# On the presence of a coastal current of Levantine intermediate water in the central Tyrrhenian Sea

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**Abstract** – The hydrological structure and the seasonal variability of marine currents in the Tyrrhenian Sea, off the coasts of Latium, are analysed using a data set obtained during several cruises between February 1988 and August 1990. Of particular interest is the fact that the hydrological surveys show the intermittent presence of a current of Levantine Intermediate Water (LIW) flowing anticlockwise along the Italian slope, at 250–700 m. This current is of particular importance in inferring the pathways of the Levantine Intermediate Water in the western Mediterranean Sea and in particular in the Tyrrhenian basin, downstream of the Strait of Sicily. These phenomena remain an open problem: our observations give support to the Millot's proposed general scheme, on the existence of a general cyclonic circulation of the LIW from the Strait of Sicily to the western Mediterranean, as opposed to a direct injection of LIW towards the Algerian basin. © Elsevier, Paris / Ifremer / Cnrs / Ird

Tyrrhenian / Levantine Intermediate Water / Margules

**Résumé – Courant côtier d'eau intermédiaire Levantine dans la mer Tyrrhénienne.** La structure hydrologique et la variabilité saisonnière des courants marins de la mer Tyrrhénienne, au large des côtes du Latium, sont analysées en utilisant des données obtenues pendant plusieurs croisières, entre février 1988 et août 1990. Le fait particulièrement intéressant est que ces recherches hydrologiques démontrent une présence intermittente du courant LIW (Eau intermédiaire Levantine–*Levantine Intermediate Water*), circulation cyclonique le long de la pente italienne, à une profondeur de 250 à 700 m. Le courant est particulièrement important pour déduire les trajectoires de l'eau LIW de la mer Méditerranée occidentale et, en particulier, dans le bassin Tyrrhénien, suivant le courant du canal de Sicile. Ces phénomènes représentent encore aujourd'hui un problème ouvert. Nos observations confirment le schéma général proposé par Millot sur la circulation générale cyclonique de l'eau LIW du canal de Sicile vers l'ouest de la mer Méditerranée, contrairement à l'entrée directe de l'eau LIW dans le Bassin algérien. © Elsevier, Paris / Ifremer / Cnrs / Ird

Tyrrhénienne / eau intermédiaire Levantine / Margules

## 1. INTRODUCTION

The presence of a Levantine Intermediate Water current flowing off the coasts of Latium in the central Tyrrhenian Sea is analysed in this study. This deep isolated basin in the western Mediterranean Sea (*figure 1*) is almost triangular in shape and is surrounded by the Italian peninsula to the northeast and east, by Sicily to the south, by Sardinia and Corsica to the west and finally by the Channel of Corsica to the north. The Tyrrhenian Sea has a com-
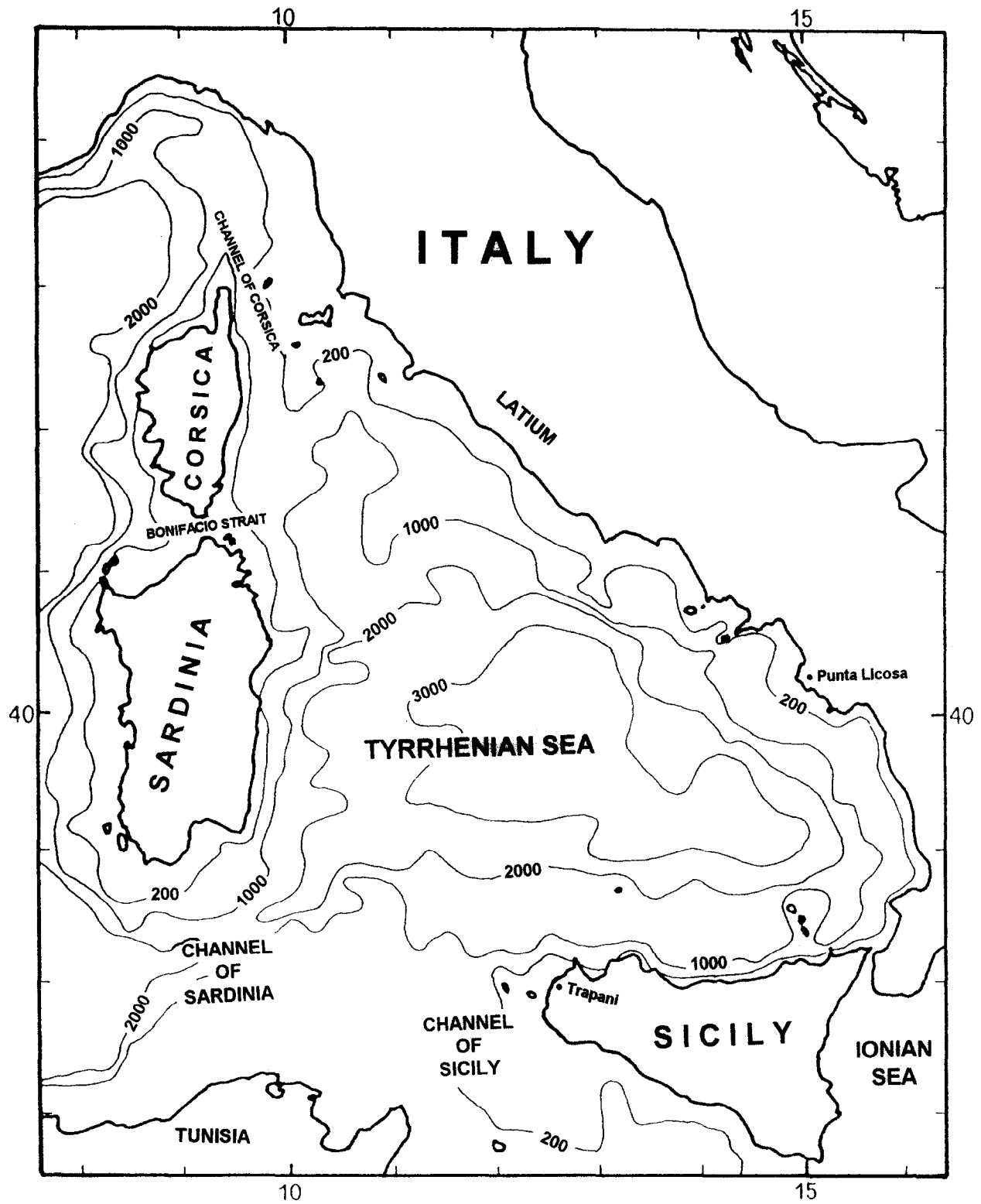
**Figure 1.** The Tyrrhenian Sea map, depths in metres.

plex bottom topography, with its deepest part (3750 m) restricted around 12° E and 39° N.

The Tyrrhenian Sea is connected with the Algerian basin through the Sardinia Strait (with a depth of 2000 m and a width $\approx$ 290 km) and with the Ligurian Sea, through the Channel of Corsica.

Although the Mistral (N–NW) plays the dominant role [16, 23], the other winds blowing across this basin are the Scirocco (SE), Libeccio (S–SW), Ponentino (W), and Tramontana (N). These forcings give rise to large-scale weak cyclonic/anticyclonic circulation systems, although many observations show that along the Italian coasts there is a prevalent anticlockwise current [18, 22]. Moreover, the effect of strong Mistral bursts passing between Sardinia and Corsica is to originate two counter-rotating gyres in the west/middle of the basin, east of the Bonifacio Strait [22, 26].

From a hydrological point of view, the Tyrrhenian Sea, like the rest of the western Mediterranean, is essentially composed of four superimposed water layers [28]:

a) the superficial layer consists of relatively fresh water of Atlantic origin, Modified Atlantic Water (MAW), down to $\approx$ 200 m (potential temperature $\vartheta$ $\approx$ 13.5–13.9 °C; salinity $S$ $\approx$ 38.0–38.5; potential density $\sigma$ $\approx$ 27.0–28.9, as is clearly marked in atlases, [10]);

b) the underlying layer is composed of Levantine Intermediate Water (LIW). It is usually found throughout the Mediterranean Sea between $\approx$ 250 m and $\approx$ 700 m ($\vartheta$ $\approx$ 13.5–13.9°C; $S$ $\approx$ 38.45–38.75; $\sigma$ $\approx$ 29.00–29.10). A mixed water mass of $\approx$ 50–100 m thickness can also be found between MAW and LIW, but in the following we will schematically assume the MAW to be $\approx$ 250 m thick and the LIW layer to be $\approx$ 450 m thick [10];

c) a denser and less salty water called Western Mediterranean Deep Water (WMDW) is present between $\approx$ 700 m and $\approx$ 3000 m [13, 17, 18, 28]. The characteristic properties of the WMDW are $\vartheta$ $\approx$ 12.90–13.50 °C, $S$ $\approx$ 38.4–38.6, $\sigma$ $\approx$ 29.10–29.11;

d) finally the bottom water, with its source in the northwestern Mediterranean, reaches depths of up to $\approx$ 4200 m [28].

In this study, we focus our attention on the LIW pathway in the Tyrrhenian Sea. This water mass is formed during winter in the eastern Mediterranean Sea, near the island of Rhodes, as a result of intense water cooling and evaporation processes. LIW is not influenced by fluvial contributions and is therefore characterized by a salinity

maximum. After its formation, LIW spreads and can be found throughout the Mediterranean Sea. LIW crosses the Channel of Sicily through two passages, the greater flow occurring in the deep eastern canyon close to the Sicilian shelf [2, 14, 15], feeding the intermediate layers of the western Mediterranean Sea [14, 15, 18, 20, 25, 28].

LIW dynamics, particularly in the Tyrrhenian Sea, are an interesting open problem. Indeed, to our knowledge, in the western Mediterranean Sea they can be described using a classical schema [28] or a more recent idea of Millot [18]. The former suggests that the flow of LIW, after passing through the central Ionian basin, crosses the Strait of Sardinia and flows along the continental slope of North Africa toward the Strait of Gibraltar. The second one suggests that the LIW flow is driven by the Coriolis force and the topography and also encounters large-scale turbulent flows. Following this schema the LIW flows anticlockwise along the continental slope all over the Mediterranean Sea; after passing through the Channel of Sicily, it deviates along the Sicilian slope, before flowing along the Italian slope up to the Channel of Corsica. Considering that the width and depth of this Channel are not sufficient to allow the draining of all the water entering the basin, LIW probably continues, at least in part, flowing southward along the continental slope of Corsica and Sardinia, again following the bathymetry. In such a context, Hopkins [12] estimated that $\approx$ 2/3 of LIW entering the Tyrrhenian Sea recirculates across the Sardinia Strait and $\approx$ 1/3 exits northward through the Corsica Channel. Garzoli and Maillard [8] found that an equal quantity of LIW enters and leaves the Tyrrhenian Sea. Furthermore, in a recent oceanographic cruise AIS96 (Atlantic Ionian Stream - August 1996) on board the R/V Alliance (NATO, SACLANT Undersea Research Centre) in the Sicily Channel and Ionian Sea, strong average velocities of LIW were measured with the Acoustic Doppler Current Profile Vessel Mounted (ADCP VM) as well as with classical CTD measurements. In the narrowest part of the Sicily Channel (figure 1), an average velocity of about 20–25 cm s$^{-1}$ at a depth of $\approx$ 200–300 m was measured. Moreover, an average velocity of $\approx$ 15–20 cm s$^{-1}$ in direction N–NW, offshore Trapani, was found at $\approx$ 300–400 m [25].

Also of interest is the recent numerical investigation of Wu and Haines [29] in which the LIW distribution in the Mediterranean Sea and its behaviour in the western basin after crossing the Channel of Sicily is analysed. In the Algerian basin, west of Sardinia, two LIW boundary currents are formed that flow northward (along the western
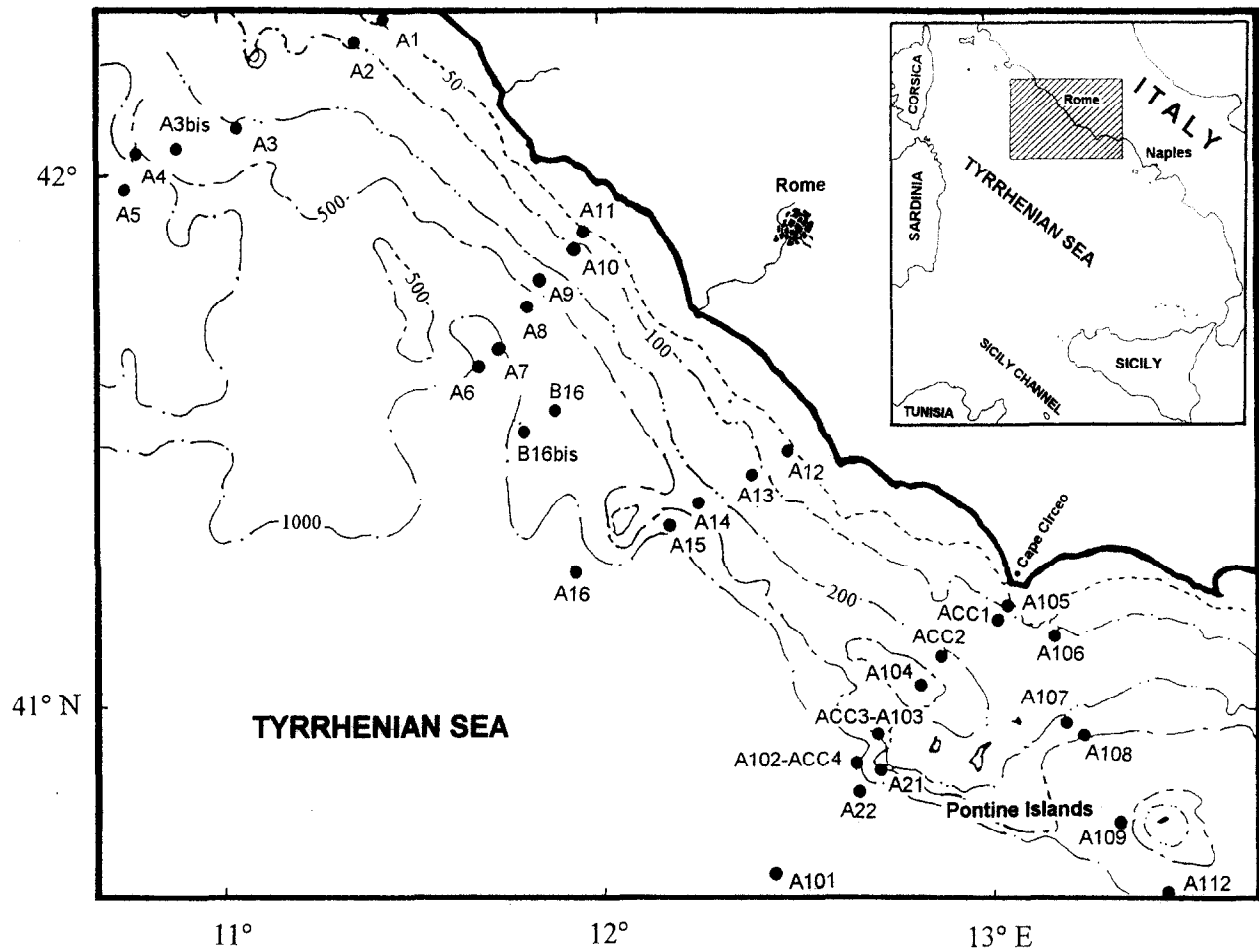
**Figure 2.** General map with detailed bathymetry of the Tyrrhenian Sea near the coasts of Latium (depths in metres) and positions of CTD stations.

slopes of Sardinia and Corsica) and westward, along the North African slope. However, no circulation of LIW along the Italian slope has been described. In general, numerical information can be said to be associated with very different hydrological distribution and circulation patterns in the Tyrrhenian Sea, which have so far not been discussed on the basis of adequate data sets.

It is consequently of interest that, in 1988–1990, several routine oceanographic cruises (University of Rome "La Sapienza") measured currents off the Latium slopes (*figure 2*; [3, 24]). In these hydrological CTD data, the LIW layer can be identified by its salinity maximum. From the vertical maps of potential isopycnals (*figures 3*a–d), an along-slope northward coastal flux at intermediate depths is evident, the analysis of which is the purpose of this article.

This flow is not totally unexpected. Indeed Hopkins and G.O.N.E.G. [11] report that LIW has been found repeatedly in the Tyrrhenian Sea, and similar results are evident in De Maio et al. [5]. Moreover, in a hydrological transect off Punta Licosa, about 200 km south-east of Naples, Astraldi and Gasparini [1] found evidence of a LIW coastal vein at about 350 m, with a slow northward velocity of about 2 cm s$^{-1}$.

It may thus be concluded that the presence of LIW in the Tyrrhenian Sea is not totally unexpected, but no clear evidence of strong northward velocities along the slopes has so far been produced. For this reason the LIW dynamics downstream of the Sicily Channel must still be considered as an open problem [14]. In such a context, the goal of this paper is to describe the presence of LIW slope currents in the central Tyrrhenian Sea, which is a novelty as

**Table 1.** Synthesis of hydrological data.

| Cruise (Date) | Stations of interest for LIW | Distance between stations [km] | Estimated no-motion layer depth [m] | LIW thickness range [m] | Estimated geostrophic velocity [cm s$^{-1}$] | Estimated flux [Sv] |
|---|---|---|---|---|---|---|
| "Antares" | A7-A6 | 8 | 325 | 300–700 | 15 | 0.50 |
| (24/2/88-3/3/88) | A108-A109 | 10 | 375 | 300–600 | 1 | 0.02 |
| "Altair" | A22-A101 | 34 | 225 | 325–700 | 3 | 0.40 |
| (25/11/88-3/12/88) | A15-A16 | 20 | 300 | 425–750 | 1 | 0.06 |
| "Arcturus" | A102-A22 | 4 | 350 | 300–500 | 10 | 0.10 |
| (18/3/89-24/3/89) | B16-B16 bis | 7 | 330 | 350–600 | 4 | 0.17 |
| "Aldebaran" | A15-A16 | 21 | 200 | 400–600 | 6 | 0.40 |
| (15/7/89-24/7/89) | | | | | | |
| "Andromeda" | ACC3-ACC4 | 5 | 250 | 300–500 | 3 | 0.05 |
| (12/9/89-25/9/89) | A15-A16 | 30 | 75 | 350–550 | 10 | 0.90 |
| "Bootes" | A6-A7 | 7 | 500 | 500–800 | 2 | 0.05 |
| (21/8/90-30/8/90) | ACC3-ACC4 | 7 | 200 | 275–500 | 8 | 0.19 |

far as field observations in the Tyrrhenian near the coasts of Latium are concerned. It has to be stressed that these coastal currents are not only of interest in themselves but also support Millot's general idea of Mediterranean Sea circulation [6, 14, 18].

## 2. DATA AND METHODS

The most interesting part of the hydrological data (CTD and bottles) collected during the oceanographic cruises off the Latium coasts is summarized in *table I*. The LIW layer has a characteristic $\vartheta/S$ profile throughout the Mediterranean Sea, as described above. Due to the importance of large-scale coastal morphology, smaller-scale effects can be disregarded and so a classical geostrophic method can be used here to analyse such flows. From the isopycnals shown in *figures 3*a–d, an estimate of the density difference between LIW and MAW:

$$\frac{\Delta\rho}{\rho} = \frac{\rho_{LIW} - \rho_{MAW}}{\rho} \approx 2 \times 10^{-4} \qquad (1)$$

is obtained. The baroclinic velocity is:

$$C = \left( g \frac{\Delta\rho}{\rho} \frac{h_{MAW} h_{LIW}}{h_{MAW} + h_{LIW}} \right)^{1/2}$$

$$= \left( g' \frac{h_{MAW} h_{LIW}}{h_{MAW} + h_{LIW}} \right)^{1/2} = 0.6 \; ms^{-1} \qquad (2)$$

finally, the internal Rossby radius $R$ is:

$$R = \frac{C}{f} \approx 6 \; km \qquad (3)$$

where as usual $g' = g \, \Delta\rho/\rho$ is the reduced gravity, $\rho_{MAW}, \rho_{LIW}$ and $h_{MAW}, h_{LIW}$ are the densities and layer thicknesses of MAW and LIW respectively and finally $f = 10^{-4} \; s^{-1}$ is the Coriolis parameter at these latitudes.

From potential isopycnal analysis (*figures 3*a–d), we see that there is a rather flat layer around 200–300 m. Moreover, *figure 4* shows that the $O_2$ reaches its minimum value at about 200–300 m and remains constant below. Using Dietrich's method [7], we decided to set the no-motion level at this depth. From this choice a reasonable absolute velocity for the various water layers can be evaluated. The resulting velocity jump $\Delta v$:

$$\Delta v \cong \frac{g}{f} \frac{\Delta\rho}{\rho} \tan\alpha = \frac{g'}{f} \tan\alpha \qquad (4)$$

can then be computed for each transect, $\alpha$ being the isopycnal slope [21].

The main result of this work is that in our measurements the isopycnal slope in some hydrological sections clearly indicates the presence of a vigorous current of LIW, with considerable N–NW fluxes (*table I*). This new determination of such currents is of considerable interest for the dynamics of water masses in the Mediterranean Sea, as it gives support to Millot's [18] schema.

In these measurements, the velocity and the flux of LIW significantly show a strong variability, either due to seasonal changes or to instabilities of currents flowing along a steep slope. Also to be taken into account is the difficulty of following this mid-depth current through stations planned for the purpose of routine measurements, and not to research a detailed "vein" of LIW water. Indeed the LIW is not fully observable in all the CTD data but is
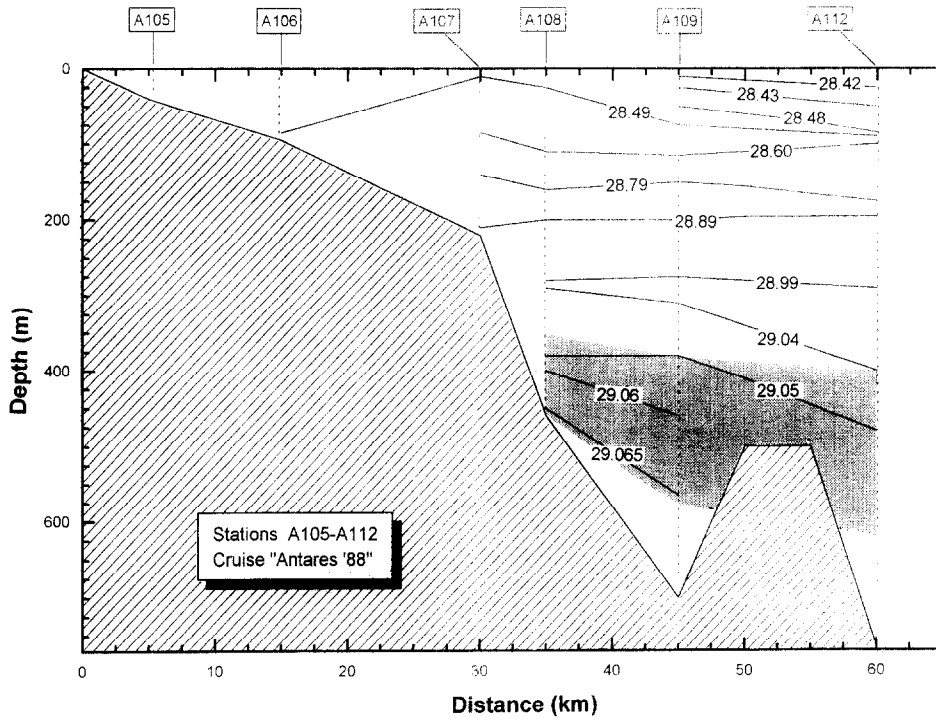
**Figure 3a.** Potential isopycnals for sections A105-A112 (Cruise ANTARES 1988). The dashed zone represents the water mass corresponding to LIW.
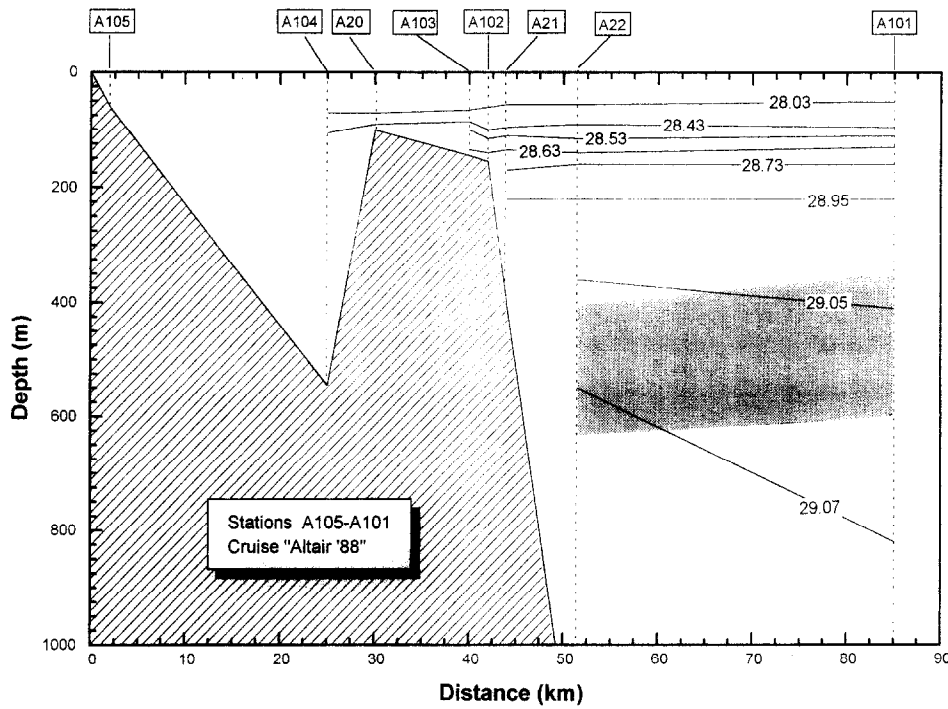


**Figure 3b.** Potential isopycnals for sections A105-A101 (Cruise ALTAIR 1988). The dashed zone represents the water mass corresponding to LIW. Note the unusual behaviour of isopycnals versus LIW, an effect due to current deflection caused by the Pontine Islands.
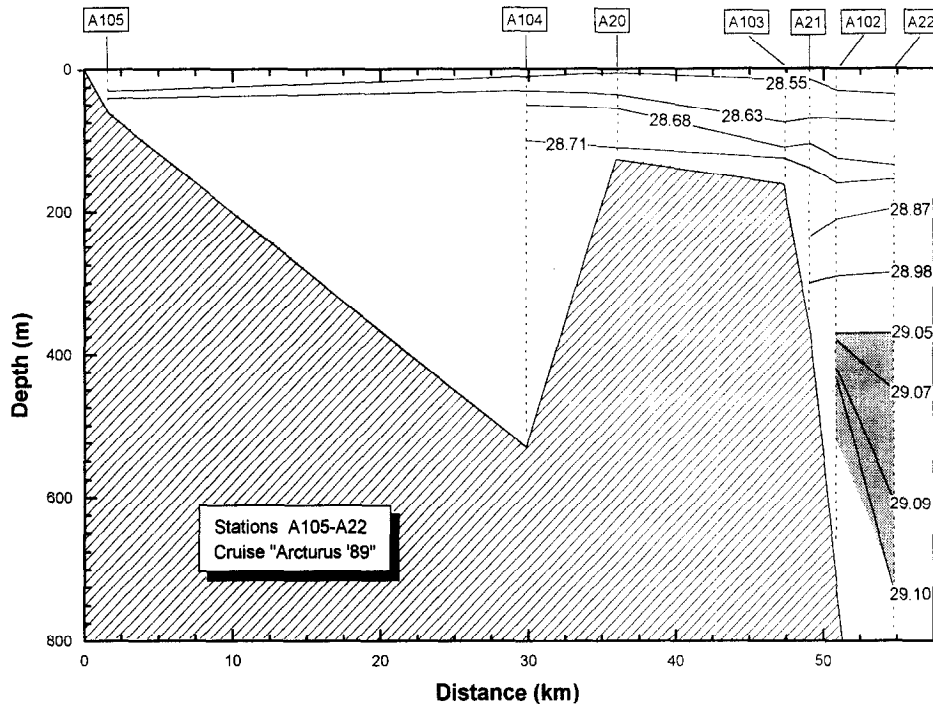
**Figure 3c.** Potential isopycnals for sections A105-A22 (Cruise ARCTURUS 1989). The dashed zone represents the water mass corresponding to LIW.
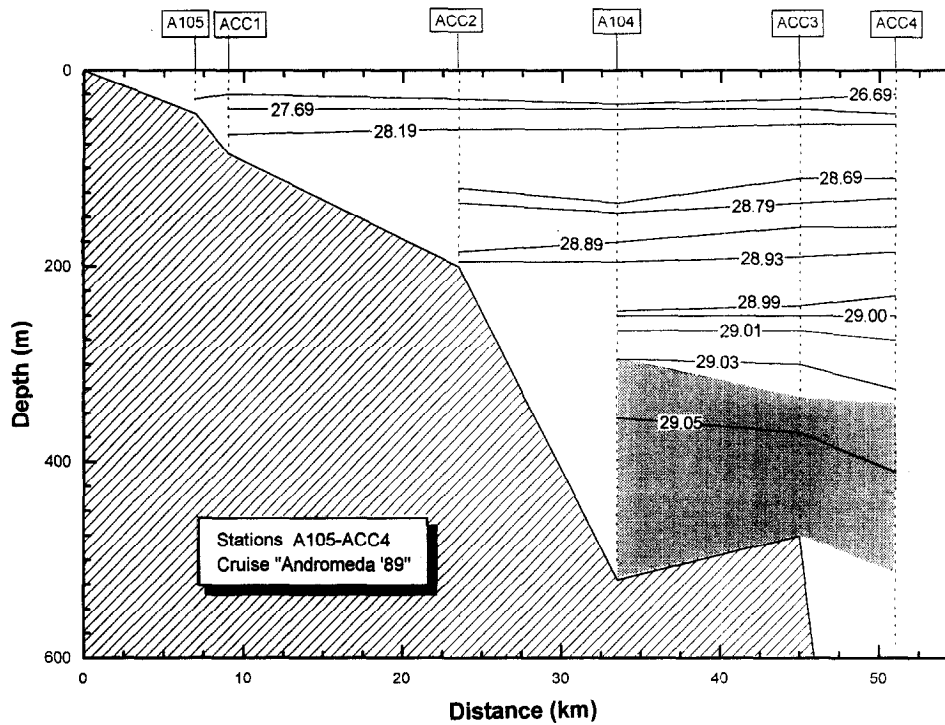


**Figure 3d.** Potential isopycnals for sections A105-ACC4 (Cruise ANDROMEDA 1989). The dashed zone represents the water mass corresponding to LIW.
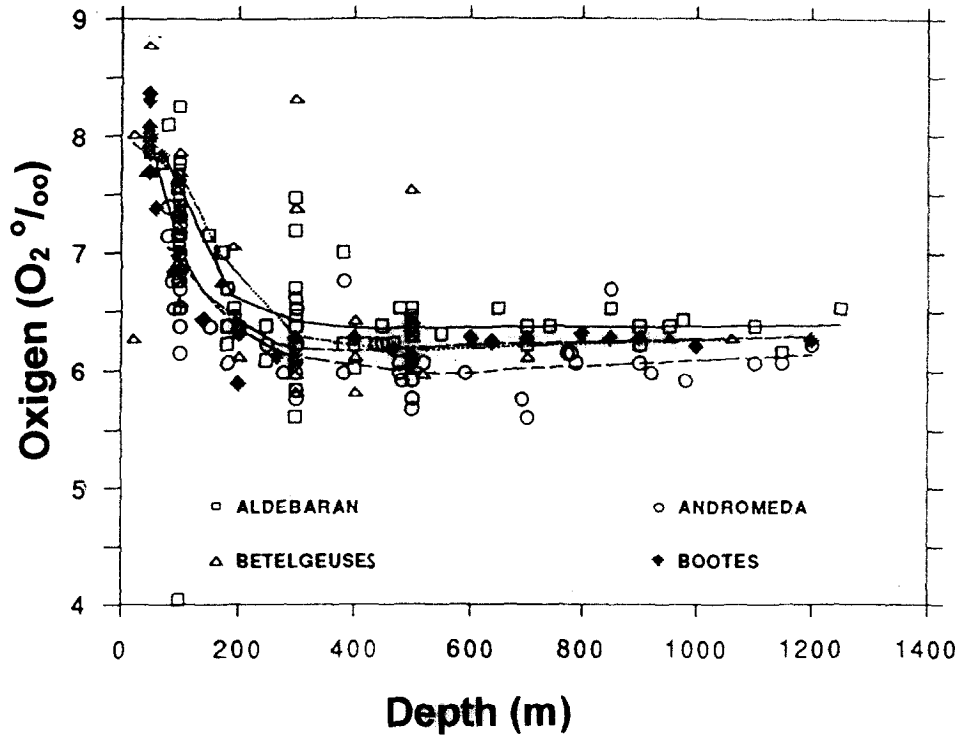
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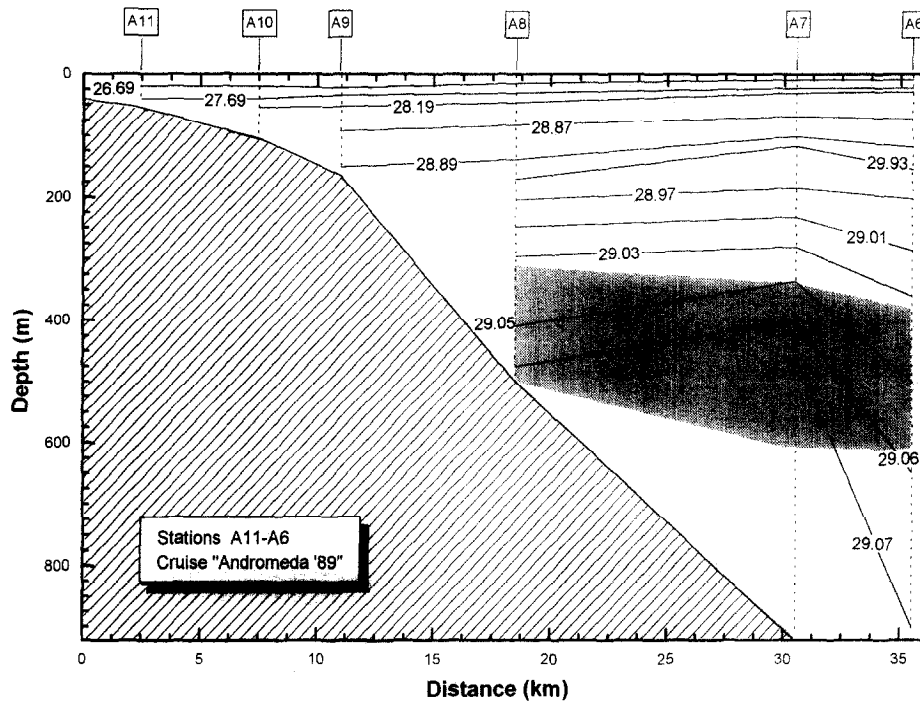**Figure 4.** Totality $O_2$ as a function of depth



**Figure 5.** Potential isopycnals for sections A11-A6 (Cruise ANDROMEDA 1989). The dashed zone represents the water mass corresponding to LIW.

usually visible only in a couple of stations of the various hydrological transects, often the most external ones. It is thus clear that this LIW core identification is not the most significant one. In *figures 3*a–d, we show that the LIW vein corresponding to one of the transects is the one with the most evident LIW, located between Cape Circeo and Pontine Islands. Moreover, the difference between the isopycnals of this Pontine Islands transect is compared with those of a northern transect (*figure 5*), where the effect of a vigorous surface current, flowing eastward from Sardinia and attaining the Latium coasts before turning northward as a coastal current [22], can be easily detected.

## 3. CONCLUSIONS

Even if we cannot fully discuss the presence of a "vein of LIW" flowing anticlockwise along the Italian slopes in the central Tyrrhenian Sea, since our measurements were not designed to consider the entire phenomenon, the presence of these coastal velocities of LIW at about 500 m is rather interesting, because this is somehow expected but never clearly observed. It is thus interesting to compare our data with results of theoretical models; the simplest ones come from Gill's observation [9] that a discontinuity on an interface (i.e. due to winds or baroclinic tidal flows over a ridge, or baroclinic currents passing through a strait) of a rotating two-fluid system can generate short-time and long-time waves. In our case, the flows are rather regular, since in their long trip from the Rhodes gyre the transient currents have probably lost their importance. The long-term solutions can then theoretically be seen as

currents propagating along-slope [4, 9, 27]. This is valid both for barotropic phenomena and for a general baroclinic system. This is not only a theoretical problem, since in many papers [6, 18, 19, 29] it is clearly stated that the pathways of LIW in the western Mediterranean, and in particular in the Tyrrhenian basin, have only been summarily investigated. In particular, the study of the thermohaline circulation in the whole Mediterranean Sea is a problem of fundamental importance, and is still uncertain and controversial [6, 19, 28, 29]. From our measurements, we found the presence of a current of LIW near the coasts of Latium, even if it is not totally clear how wide the vein is. These measurements are of interest since the literature contains insufficient indications concerning the presence of LIW north and south of the Latium coasts, while the presence of LIW in the whole Tyrrhenian basin is a rather commonly accepted fact. In general, these measurements support Millot's idea, although this work suggests the utility of planning further field measurements to elucidate such fundamental problems.

## Acknowledgements

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