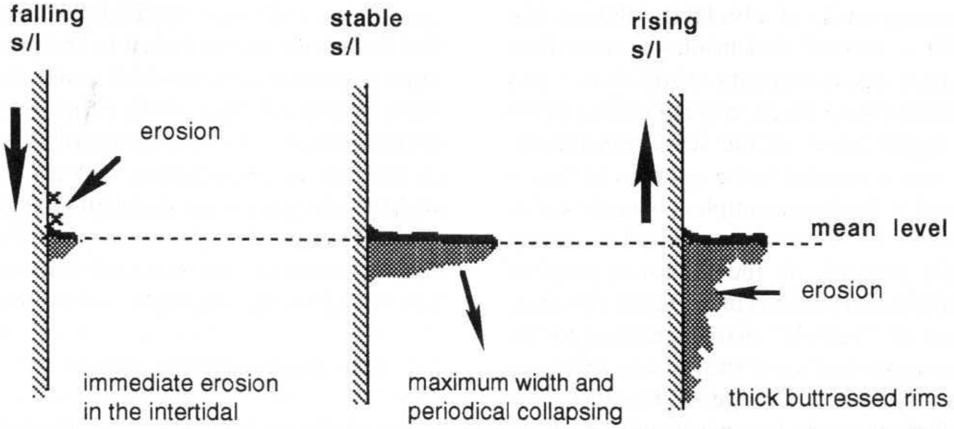

Fig. 4. Influence of relative sea-level variations on the development of the *Lithophyllum* rim.

the present algal rim down to the lower limit of fossil bioconstruction.

Selection of samples

A first visual selection of the rock samples was done underwater on freshly broken rim rock: the grey, vermiculated with white, section of the *Lithophyllum lichenoides* rim rock (Fig. 12) contrasting with the white of the *Corallina* rock and the brown with white irregular layers of *Lithophyllum incrustans* and *Mesophyllum lichenoides* constructions.

Depth measurement of samples

Depth measurement (levelling) of samples was obtained without reference to the actual sea water level at the moment of study. This method of study without any reference to the tidal variations (normal tidal range is about 15 cm in the region of Marseilles and exceptional ranges of about 1 m linked to variations of the atmospheric pressure are not uncommon) has been discussed elsewhere (Laborel 1980, 1986; Laborel et al., 1983; Jardine, 1986).

Levelling was done by direct measurement of the vertical distance between the outer edge of the living rim taken as the reference datum and the center of the broken section (Figs. 5 and 6; Laborel et al., 1983; Laborel, 1986).

The error range on height measurement was found to depend on several experimental factors related to the difficulty of measuring a vertical distance underwater, the size of the sample and the inherent irregularity of a biological datum. For samples with a vertical dimension of more than 10 cm separate measurements were done, and different samples were taken, corresponding to the lower and upper limits of the scar, respectively. Total error was estimated to be ±10 cm in favorable cases and ±20 cm for samples collected under very thick rims, i.e. in crevices exposed to strong surf (like, for example, in the shallower parts of Centuri and Giraglia stations in northern Corsica). Another kind of "built-in" error is related to the choice of the upper surface of the rim as a reference datum: since the present range of the species is presently offset upwards by an amount of about 10 cm by the effect of the secular rise of sea level (Blanc and Faure, 1990). We considered that our measurements should be corrected with the same amount, but for different reasons (see Discussion) we decided not to include the latter correction into our results.

Further sample treatment

Specimens were labelled, cleaned, rinsed and dried. They were cut with a diamond saw and the section was checked under a stereomicroscope, allogenous material and biologically altered parts chiselled off with a pneumatic tool. Material was then sent to the *Laboratoire de Geochronologie du Quaternaire*, CNRS, Marseilles Luminy.

2.3. *Radiocarbon dating*

Samples weighing about 40 gram were ground (200 μm), then cooked for 12 hours in an oven at 300°C for destruction of organic matter, attacked by orthophosphoric acid and dated by the method of liquid scintillation. After a preliminary calibration by means of the ^{12}C versus ^{13}C ratio, results were expressed in uncorrected radiocarbon years. A control dating was also done on living algal thalli, which indicated that *Lithophyllum lichenoides* does not appear to be subject to any kind of reservoir effect (Stuiver et al., 1986).

Dating was generally easy on material correctly sampled and cleaned of any kind of secondary, potentially younger, incrustations: *Cliona* perforations filled up with younger material were found to be the commonest cause of contamination. A special cause of error that could be neither quantified nor eliminated is linked to the presence of the inner deposited cement which cannot be separated from imbedded algal thalli either by physical or chemical means. In the absence of a detailed study of the rate of cementation, this error, leading to slightly younger dates (about 50–100 years?) could not be quantified with accuracy, so it was considered as more or less constant but no correction was added to our diagrams and tables.

2.4. *Statistical analysis of data*

Two different types of tests were used (Dagnelie, 1975; Zar, 1984):

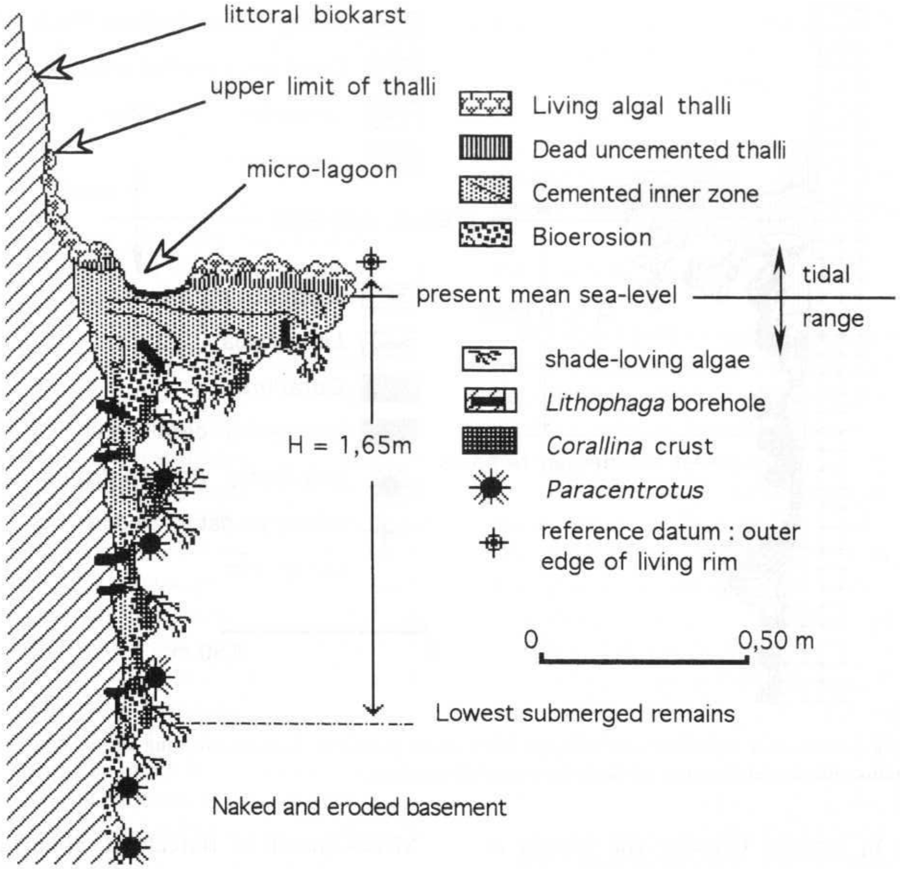

Fig. 5. Profile of a typical section of the conglomerate cliffs at La Ciotat (southern France) showing present rim structure and bioeroded submersed remains of former rims. Dated samples were collected at increasing depths along this profile.

(1) Comparison of stations, in order to look for significant stational differences. Stations with less than three dates (or presenting large contamination problems) were not treated. We compared the adjusted mean of the ages obtained for one standardized depth (the average depth of all our stations). For that purpose, we used the analysis of covariance (ANCOVA) followed by an a posteriori test of Student, Neumann and Keuls (SNK), a technique with a better accuracy than ANOVA, thanks to the introduction of linear regression.

(2) In order to test the possibility of regional variations in the rates of relative sea-level rise, a comparison of the slopes obtained through linear regression (*t*-test) of date–depth data was attempted for two different levels (over and under −0.25 m depth) for the most complete station (La Ciotat): The slope (*a*) (expressed in years per metre) was calculated, along with the standard deviation (*SD*) for two different depth levels and the calculated corresponding average rate of sea-level rise expressed in millimetres per year.

3. Results

3.1. Regional study

As could be expected, the best preserved and complete sets of remains were found in places where the present littoral rim is best developed,

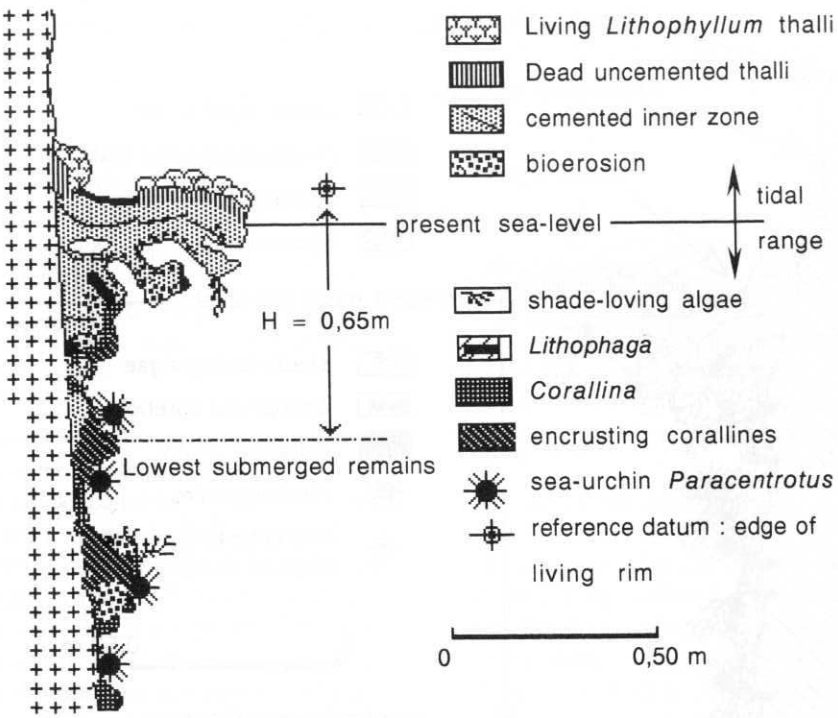

Fig. 6. Profile on a section of a rhyolithic cliff at Cape Drammont (southern France), showing the relative lack of submersed *Lithophyllum* remains and the development of shade-loving coralline algae.

that is to say in western Corsica, the islands of Port Cros and Le Levant and near La Ciotat.

On the other hand, bad preservation was found to be the rule in zones where present rims are thinner or less consolidated, between Cannes and Menton, on the Italian Riviera and on the sectors of the Catalonian Costa Brava we could survey.

These regional variations are interpreted, as stated before, as a consequence on algal development of the gradual fading out of the prevaling northwestern winds east and west of the Rhône valley (Fig. 2).

Several types of regional variations may also be observed:

At Cape Drammont (French Riviera) most specimens gave aberrant dates. Further examination showed that the latter samples had been contaminated by younger material and that some others were mainly built up by corallines other than *Lithophyllum lichenoides* and hence could not be used as sea-level indicators.

At Banyuls (Franco-Spanish border) and Islas Medes (north of Barcelona, Spain) a similar case occurred. Consequently the study of the latter regions was postponed, waiting for further development of methods with a finer degree of spatio-temporal resolution.

In the near vicinity of large cities such as Marseilles or Toulon, the recent development of marine pollution leads to a strong increase of marine bioerosional factors, which, in turn, may rapidly destroy the living *Lithophyllum* rims as well as their submerged remains (Morhange et al., 1992).

3.2. *Results of datings*

More than 80 samples were dated, including 8 for calibration or for comparing new datings with our former data series. Out of the remaining specimens, 10 yielded datings obviously too young, which proved to be due to contamination by younger biological material, and had to be put aside.

Couples of age–depth values were then arranged on diagrams for each station, without construction of a curve and with indication of error boxes (Kidson, 1986) (Table 1; Figs. 7–9).

3.3. Statistical analysis of data

Our first sorting of the data (adjusted mean) gave a list of stations of increasing age at the standardized depth of 0.77 m ($F_{\mathrm{dss}}=7.2$; $P<0.05$) (Table 3).

After an a posteriori SNK test, the 1983 Port Cros station was found to be significantly ($P<0.05$) offset from the other stations and 678 years younger than corresponding mean date of the 1992 Port Cros station. A significant, although slighter difference was also observed between the Palazzu 1983 and Palazzu 1992 stations. We interprete the latter discrepancies as technological differences between datings done ten years apart by two different laboratories. For that reason an extra ANCOVA was made after discarding all the older dates and allowed a sorting for a new mean depth of -0.8 m (Table 4).

This new sorting is more homogeneous ($F_{\mathrm{dss}}=2.32$, $P=0.6$), and Corsican dates appear to be slightly older for a given depth than their continental counterparts.

Table 5 gives the slope (*a*) (expressed in years per metre), along with the standard deviation (*SD*) for two different depth levels (above and under -0.25 m, mean depth of the base of the present rim) and the average rate of sea-level rise expressed in millimetres per year:

Comparison of the slopes by the test of Student ($t=1.96$ and $0.025<P<0.05$) indicated that the slope (*a*) of the upper part (0 to -0.25 m) of the curves was significantly steeper than for the part deeper than 0.25 m, indicating that the rate of sea-level rise decreased significantly when it neared the present datum.

4. Discussion

Although the general pattern we obtain for the last 4500 years in northwestern Corsica and continental southwestern France fits at first sight, with the upper part of the curve from Barbados (Bard et al., 1990), it is now widely admitted that local curves of sea-level variations should not be directly compared to other local curves or to global models obtained from paleoclimatic and glacial studies, since the former are the resultant of climatic phenomena as well as of complex local tectonic trends and isostatic reactions (Kidson, 1986).

4.1. Tectonic background

Bonifay (1980) recently gave a survey of local tectonic tendencies of the different regions of the northwestern Mediterranean basin. According to Bonifay several types of tectonic zones may be recognized:

– A *northern elevated arc* with an upward movement, north of Montpellier and Arles, including the littoral region of Nice and Menton (De Lumley, 1976; Dubar et al., 1992), with raised Pleistocene beaches several tens of metres to 100 m above present datum.

– A *slightly subsiding littoral zone*, including the lower Provence west of Toulon with the younger Pleistocene interglacial shorelines around or slightly below present level (Bonifay and Courtin, 1980). The Hercynian region of the Maures is, nevertheless, generally considered as very stable (Oliver Barros and Fonteilles, 1980).

– *Local subsidence is stronger in the region of the Rhône delta* and in tectonically active areas such as the Gulf of Fos and the region of Marseilles (Monguilan et al., 1977).

– *Elevation movements* are observed near the Etang de Berre and west of the Rhône valley (Ambert et al., 1980).

– *Northern Corsica and the continental French littoral zone between Toulon and Fréjus* seem to have been rather stable since Pliocene times (Conchon, 1977; Froget, 1974) with Pleistocene pebble beaches a few metres above present level (Chamley, 1969, 1976; Chamley et al., 1971).

Unfortunately these various trends are difficult to quantify except by direct observation (Fourniguet, 1987; Le Notre, 1990), since most of the Pleistocene shorelines reported are either fossil pebble beaches without any datable fauna or submerged morphological features. Very few isotopic datings, if any, are available and their degree of reliability is low.

Table 1
Radiocarbon dated obtained on *Lithophyllum* in 1991–1992. L.G.Q. = *Laboraoire de Géologie du Quaternaire*, Marseille (R. Lafont)

Id. no.	Locality	Depth (m)	Accuracy (m)	Age B.P.	2 *SD* (years)	Observations
LGQ 835	Giraglia	0.2	0.2	1050	120	thick rim
LGQ 836	Giraglia	0.65	0.1	2340	130	
LGQ 837	Giraglia	0.75	0.1	2640	130	
LGQ 838	Giraglia	1	0.1	3120	120	
LGQ 839	Centuri	0.3	0.2	1730	130	thick rim
LGQ 840	Centuri	0.45	0.2	830	120	thick rim
LGQ 841	Centuri	0.85	0.1	2960	130	
LGQ 842	Centuri	1	0.1	3580	130	
LGQ 843	Centuri	1.2	0.1	3470	150	
LGQ 804	LC 1/Cannier	0.05	0.1	140	110	
LGQ 803	LC 1/Cannier	0.08	0.1	150	120	
LGQ 802	LC 1/Cannier	0.11	0.1	670	120	
LGQ 801	LC 1/Cannier	0.15	0.1	960	120	
LGQ 799	LC 1/Cannier	0.2	0.1	510	120	
LGQ 800	LC 1/Cannier	0.25	0.1	1360	120	
LGQ 797	LC 1/Cannier	0.3	0.1	540	120	
LGQ 798	LC 1/Cannier	0.3	0.1	1200	120	
LGQ 760	LC 1/Cannier	1	0.1	3420	130	
LGQ 763	LC 1/Cannier	1.15	0.1	3420	130	
LGQ 761	LC 1/Cannier	1.2	0.1	3200	130	
LGQ 762	LC 1/Cannier	1.6	0.1	4350	130	
LGQ 773	LC 2/Gameu	0.1	0.1	810	120	
LGQ 769	LC 2/Gameu	0.38	0.1	1590	130	
LGQ 768	LC 2/Gameu	0.75	0.1	2530	120	
LGQ 764	LC 2/Gameu	0.85	0.1	2850	130	
LGQ 770	LC 2/Gameu	0.9	0.1	2900	130	
LGQ 765	LC 2/Gameu	1.2	0.1	3750	130	
LGQ 766	LC 2/Gameu	1.2	0.1	3160	130	
LGQ 767	LC 2/Gameu	1.3	0.1	3370	140	
LGQ 823	Port Cros 92	0.75	0.1	2140	130	contaminated
LGQ 829	Port Cros 92	0.8	0.1	2730	130	
LGQ 821	Port Cros 92	0.95	0.1	2510	140	contaminated
LGQ 826	Port Cros 92	1	0.1	2600	120	
LGQ 825	Port Cros 92	1.1	0.1	2850	140	controlled
LGQ 832	Palazzu 92	0.3	0.1	1450	130	
LGQ 834	Palazzu 92	0.5	0.1	2300	130	
LGQ 833	Palazzu 92	1	0.1	3270	140	
LGQ 775	Mèdes	0.3	0.1	2270	130	
LGQ 866	Drammont	0.3	0.1	1120	120	contaminated
LGQ 703	Drammont	0.3	0.1	2330	130	
LGQ 697	Drammont	0.65	0.1	2800	130	
LGQ 698	Drammont	0.8	0.1	1050	120	contaminated
LGQ 699	Drammont	0.9	0.1	1880	120	contaminated
LGQ 700	Drammont	1.1	0.1	1840	120	contaminated
LGQ 702	Drammont	1.5	0.1	1540	130	contaminated
LGQ 701	Drammont	1.6	0.1	2490	130	contaminated
LGQ 860	Cap Ferrat	0	0	170	110	present
LGQ 859	Cap Ferrat	0.1	0.1	1310	120	
LGQ 682	Giens 91	0.4	0.1	1750	120	
LGQ 683	Giens 91	0.6	0.1	2200	130	
LGQ 684	Giens 91	0.8	0.1	2340	130	
LGQ 685	Giens 91	0.95	0.1	1030	120	contaminated

Table 2
Radiocarbon dates obtained on *Lithophyllum* samples in 1982–1983. Gif=CNRS, Gif sur Yvette (G. Delibrias), PA=*Université Pierre et Marie Curie* (R. Letolle)

Id. no.	Locality	Depth (m)	Accur. (m)	age B.P.	2 *SD* (years)	Observations
Gif 5922	Port Cros 83	0.25	0.1	820	60	
Gif 6344	Palazzu 83	0.25	0.1	210	60	unconsolidated thalli
Gif 5620	Palazzu 83	0.25	0.1	150	80	unconsolidated thalli
Gif 5916	Port Cros 83	0.47	0.1	1100	60	LGQ 864: 1240±140
Gif 5917	Port Cros 83	0.67	0.1	1530	60	
Gif 5918	Port Cros 83	0.8	0.1	1430	80	contaminated
Gif 5919	Port Cros 83	1.25	0.1	2650	70	LGQ 865: 2840±190
Gif 5920	Port Cros 83	0	0	0	0	living thalli
Gif 5921	Port Cros 83	0.07	0.05	300	60	
Gif 5923	Port Cros 83	0.5	0.1	1490	60	
Gif 6345	Palazzu 83	0.4	0.1	1720	60	ctrl. LGQ 861: 1740±140
Gif 6346	Palazzu 83	0.8	0.1	2570	70	
Gif 6347	Palazzu 83	0.9	0.1	2700	80	
Gif 6348	Palazzu 83	1.1	0.1	3200	70	
Gif 6349	Palazzu 83	1.45	0.1	3530	70	ctrl. LGQ 863: 3650±120
Gif 6518	Palazzu 83	0.7	0.1	2340	70	ctrl. LGQ 862: 2160±180
Gif 6519	Palazzu 83	0.9	0.1	2230	70	contaminated
PA 126	Palazzu 83	1.5	0.1	3865	50	

Table 3
Computer sorting of stations of increasing age (adjusted mean) for the standardized average depth of −0.8 m including samples collected and dated in 1983 and 1992

Locality and date of collecting	^{14}C age at −0.8 m (adjusted mean)
Port Cros 1983	1703 yrs B.P.
Port Cros 1992	2373 yrs B.P.
La Ciotat 1 (1992)	2411 yrs B.P.
Palazzu 1983	2416 yrs B.P.
Giens 1992	2465 yrs B.P.
Giraglia 1992	2560 yrs B.P.
La Ciotat 2 (1992)	2522 yrs B.P.
Palazzu 1992	2708 yrs B.P.
Centuri 1992	2794 yrs B.P.

Table 4
Computer sorting after discarding all the older dates and for a calculated mean depth of −0.8 m

Locality and date of collecting	^{14}C age at −0.8 m (adjusted mean)
Port Cros 1992	2411 yrs B.P.
Giens 1992	2530 yrs B.P.
La Ciotat 1,1992	2574 yrs B.P.
La Ciotat 2 1992	2591 yrs B.P.
Giraglia 1992	2721 yrs B.P.
Palazzu 1992	2774 yrs B.P.
Centuri 1992	2860 yrs B.P.

Our results for the western Provence and Corsica indicate a relative sea-level rise at a rate of about 0.4 mm per year from 4500 yr B.P. to about 1300 yr B.P. slowing off to about 0.2 mm per year from 1300 yr B.P. to a very recent period. The present rim was built between 1000–900 yr B.P. and present. Our dates are also in concordance with those obtained from the ancient harbour of Marseilles (Pirazzoli and Thommeret, 1973; Morhange, 1994).

Although our results are coherent with the model proposed by Bonifay (1980), we cannot yet separate the climatic component of the rise with a tectonic or hydro-isostatic origin (Chappell, 1974; Clark, 1980).

4.2. Regional differences

Regional differences are difficult to put into evidence:

Corsican samples are slightly older for a given depth than their mainland counterparts. Such a

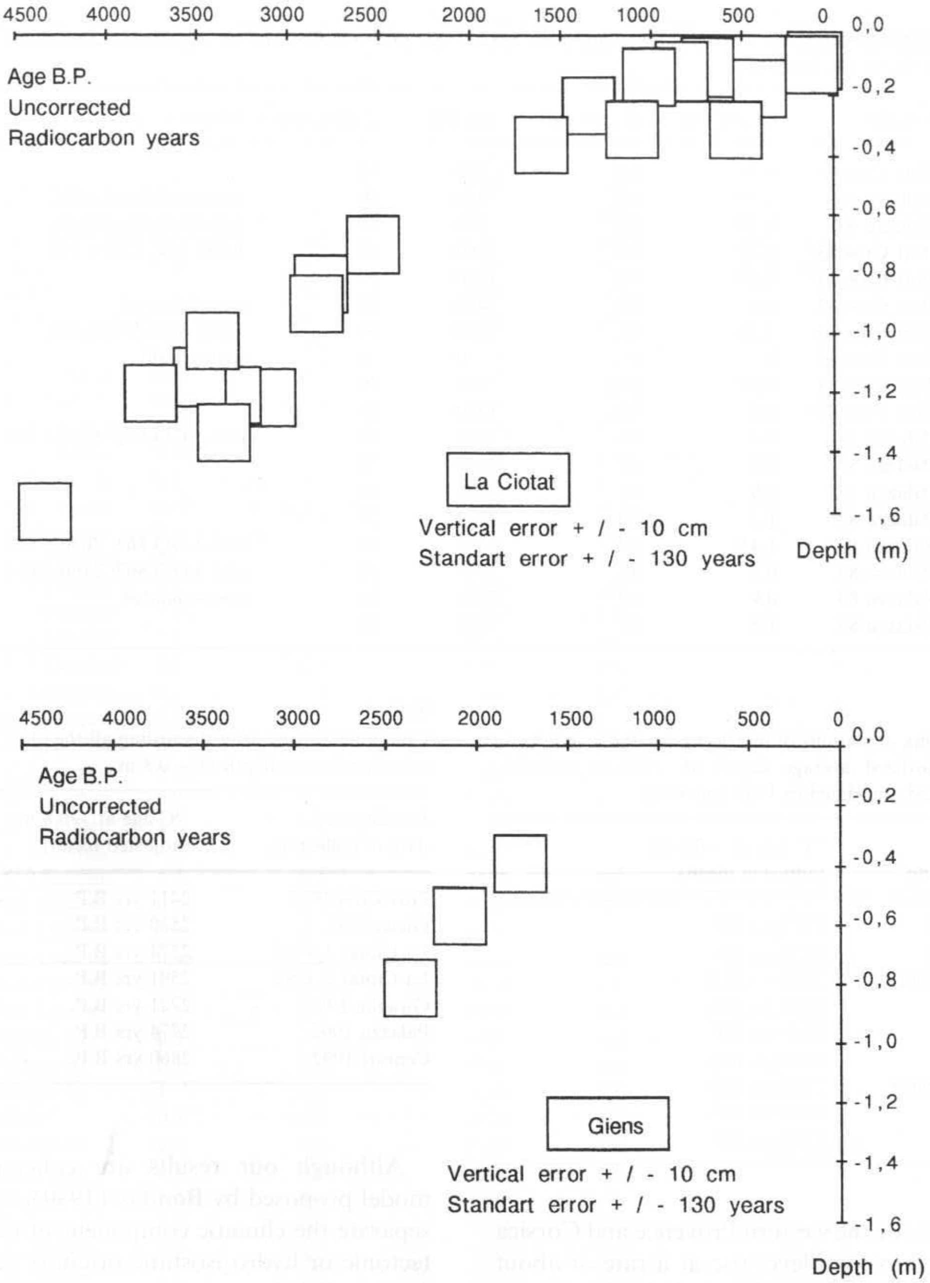

Fig. 7. Age versus depth graph for the stations at La Ciotat and Giens. Each couplet is represented with an error box corresponding to the vertical estimation error and standard age.

difference, if found significant, would be coherent with the slow rate of tectonic submergence generally admitted for Corsica (Conchon, 1980).

At the periphery of study area, scarcity and bad preservation of *Lithophyllum* remains in the Alpine (Nice, Menton and northern Italy) and Pyrenean (Banyuls and l'Estartit) areas may be interpreted in part as the result of lesser rim development due

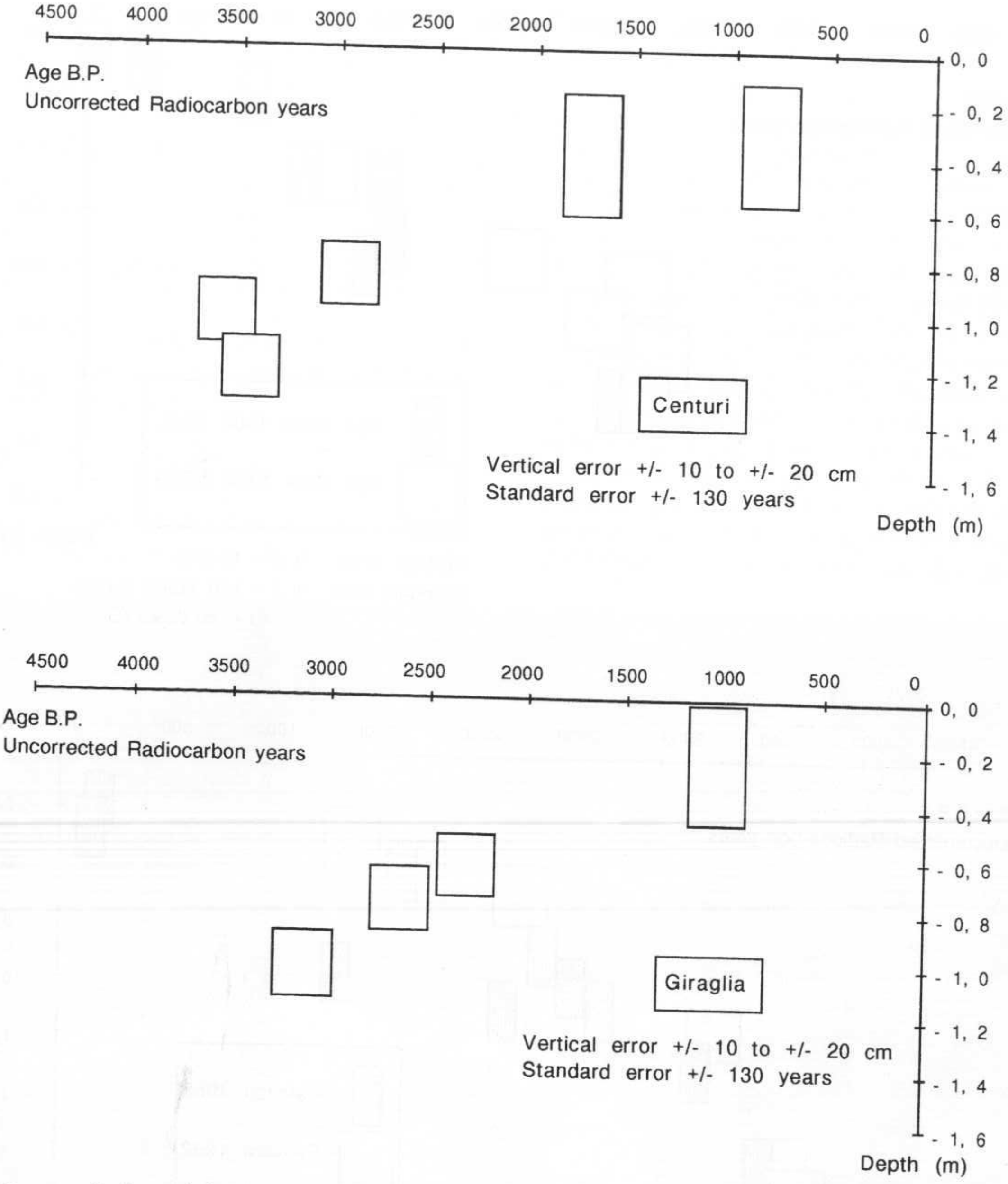

Fig. 8. Age versus depth graph for the stations at Centuri and Giraglia (northern Corsica). Each couplet is represented with an error box corresponding to the vertical estimation error and standard age.

to adverse oceanographic conditions and strong bioerosion (as discussed above), but they may also be related to regional upward tectonic trends during the Holocene (Bonifay, 1980; Dubar, 1987; Dubar et al., 1992) which would not allow the development of important rims.

We have very few correct dates of uncontaminated material from the latter regions (Table 6). Although too few in number to be significant, these dates may nevertheless indicate a general upward crustal trend, since their age is old for their average depth compared with the average

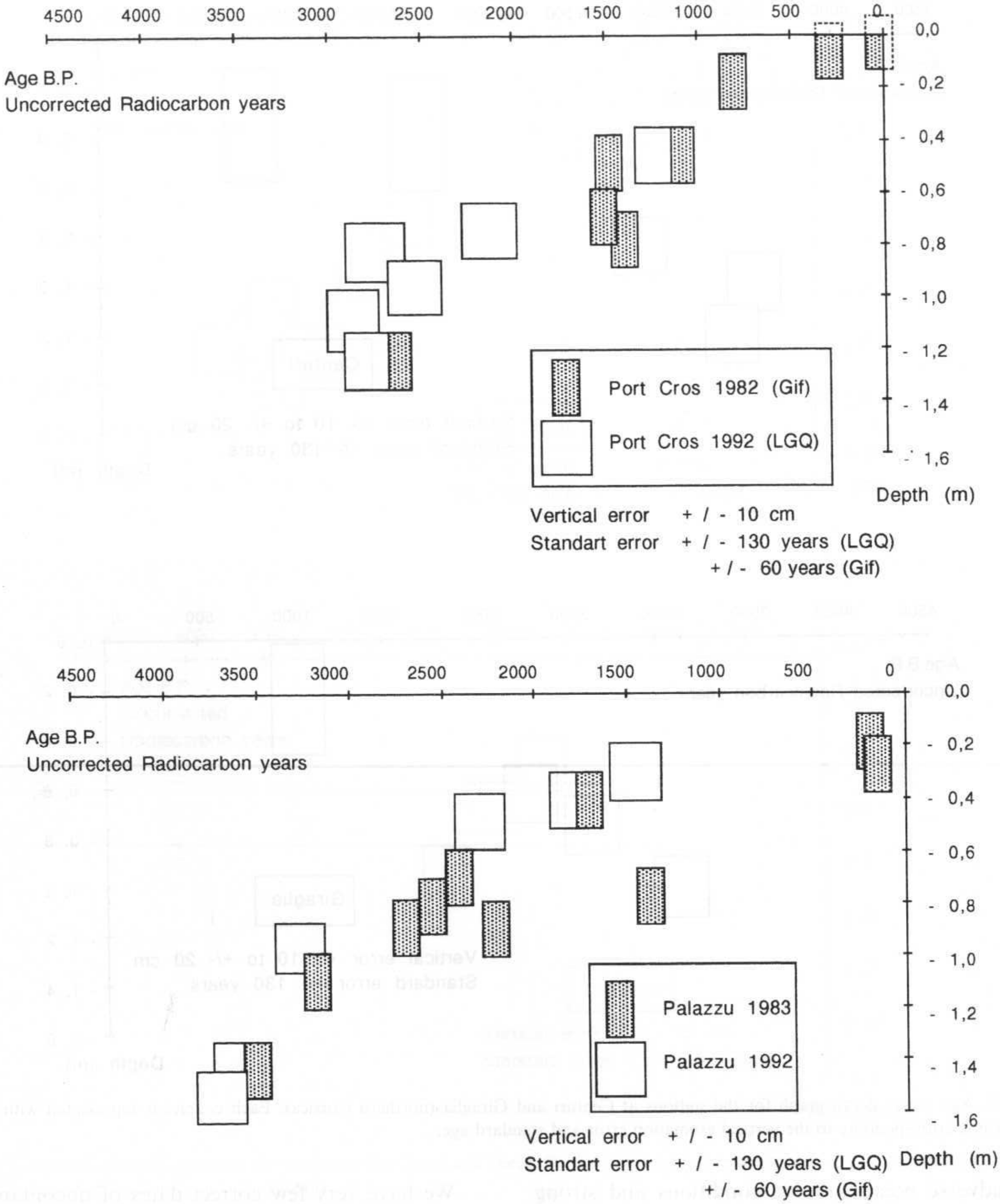

Fig. 9. Age versus depth graph for the stations at Port Cros (southern France) and Palazzu (northern Corsica). Each couplet is represented with an error box corresponding to the vertical estimation error and standard age.

Table 5
Slope (*a*) (expressed in years per metre), standard deviation (*SD*) for two different depth levels of *Lithophyllum* remains above and under −0.25 m (mean depth of the base of the present rim) and calculated average rate of sea-level rise expressed in millimetres per year

Depth level	(*a*) in ^{14}C years	*SD*	Rate of sea-level rise
>0. 25 m	4226.10	1193.73	0.24 mm per year
<0.25 m	2054.84	239.13	0.49 mm per year

value of 2400–2800 years at the depth of 0.80 m observed in the continental western Provence and northwestern Corsica.

4.3. *Problem of standstills*

Our first results (Laborel et al., 1983) suggested that the rise of sea level during the last few millennia had not been a smooth one but had been relatively irregular. Statistical analysis of our present data does not support this first impression, due to the relative lack of accuracy of both altitudinal levelling and of radiocarbon dating.

Since visual observation of the spatial distributionof drowned remains presents an alternance of major and minor submerged rims, we are presently starting a new programme of high precision levelling and topographic study, using pneumatic tools for complete dissection of the submerged remains on several vertical profiles, coupled with more precise dating. So the dilemma between minor standstills followed by small scale accelerations versus a smooth rise is not settled yet.

We had also observed periods of erosion alternating with renewed algal development in the inner structure of the present rim (Laborel et al., 1983), but they could not be dated with reasonable

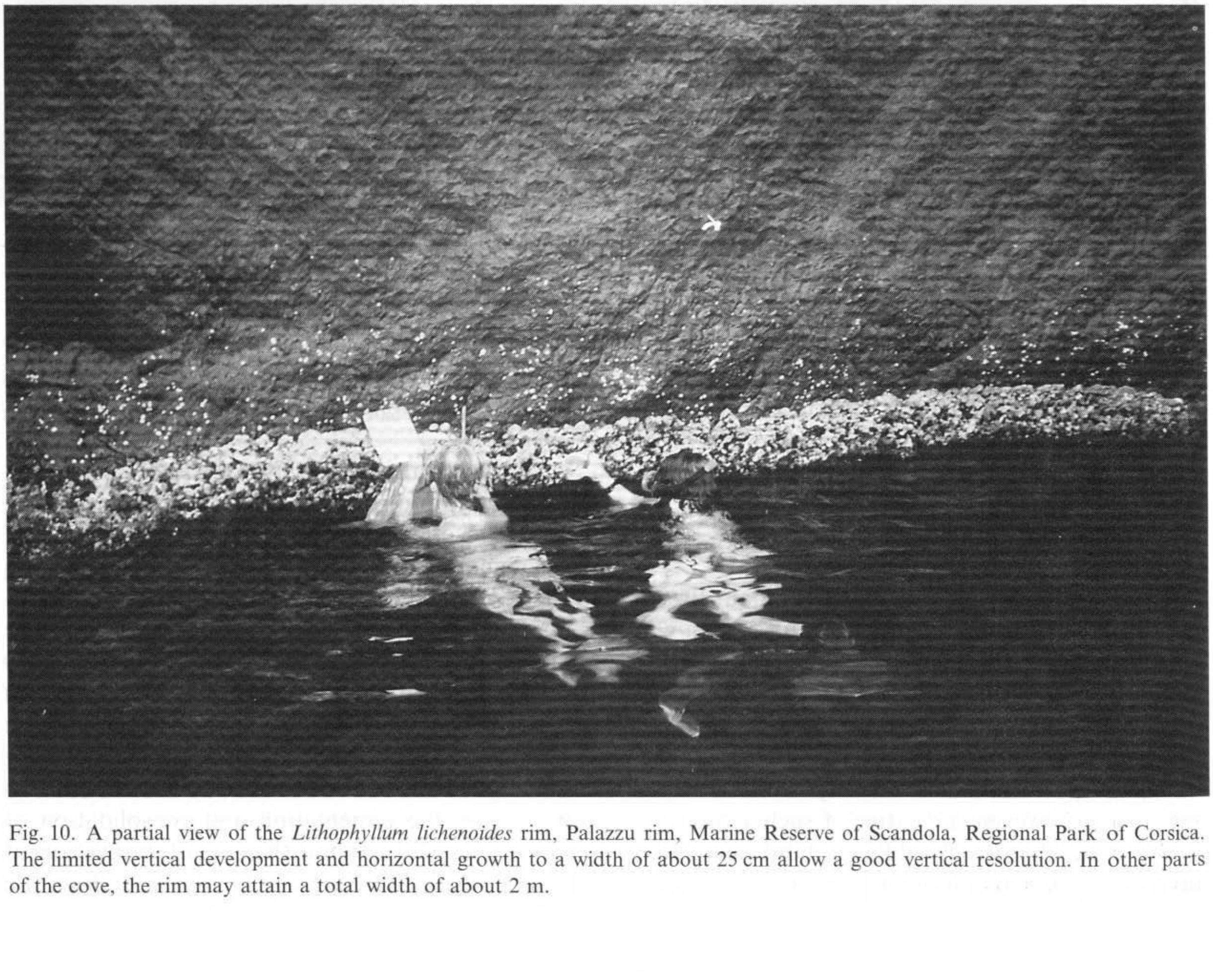

Fig. 10. A partial view of the *Lithophyllum lichenoides* rim, Palazzu rim, Marine Reserve of Scandola, Regional Park of Corsica. The limited vertical development and horizontal growth to a width of about 25 cm allow a good vertical resolution. In other parts of the cove, the rim may attain a total width of about 2 m.

Fig. 11. Section through the present rim at La Ciotat. Algal thalli appear in white and cemented areas in brown. Several horizontally superposed layers of hardened thalli are also visible. The length of the specimen is about 20 cm.

accuracy by the current methods of radiocarbon dating and it could not be decided yet whether such discontinuities were due to atmospheric factors or to centimetric sea-level oscillations of climatic origin.

4.4. *Secular sea-level rise*

The secular rise of sea level of about 10 cm beginning at the end of the last century which was recently put into evidence by maregraphic data (Pirazzoli, 1976, 1986; Blanc and Faure, 1990), could not be checked by radiocarbon dating since it is too recent. A number of morphological and biological features on the rocky coasts of our region are, however, indicative of such a rise:

On many hard-rock cliffs without any tidal notch, populations of living *Lithophyllum* have their upper limit about 20–40 cm above the upper surface of the rim, which is generally dead and covered by sublittoral weeds (Morhange et al., 1992).

On limestone cliffs near Marseilles, a conspicuous filling-up of the upper part of the tidal notch by unconsolidated living *Lithophyllum* is a feature of common observation (Fig. 13) which was studied in detail by Dalongeville (1986). The drawings of figs. 152–158 of Dalongeville (1986) are highly characteristic.

Since the rate of development of *Lithophyllum* is strong (about 1–3 cm per year; Boudouresque et al., 1972), their thalli are able to closely follow the movements of the water surface and to anticipate upon the cementation and consolidation of the rim as well as upon the rate of excavation of tidal notches (about 1 mm per year at best; Le

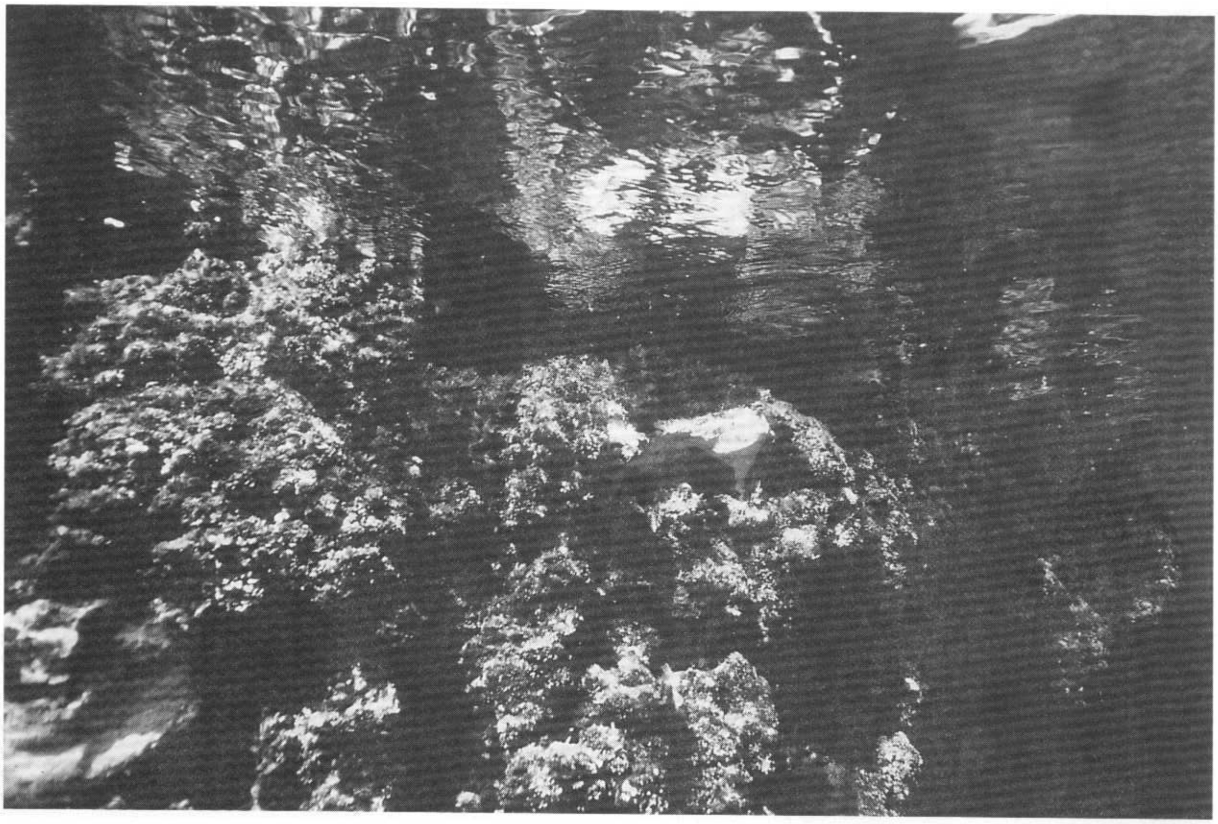

Fig. 12. Underwater wiew of the submerged part of the cliff, below the present rim. Palazzu, Marine Reserve of Scandola (Corsica). The present *Lithophyllum* rim is completely out of the water, like in Fig. 10 and cannot be seen. Submerged remains capped by shade loving Coralline algae are visible on the cliff. In two places, near the water surface at right of the picture and about 1 m deep at the left, two specimens have been broken for dating whose scars appear as white blotches on the dark ground of the cliff.

Table 6
Isolated dates of uncontaminated *Lithophyllum* submersed samples from regions outside the main zone of study

Sample	Locality	Depth	Uncorrected ^{14}C age
LGQ 860	Cap Ferrat	-0.1 ± 0.1 m	1310 ± 120 yr B.P.
LGQ 703	Drammont	-0.3 ± 0.1 m	2330 ± 120 yr B.P.
LGQ 775	Islas Mädes	-0.3 ± 0.1 m	2270 ± 130 yr B.P.

Campion-Alsumard, 1970). It is thus clear that the upward displacement of the upper limit of living thalli is a very good indicator of a rapid elevation of the water level. Although a number of local factors may alter the vertical distribution of thalli, we nevertheless think that the latter examples are coherent with a rise of about 10 cm during the last century. Such a rise, if firmly established, would correspond to a secular rise of about 1 mm/year, strongly contrasting with the former rate of 0.2 mm established above.

Our dates do not go back to before 4500 yr B.P., due to the importance of marine bioerosion in our area of study. So, the present study does not cover the period 5000–6000 yrs B.P., for which a number of sea-level stands at or just above the present level have been reported for several parts of the world (Pirazzoli, 1991).

Dated Holocene sea-level stands in our study area are very scarce: the marine fauna sampled at −24 m and dated 5800 yr B.P., in the Grotte des Trémies, an underwater cave a few kilometres west from La Ciotat (Bonifay et al., 1971), indicates shallow water conditions but not a clear cut shoreline so it cannot be retained. One of us (S.S.) is

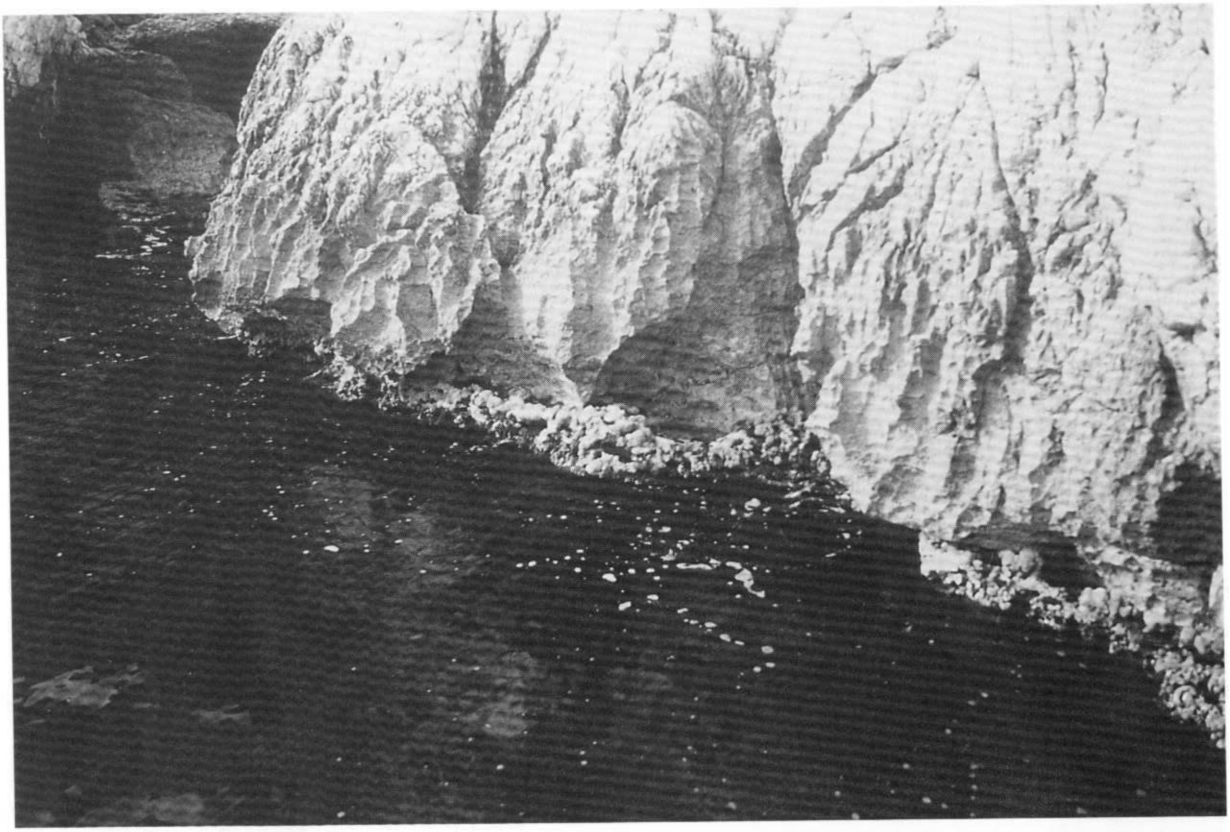

Fig. 13. On middle Cretaceous limestone cliffs, near Marseilles, the midlittoral wave cut notch is partly infilled by the development of the present *Lithophyllum* rim. This disposition is coherent with the sea-level rise of about 10 cm during the last century.

presently trying to get new evidence in deeper waters by coring and dating the basal layers of various types of underwater bioconstructions in the hope that the date of their formation could be correlated to the rise of the water level.

During the course of the present study we have never found any fossil remains of *Lithophyllum* above the present living range of the species, or any indication, whether morphological or else of a very recent stand above present level. Extrapolating the trend observed in our best documented stations (La Ciotat, Palazzu, La Giraglia) would place the sea-level at 6000 yr B.P. about 2.5–3.0 m below present level. The only known case of a Holocene sea-level stand higher than present (+2 m) on the French Mediterranean coasts was recently reported at Cape Romarin, near La Nouvelle (Aloisi et al., 1978; Ambert et al., 1980), but it was not dated directly. A very recent survey allowed us to find biological material in situ (*Chthamalus* barnacles) which is still in the process of dating at the Tandetron in Gif sur Yvette (Dr. M. Arnold). However, Cape Romarin lies in a region with tectonic characteristics very different from the coasts of the Provence and northern Corsica.

In the lack of positive evidence, the negative proof of the non existence of a recent relative sea-level stand above present datum in our region is supported by the recent discovery of a group of horses of late Paleolithic age painted on a wall in the half-submerged "Cosquer cave" near Marseilles (Clottes and Courtin, 1992). Legs and bellies of the horses have been gradually destroyed by water from about 50 cm above the present water level downward to the surface. This destruction occurred only inside the limits of the present range of sea-level variation in the cave (in relation with tides and changes of atmospheric pressure). Would the sea-level recently have attained a value higher than its present one, then these pictures would have been destroyed up to a higher level.

Since the tectonic conditions in the region of Cape Romarin are different from those prevailing in the more stable regions of Var and Corsica (Bonifay, 1980), we conclude that the high level found in the former place is not a general feature and cannot be generalized to the western Mediterranean region. The possibility of a yet undetected oscillation, with a maximum slightly under the present level cannot be completely discarded.

In conclusion, our results are coherent with local archaeological and sedimentological evidence (Pirazzoli, 1976, 1991). Although affected by the relatively low resolution of radiocarbon in its nearest age range and by some uncertainties inherent to the use of biological indicators, they allow a good accuracy, unbiased by sediment compaction, reworking and other drawbacks common to sedimentary indicators.

We hope that, in the scope of a current C.E.E. project, higher resolution studies will be possible in places where the fossil record is best preserved and that new regional studies will be developed.

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