Reports

Sea Level Variations in the Northwest Mediterranean During Roman Times

Abstract. *Archeological remains indicate an average rise of sea level of 7.5 centimeters per 100 years from 300 B.C. to A.D. 150. At A.D. 0 mean sea level was about 0.5 meter below the present value. Eustatic fluctuations have not exceeded 0.15 meter.*

The Provençal and Tyrrhenian coasts, from Marseilles (France) to Formia (Italy), display several archeological remains that allow an accurate reconstruction of former sea levels. Although seismic activities have been reported from time to time in these regions, mainly in Italy, their tectonic effects seem to have produced major vertical displacements only in some limited areas: Populonia and, on the same axis, the islands Elba and Pianosa; the volcanic region of Naples; and probably also the islands Ponza and Ventotene (*1*). The data from these tectonic areas, as well as those from the subsiding Rhone delta region, west of Marseilles, have not been taken into account.

Up to the present, the remains of the investigated area have mostly been studied from a local archeological point of view, and wide-scale synthesis relative to former sea levels has seldom been attempted. Benoit (*2*) and Denizot (*3*) infer that sea level has not changed since Roman times along the French coasts. Flemming (*4*) believes that sea level was stable in the whole western Mediterranean. However, according to Denizot and Flemming, sea level stability does not preclude variations of ± 50 cm. On the other hand, a sea level rise of about 1 m is suggested for the Tyrrhenian coasts of Italy and for the same period by Schmiedt (*5*) and for the Latium coasts by Pongratz (*6*). In this report I present a more precise interpretation of the data from the French and Italian coasts.

Eighteen Roman remains have been investigated. They include a fountain house for supplying water to boats, a harbor wharf, two sewer canalizations, an aqueduct, some unidentified remains, and 12 piscinae. Heights are referred to present mean sea level.

The fountain house. In the inner ancient harbor of Cosa (*5, 7*) the water of a fountain is taken across the dock by a narrow channel at 0.14 m and then discharges into the canal. Lower down, at −0.66 m, a step is found, on which amphorae were formerly filled. Assuming that the step was above water at the time of construction (200 to 150 B.C.), a sea level rise of at least 0.8 m may be deduced.

The wharf. In Marseilles harbor, a line of fossil barnacles remains affixed to the wall of the Roman wharf. Identification and radiocarbon dating of the cirripedes allow an estimate of about 0.5 m for sea level rise since A.D. 100 ± 75 (*1, 8*).

Sewer canalizations can have a good discharge only if the outlet base is situated higher than high-tide level. Accordingly, a sea level rise of at least 0.3 m since Roman times may be inferred in La Vieille–Couronne cove (*3*) and a rise of at least 0.6 m since 177 B.C. at Luni (*5*).

The aqueduct at Varignano was built of masonry in about 50 to 40 B.C. Its bottom is now submerged under 0.5 m of groundwater, which is at the same level as seawater and fluctuates with tide. Submergence here is at least 0.5 m.

Some *unidentified remains* (Roman piscinae?) may be found in Orbetello lagoon, hugging Feniglia's tombolo, submerged under up to 0.5 m of seawater and indicating a sea level rise of at least 0.6 m.

Roman piscinae are either completely cut in shore platforms, partly built, or

Table 1. Main archeological remains from the Provençal and Tyrrhenian coasts.

Locality			Latitude (N)	Longitude (E)	Age	Position of dated sea level below present one (cm)	
No.	Name	Type of remain				Minimum	Maximum
1	La Vieille-Couronne	Sewer	43°19′45″	5°03′22″	Roman times	30	
2	Marseilles	Wharf	43°17′50″	5°22′ 0″	A.D. 100 ± 75	40	60
3	La Gaillarde	Piscina	43°21′27″	6°42′56″	Roman times	70	20
4	Antibes	Piscina	43°35′10″	7°07′35″	Roman times		50
5	Varignano	Aqueduct	44°03′49″	9°50′31″	50–40 B.C.	50	
6	Luni	Sewer	44°03′51″	10°00′57″	177 B.C.	60	
7	St. Liberata	Piscina	42°26′08″	11°09′02″	A.D. 81–96	45	
8	Orbetello	Unclear	~42°25′	~11°14′	300–280 B.C.	60	
9	Cosa	Fountain	42°24′35″	11°17′37″	200–150 B.C.	80	
10	Giglio Island	Piscina	42°21′23″	10°55′22″	A.D. 50–100	40	60
11	Torre Valdaliga	Piscina	42°07′28″	11°45′29″	50–25 B.C.	40	65
12	Mattonara	Piscina	42°06′44″	11°46′15″	50–25 B.C.	40	65
13	Vipera Point	Piscina	42°02′28″	11°49′41″	27 B.C.–A.D. 14	45	
14	Grottacce	Piscina	42°02′00″	11°52′17″	~A.D. 50	40	
15	Astura	Semicircular piscina	41°25′50″	12°43′52″	27 B.C.–A.D. 14	50	
16	Astura	Rectangular piscina	41°25′12″	12°44′51″	27 B.C.–A.D. 14	50	
17	Cape Circeo	Piscina	41°15′00″	13°02′38″	A.D. 50–100		45
18	Formia	Piscina	41°15′21″	13°36′45″	End first century B.C.	40	

wholly built. Construction differences are strictly correlated with the morphological characteristics of the coast. Dated by the nearby Roman structures, many piscinae clearly define the upper and lower limits of sea level at the time of their construction.

Estimates of the upper limits are based on the measurement, relative to mean sea level, of the present height of the top of some parts (surrounding walls, partition walls between basins, shore benches in which channels for water supply have been cut, and grooves for sliding of water gates and of fishing nets) and on the assumption that these parts were above water at high tide. Estimates of the lower limits are mainly based on the fact that with less than 5 or 10 cm of water at high tide over the bottom of the channels or at the basin entrances, water or fry inflow would not have been possible (*5*).

Finally, the so-called piscina of Lucullo, at cape Circeo, is worth special attention. This piscina is formed by several basins, three of which contain some lines of small amphorae used for fry culture and cemented to the basin walls. High-tide level cannot have been lower than the higher line of amphorae, and this implies a mean sea level lower than the present one by less than 0.45 m.

Table 1 summarizes the available information. For locations, see Fig. 1. Typical tidal range values in the region vary from 0.1 to 0.3 m. The difference in height between the annual highest and lowest tides does not normally exceed 0.3 or 0.4 m. Age and depth for each datum have been plotted in Fig. 2.

The data, on a whole, show remarkable consistency over more than four centuries and for nearly 1000 km of coasts. Two least-square lines have been calculated for the 15 best-dated remains.

The upper-limit line is

$$H = 0.0771T - 45.92$$

where ancient sea levels (H, in centimeters) are related to present mean sea level, and time T is expressed in years B.C. (−) or A.D. (+). The average rise is about 7.7 cm per 100 years between 300 B.C. and A.D. 150. The deviation is always less than 10 cm, except for Cosa (20 cm), and the standard deviation is 7.41 cm.

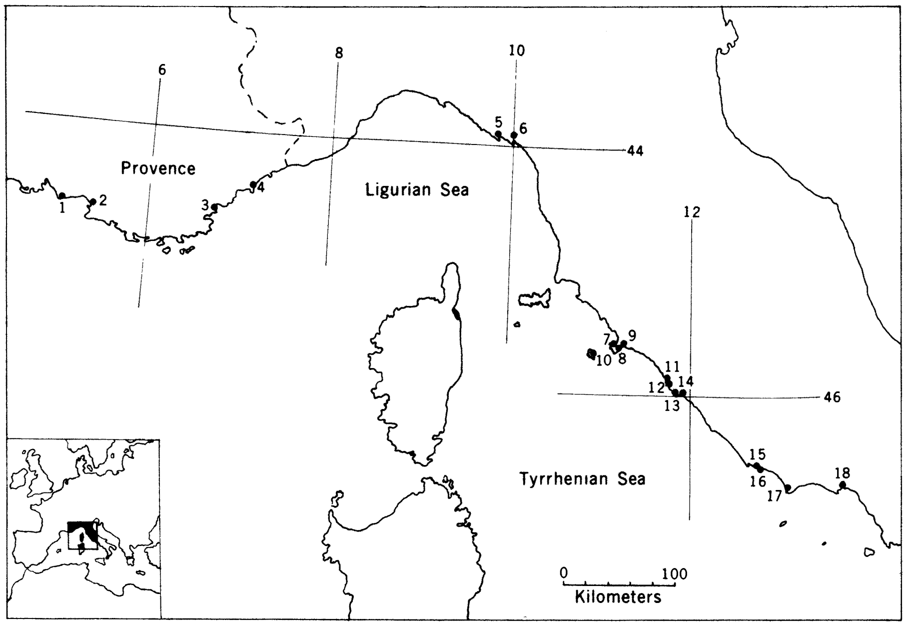

Fig. 1. Location map of the investigated archeological remains.

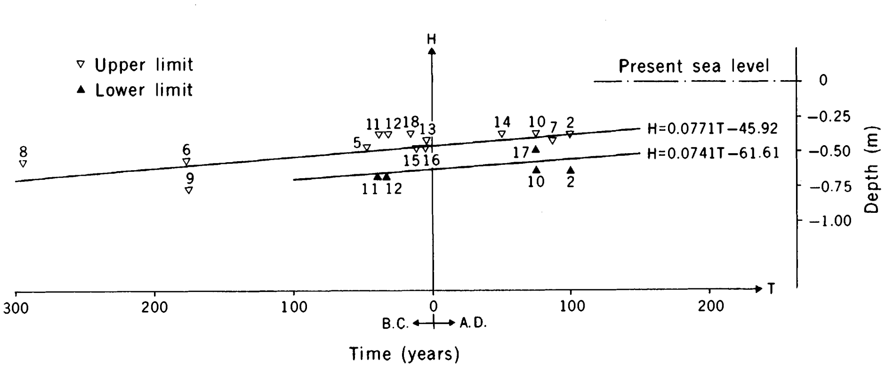

Fig. 2. Archeological data mark upper and lower limits of past mean sea levels in the northwest Mediterranean. They indicate an average sea level rise of 7.5 cm per 100 years without major fluctuations. See Table 1 for localities.

The lower-limit line is

$$H = 0.0741T - 61.61$$

and shows a similar average rise of 7.4 cm per 100 years between 50 B.C. and A.D. 150. The standard deviation is 5.85 cm. The two lines are almost parallel, 15 to 16 cm apart.

To determinate the eustatic sea level at a particular period an absolute reference basis would be necessary, but none is available. The data from a single coastal region, even an apparently stable one, are therefore not adequate for a general conclusion about eustatic changes, as the existence of vertical displacements on a regional or even continental scale may hardly be left out (*1*). Consequently, sea level of the Tyrrhenian area may not be fully representative of the eustatic situation.

On the other hand, a short-lived sea level fluctuation can be determined even by reference to the local and relative bases. Moreover, a possible eustatic fluctuation would have left marks on the shores all over the world, even on uplifting or subsiding coasts. It is therefore possible from the data for the Tyrrhenian coasts to draw some conclusions that are applicable to sea level changes on other coasts. The "Romano-British transgression" or the simultaneous "Roman emergence" (*bas niveau romain*), which have been postulated along the North Sea (*9*), the English Channel and the French Atlantic coast (*10*), in Japan (*11*), or on a global scale (*12*), now appear in a broader perspective.

At Roman times, sea level was effectively a little lower than at present, at least in the northwest Mediterranean. Its slow rise must have produced transgressions in several coastal regions. However, the archeological remains of the "tideless" Provençal and Tyrrhenian coasts do not indicate large variations of sea level. The 2- to 3-m fluctuations suggested by some authors for other coastal regions should therefore be ascribed to noneustatic causes: local tidal changes, storm surges, tectonics, climate changes, or misinterpretations.

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Potassium Accumulation in Muscle: A Test of the Binding Hypothesis

Abstract. *Living frog skeletal muscle can accumulate potassium in vitro to concentrations up to 580 millimolar. Both the amount of potassium accumulated and the relationship between intracellular and extracellular potassium concentrations indicate that potassium is "free" under all conditions, rather than bound to cellular macromolecules. The data also indicate that at most 20 percent of the cell water is "bound" in the sense that it excludes electrolytes.*

Several reports (*1, 2*) have recently been published in support of the association-induction hypothesis of Ling (*3*). According to this theory, intracellular ion and nonelectrolyte contents are controlled not by membrane permeability and active transport, but by selective binding to cellular macromolecules and by exclusion by "ordered" or "bound" water. Thus, Na is kept at low concentrations within cells because of a low partition coefficient between cell water and extracellular water, whereas K is abundant within the cell in spite of this reduced ionic solubility because it is bound to intracellular charged sites with high selectivity over Na.

Sophisticated techniques have been used to probe the physical state of water and ions in cells to test this hypothesis. Intracellular ion activities measured with ion-selective electrodes are generally consistent with an activity coefficient for K close to that in extracellular fluids (*4*). However, in many cells, including the frog skeletal muscle, K is found to be at electrochemical equilibrium across the cell membrane. This is therefore also consistent with the binding hypothesis, which maintains that all solutes are at equilibrium between the cell and the extracellular fluid (*5*). Early nuclear magnetic resonance measurements of Na (*6*) and K (*7*) were interpreted as showing considerable immobilization of these ions. More recently, alternative explanations requiring only small amounts of bound ions have been presented (*8*). Conductivity studies (*9*) and diffusion coefficient measurements (*1, 10*) have indicated that the mobilities of intracellular ions are between 10 and 50 percent of their mobilities in free solution. The binding hypothesis, however, does not necessarily predict drastically lowered mobilities, since site-to-site migration of ions could be rapid (*3*).

One crucial prediction of the association-induction hypothesis which can be tested relatively simply is that the K content of the cell should be a saturable function of external K. After the putative binding sites are filled, K, like Na, should be excluded from the ordered water system. Saturation at 90 to 100 μmole of K per gram of tissue (or about 140 mmole per liter of cell water) has been observed in frog skeletal muscle at external concentrations up to 10 m*M* (*11, 12*). Boyle and Conway, in their classic 1941 paper (*13*), however, reported that as the external K was increased up to 300 m*M*

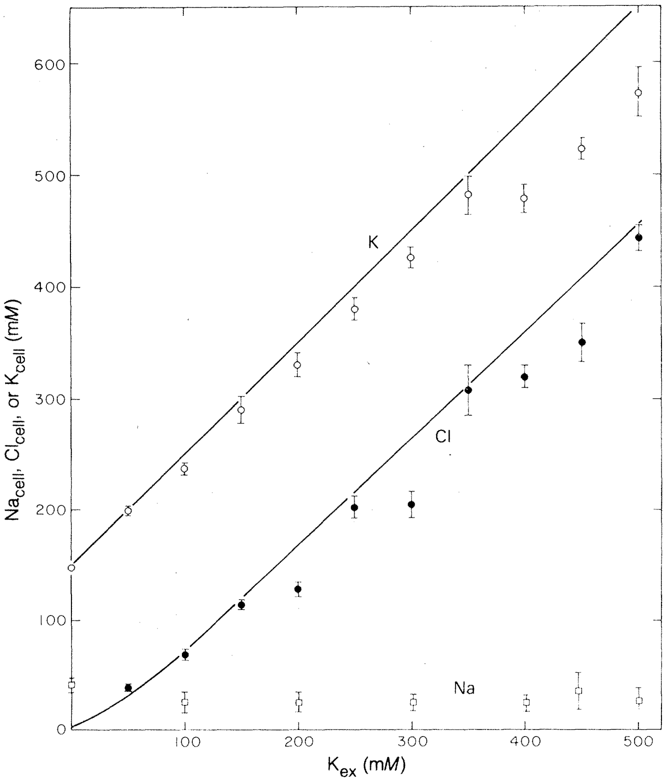

Fig. 1. Steady-state concentrations of K, Na, and Cl in the cells as a function of external K concentration. The cellular ion concentrations are given in millimoles per liter of cell water and are calculated from the equation $C_{cell} = (C_T - C_{ex}f_{ecs})/[1 - (W_d/W_w) - f_{ecs}]$ where C_T is the measured ion content of the tissue in micromoles per gram (wet weight), C_{ex} is the concentration of the ion in the external solution, W_d and W_w are the measured dry and wet weights of the tissues, and $f_{ecs} = 0.13$ is the extracellular space fraction of the tissue. The concentration of NaCl was held constant at 91 m*M* in each solution. The points shown for $K_{ex} \leq 400$ m*M* are from four to eight measurements (± standard error of the mean) made after 8-hour incubations. The points for $K_{ex} = 450$ m*M* and 500 m*M* were obtained after 1-hour incubations (*17*). The solid lines are theoretical fits drawn from Eqs. 1 and 2 (*14*). The parameter $(\epsilon - \eta)/2V$ was chosen to fit the measurement of K_{cell} at a physiological K_{ex}. The value obtained was 30 m*M* with $\epsilon/V = 145$ m*M* and $\eta/V = 85$ m*M*. These values were assumed to be constant in solutions of varying KCl.