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Intermediate water formation
Eddy
Eastern Mediterranean
Cretan Sea
POEM-86

Formation des eaux intermédiaires
Tourbillon
Méditerranée Orientale
Mer de Crète
POEM-86

Intermediate water formation in the Cretan Sea (South Aegean Sea)

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ABSTRACT

During the POEM-01-86 cruise, CTD data were collected from 25 stations in the Cretan Sea, from 19-21 March 1986, using an SBE-9 CTD profiler on board R/V "Aegaio"

Favourable weather and hydrographic conditions for the development of the winter convective mixing would appear to lead to the homogenization of the water column in the upper layer to a depth of 250 m.

The density of the surface water ($\sigma_\theta = 29.014$) off the eastern part of the Cretan shelf area exceeded that of the underlying waters.This fact was observed after a meteorological event of brief duration (4-5 days), consisting of strong, cold and dry, north winds (up to 20 m/s) and low air temperature (8.2-13°C). The mixed dense water sinks vertically and spreads along isopycnal surfaces at intermediate depths (200-250 m). An anticyclonic eddy exists off the eastern Cretan shelf area. The waters formed over the shelf and probably in the surrounding cyclonic flow regions accumulate in the convergent anticyclonic area, where their characteristics ($15.25 < t < 15.30$°C, $38.99 < S < 39.01$) become almost uniform in the water column from the surface to a depth of 250 m. These features revealed a new source of intermediate water in the Cretan Sea.

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RÉSUMÉ

Formation des eaux intermédiaires en Mer de Crète (Mer Égée du Sud)

Durant la campagne océanographique POEM-01-86 en Mer de Crète (Mer Égée du Sud), du 19 au 21 mars 1986, 25 stations hydrologiques ont été effectuées par le navire océanographique « Aegaio », en utilisant la bathysonde SBE-9 du Centre National de Recherches Marines (Grèce).

Des conditions météorologiques et hydrologiques favorables au développement du mélange vertical, ont conduit à une homogénéisation de la couche de surface sur une épaisseur de 250 m. A l'est de l'île de Crète et hors du plateau continental, la densité des eaux superficielles ($\sigma_\theta = 29{,}014$) est légèrement supérieure à celle des eaux sous-jacentes. Cette observation a été faite à la suite d'une courte période (4 à 5 jours) de conditions météorologiques très rigoureuses sur la mer Égée : masse d'air froid (8,2 à 13°C) et sec, et fort vent du nord (jusqu'à 20 m/s). Les eaux denses coulent verticalement et ensuite glissent le long des surfaces isopycnes jusqu'à la profondeur de 200 à 250 m.

Un tourbillon anticyclonique existe au-delà du plateau continental à l'est de l'île de Crète. Les eaux formées sur le plateau continental, et probablement dans les tourbillons cycloniques qui existent autour du mouvement anticyclonique, s'accumulent dans la convergence anticyclonique. Leurs caractéristiques sont presque uniformes : 15,25°C $< t < 15{,}30$°C et $38{,}99 < S < 39{,}01$ dans les 250 premiers mètres. Ces caractéristiques révèlent l'existence d'une nouvelle région de formation d'eau intermédiaire en Mer de Crète.

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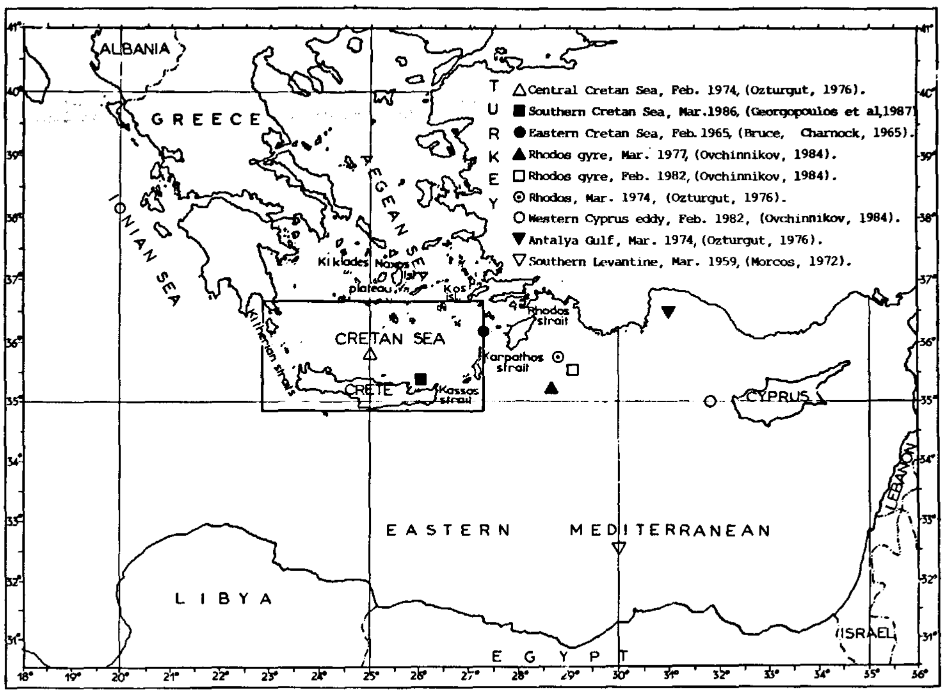

Figure 1

Chart of the area under investigation and location of identified sources of Levantine Intermediate Water over the Eastern Mediterranean. The code for various sources is given in the insert in the top right-hand corner.

Carte de la région étudiée et position des sources identifiées de l'Eau Levantine Intermédiaire en Méditerranée Orientale. Le code utilisé est indiqué en haut à droite.

INTRODUCTION

The Cretan Sea, which constitutes the major part of the Southern Aegean Sea, lies between the Kiklades islands and the islands of the Cretan arc. It communicates with the Levantine basin through the eastern straits of Kassos, Karpathos and Rhodos and with the Ionian sea through the three Kitherian straits (Fig. 1).

The Cretan Sea receives less saline waters from the North Aegean and the more saline waters from the Levantine (Theocharis *et al.*, 1986; Papageorgiou, 1986; Lascaratos and Papageorgiou, 1987). In the central area, an east-west depression, with depths from 1,000 to 2,000 m, is bounded to the north by the Kiklades plateau, at a depth of 400 m, and to the south by the shelf of the island of Crete, which extends some 5 nautical miles from the northern coast with depths reaching 200 m (Fig. 2). In the eastern part two deeper depressions, reaching 2,500 m, exist.

The Cretan Sea was visited from 19-21 March 1986 by R/V Aegaio, during the POEM-01-86 cruise. CTD data, up to 1,000 dbars, were collected from a grid of 25 hydrographic stations (Fig. 2).

Earlier research indicates the Cretan Sea a region in which vertical mixing leads to intermediate or deep water formation. Nielsen (1912) evoked the possibility of deep water formation, north of Crete. Miller (1963) noted that the Cretan Sea is a source of the deep Eastern Mediteranean water. El Gindy and El-Din (1986) calculated the percentages (10-40 %) of deep Cretan water in the deep water of the Eastern Mediterranean Sea. A source of cold and high salinity water in the Eastern Cretan Sea, between the islands of Karpathos, Rhodos and Kos, identified by Bruce and Charnock (1965). The water was sinking to a maximum depth of 150-300 m. These findings were confirmed from data of the Israeli winter cruise C-04 in the Eastern Mediterranean and the Aegean, and two source areas of deep water in the Aegean were identified, one in the eastern part of the Cretan Sea and the other off the NW coast of Rhodos (Burman and Oren, 1970).

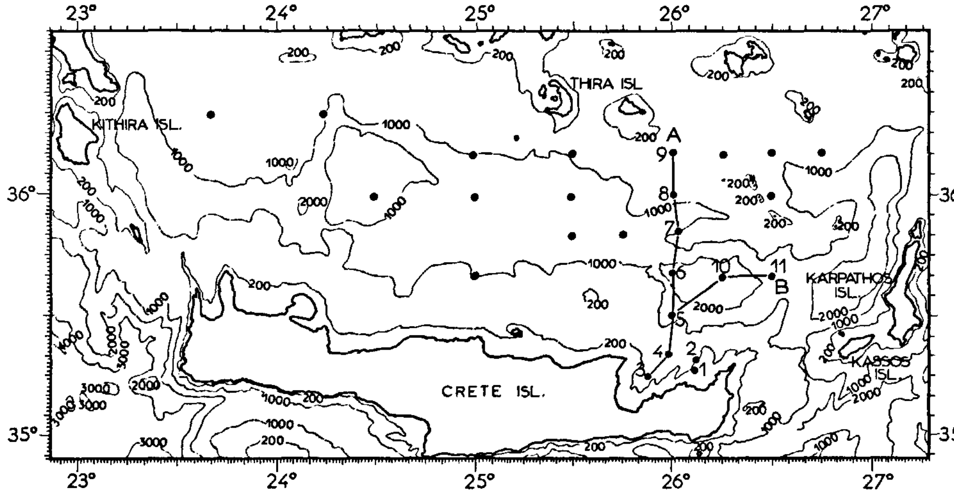

Figure 2

Bathymetric chart (depths in metres) and location of stations.

Carte bathymétrique (profondeurs en mètres) et emplacement des stations effectuées.

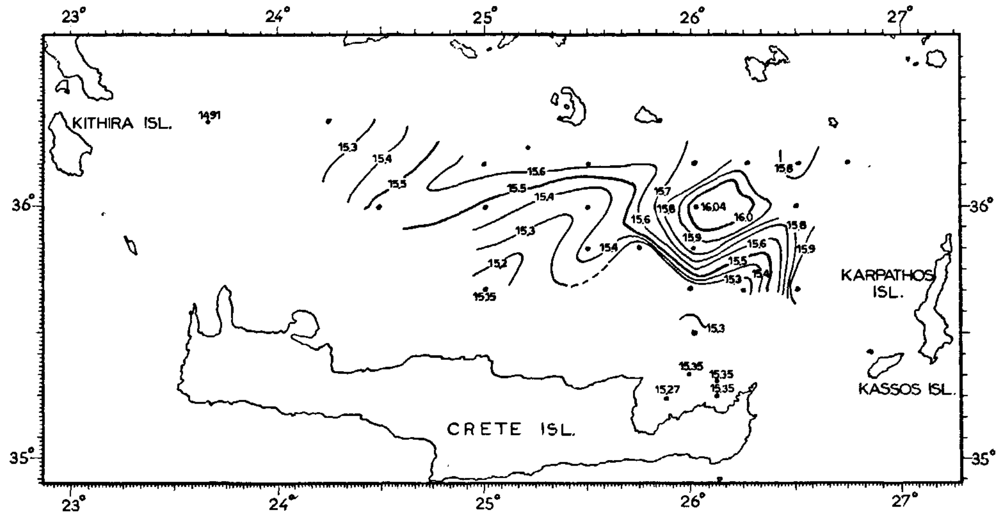

Figure 3 *a*
Surface (5 dbars) temperature distribution
Répartition de la température en surface (5 dbars).

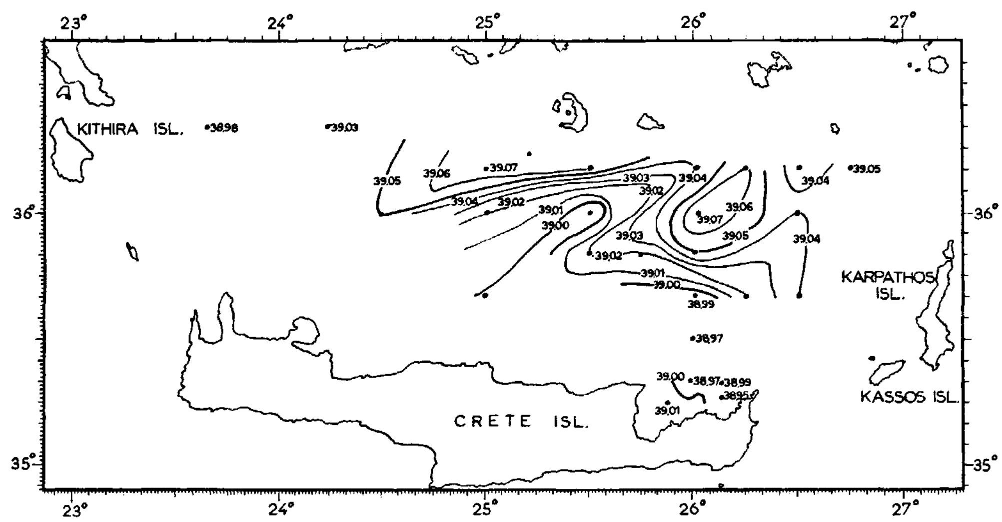

Figure 3 *b*
Surface (5 dbars) salinity distribution
Répartition de la salinité en surface (5 dbars).

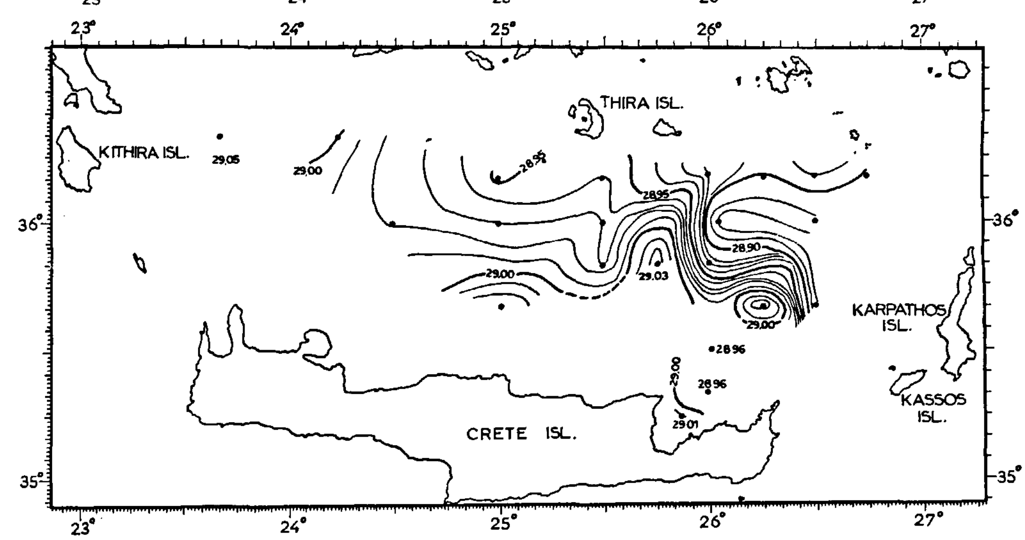

Figure 3 *c*
Surface (5 dbars) potential density distribution
Répartition de la densité potentielle en surface (5 dbars).

Wüst (1961) reported the southern Aegean Sea as a deep and bottom water formation area, probably of minor importance. Lacombe and Tchernia (1972) indicated that the SE Aegean is a region of intermediate water formation. Miller (1974), stating that the Aegean Sea and particularly the deep Cretan Sea (2 500 m) could be included in the list of ocean areas where deep vertical circulation processes occur, suggested a significant turnover of the water column, based on high dissolved oxygen content at the very lowest depths, compared with that of adjoining seas.

The present contribution deals with the formation of intermediate water over the Cretan shelf. It is now generally accepted that the Rhodos cyclonic gyre is the main source of the Levantine Intemediate Water (LIW) of the Eastern Mediterranean (Ozturgut, 1976; Hopkins, 1978; Ovchinnikov, 1984; Ovchinnikov and Plakhin, 1984). Morcos (1972) suggested the existence of more than a single source of LIW, based on the considerable amount of scatter found in the T-S values, and indicated a broader area within the Southern Levantine as one of them. Subsequently, a series of

LIW sources have been identified by several workers. Ozturgut's studies (1976) revealed the Antalya bay as a second source region of LIW in the northern Levantine basin. He also identified the southern Aegean as an area of intermediate water formation, pointing out that winter convection in the central part of the Cretan Sea had reached to a depth of 200 m. The characteristics of the mixed layer are nearly $t = 15°C$ and $S = 38.95$. It is argued that this process is related to the presence of cyclonic circulation in the upper layer. Ovchinnikov (1984) found, on the basis of field observations (March 1977, February 1982), a third source in the northern Levantine, near the western coast of Cyprus. Ünlüata (1986) reported evidence of the formation of LIW in the Cilician basin and off the gulf of Iskenderun.

RESULTS AND DISCUSSION

Continuous records of temperature, salinity and density have been studied and dissolved oxygen measurements are also used. These data provided the means of investigating important features concerning convection and the formation processes of intermediate water.

The horizontal distribution of temperature, salinity and potential density (Fig. 3 *a*, *b*, *c*) within the surface layer shows that the northeastern part of the Cretan Sea is covered by a water mass of Levantine origin (Theocharis *et al.*, 1986) ($t_{max} = 16.04°C$, $S_{max} = 39.07$, $\sigma_\theta < 29.00$), while in the southern and central part a colder ($t_{min} = 15.15°C$) and denser ($\sigma_\theta > 29.00$) but slightly less saline ($38.97 < S < 39.02$) water mass is observed.

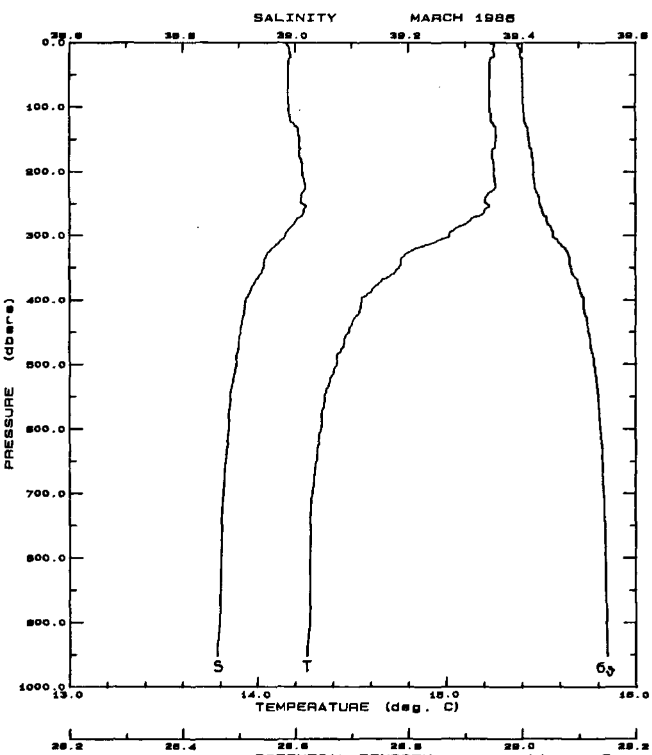

Figure 4

Temperature, salinity and potential density profiles in the Cretan Sea (station 6).

Profils de température, salinité et densité potentielle en Mer de Crète (station 6).

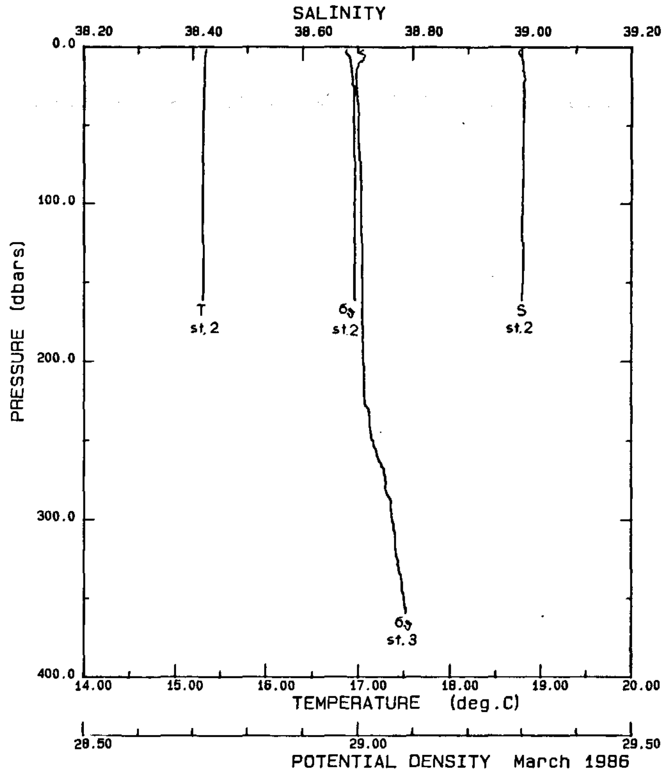

Figure 5

Temperature, salinity and potential density pofiles at station 2 and potential density profile at station 3.

Profils de température, salinité et densité potentielle à la station 2 et profil de densité potentielle à la station 3.

The vertical distribution of temperature, salinity and potential density shows a well-developed mixed layer extending mostly from 100 to 250 m. Within this layer,

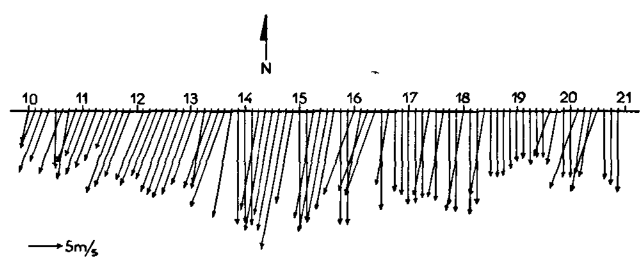

Figure 6 *a*

Wind speed and direction at Naxos meteorological station

Vitesse et direction du vent à la station météorologique de Naxos.

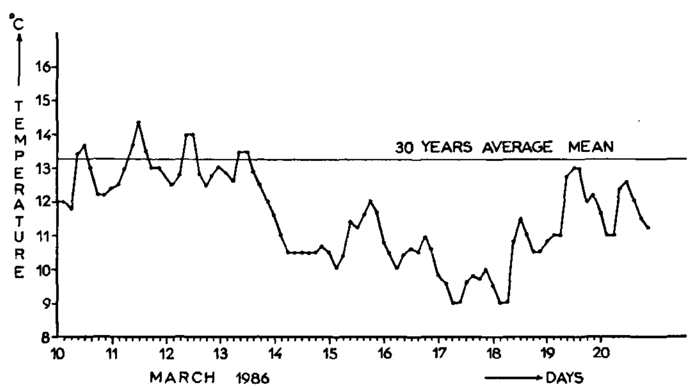

Figure 6 *b*

Air temperature variation at Naxos meteorological station.

Variation de la température de l'air à la station météorologique de Naxos.

high oxygen values (5.3 to 5.6 ml/l) have been measured. These features constitute strong evidence of convective activity over the Cretan Sea. Saline water within the upper layer has been cooled during the winter; the seasonal pycnocline has consequently been relaxed and a homogeneous layer has been formed (Fig. 4). The thickness of the mixed layer increases towards the shelf area of the island of Crete, to a depth of 250 m. Below the mixed layer, temperature and salinity decrease with depth and a weak stratification is developed in the lower layers. The profiles of temperature, salinity and potential density (Fig. 5) of the stations found over the shelf area show that the mixed layer extends from the surface to the bottom.

The predominance of northerly winds characterized the weather conditions during the period from 10-20 March 1986 (Fig. 6*a*). The continuous north wind field, with values up to 20 m/s was accompanied by air temperature values lower than the 30-year average mean (Fig. 6*b*). More particularly, air temperature ranged between 8.2 and 13.0°C, from 14-18 March (Thira meteorological station).

Evaporation also increased. Thus, three processes operated simultaneously. Salinity increased due to the high evaporation rate. Surface water was cooled as a result both of the loss of heat required for evaporation and of direct cooling due to the low air temperature. Thanks to short-lived meteorological event over the Aegean, the surface water off the shelf area became denser ($\sigma_\theta=29.014$, station 3) than the underlying waters (Fig. 5), first sinking vertically, mixing with surrounding waters, then sliding along the isopycnals to reach intermediate depths of 200 – 250 dbars, as may be ascertained from examination of the S-N cross-section at the eastern end of the island of Crete

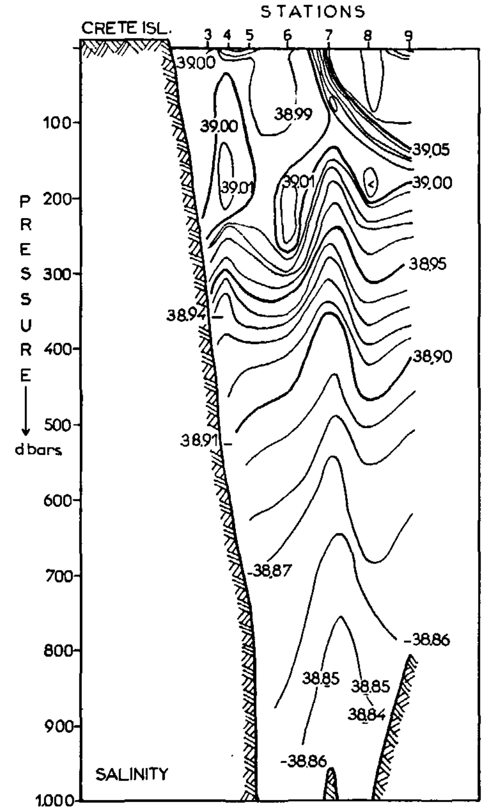

Figure 7*b*

Vertical distribution of salinity along transect A.

Répartition verticale de la salinité le long de la coupe A.

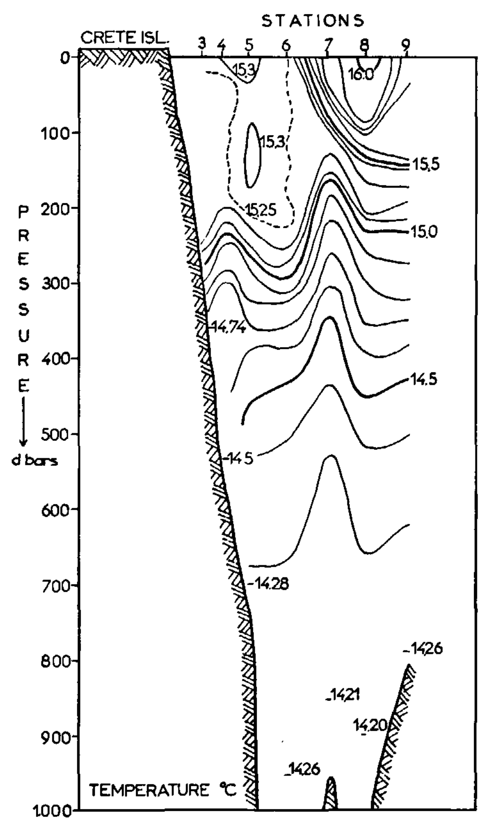

Figure 7*a*

Vertical distribution of temperature along the transect A.

Répartition verticale de la température le long de la coupe A.

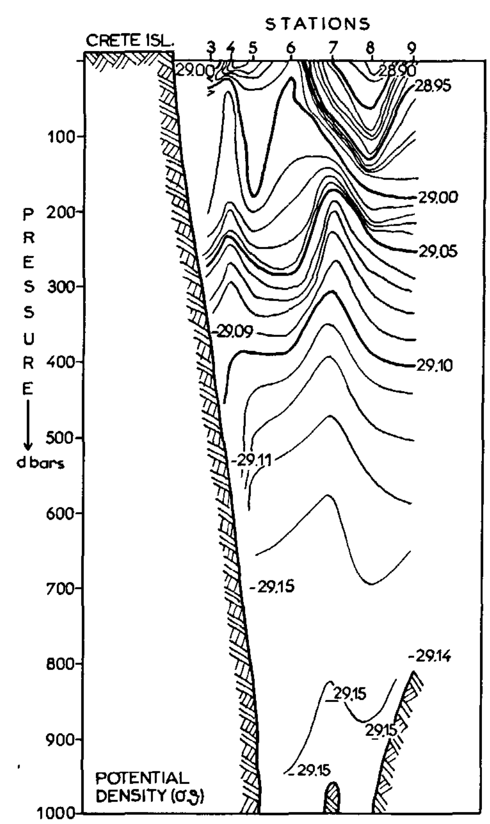

Figure 7*c*

Vertical distribution of potential density along transect A.

Répartition verticale de la densité potentielle le long de la coupe A.

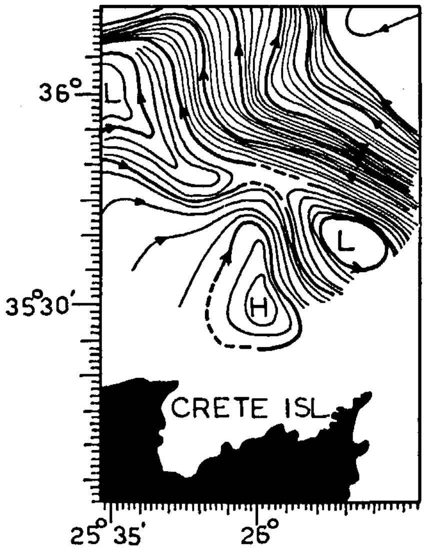

Figure 8
Surface circulation over 500 dbars (March 1986).
Circulation de surface par rapport à 500 dbars (mars 1986).

(Fig. 7 *c*). It is also evident that at the north end of the cross-section (stations 7, 8, 9) the warmer and more saline but less dense water (Fig. 7 *a*, *b*, *c*) of Levantine origin appears, as mentioned before. An almost homogeneous bulk of water is found approximately in the centre of the transect (stations 4, 5, 6). In addition, dynamical calculations (Pond and Picard, 1983) based on the same cruise data (March, 1986) revealed an anticyclonic eddy off the Cretan shelf region, covering an area of approximately 1,200 km^2 (Fig. 8). This eddy is surrounded by two cyclonic flow regions and the coasts of Crete. Combining the above geostrophic circulation pattern with the features revealed in the cross-section, we may assume that the anticyclonic region receives the dense water formed over the shelf area and, in all probability, the waters formed within the cyclonic circulation areas, sliding at the peripheries of their respective domes (Fig. 9 *a*, *b*, *c*). A salinity of 38.99-39.01 and a temperature of 15.25-15.30°C constitute the signature of the intermediate water mass generated in this region of the Cretan Sea. Comparing the characteristics of the source waters in the different source areas, even in the Cretan Sea, we reconfirm the scatter in the T, S values (Fig. 1, 10). There is, however, a more or less general trend in the T-S diagram, suggesting that the source waters are warmer and saltier at the eastern than at the western source areas. This is due to the different characteristics of the water masses participating in the formation processes in various source regions, local prevailing meteorological conditions and annual variation. The formation processes which appear to take place in several regions of the Cretan Sea contribute to the renewal of the LIW. This is also apparent from the high oxygen content measured at intermediate depths. Since low temperature and sufficient high salinity values have been measured during the late winter period, we assume that the southern Cretan Sea could be considered as a formation zone of LIW along the Cretan shelf, under the influence of strong, dry, cold, north winds. More studies are needed for the estimation of the contribution of the water masses formed in the Cretan Sea to the evolution of Eastern Mediterranean intermediate water.

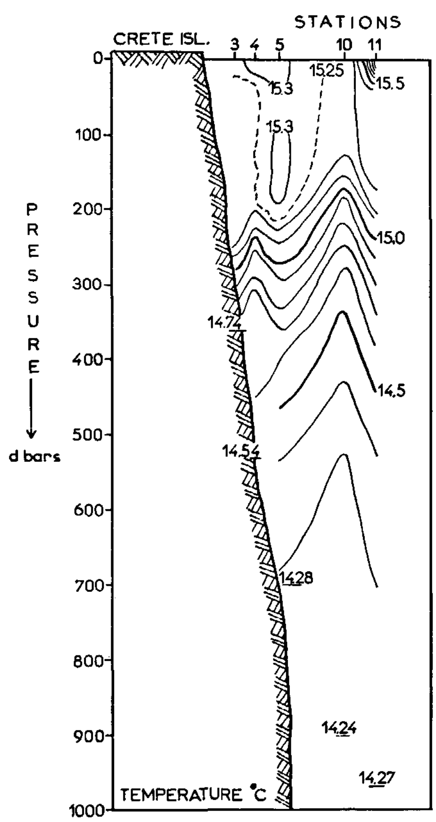

Figure 9 *a*
Vertical distribution of temperature along transect B.
Répartition verticale de la température le long de la coupe B.

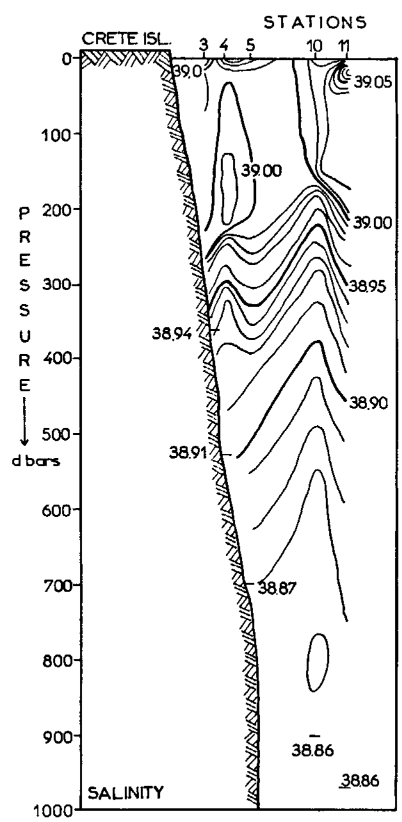

Figure 9 *b*
Vertical distribution of salinity along transect B.
Répartition verticale de la salinité le long de la coupe B.

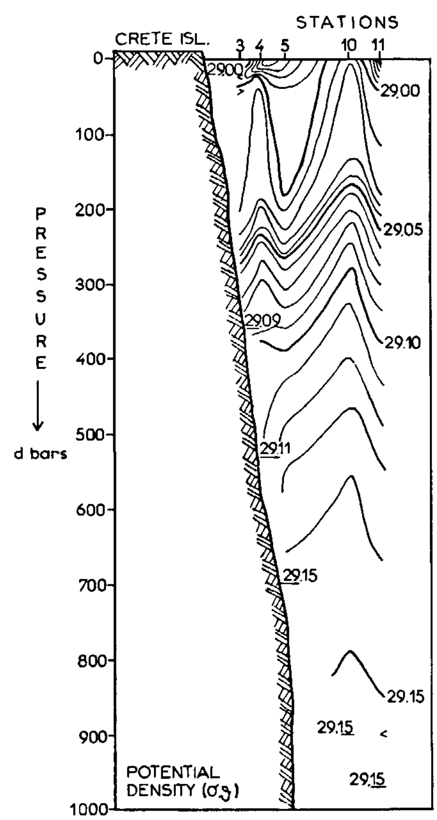

Figure 9 *c*
Vertical destribution of potential density along transect B.
Répartition verticale de la densité potentielle le long de la coupe B.

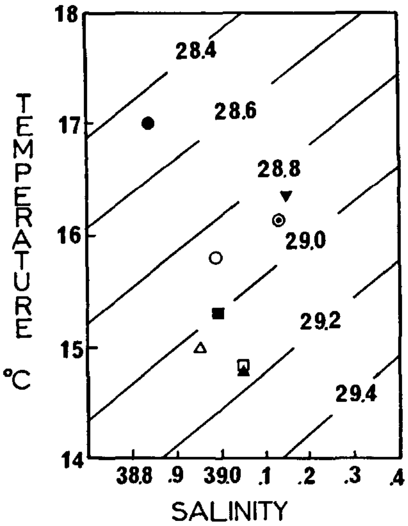

Figure 10

T-S diagram of the source water at the different source areas of the Eastern Mediterranean.

Diagramme T-S des eaux de sources diverses trouvées en différentes régions de la Méditerranée Orientale.

● *Eastern Cretan Sea, February* 1965 (*Bruce and Charnock*, 1965).
■ *Southern Cretan Sea, March* 1986 (*Georgopoulos, Theocharis, Zodiatis*).
▲ *Rhodos gyre, March* 1977 (*Ovchinnikov*, 1984).
□ *Rhodos gyre, February* 1982 (*Ovchinnikov*, 1984).
○ *Western Cyprus eddy, February* 1982 (*Ovchinnikov*, 1984).
△ *Central Cretan Sea, February* 1974 (*Ozturgut*, 1976).
▼ *Antalya Gulf, March* 1974 (*Ozturgut*, 1976).
⊙ *Rhodos, March* 1974 (*Ozturgut*, 1976).
▽ *Southern Levantine, March* 1959 (*Morcos*, 1972).

CONCLUSIONS

CTD measurements carried out over the Cretan Sea, during the late winter POEM-01-86 cruise revealed a new source area of intermediate water over the eastern part of the Cretan shelf.

The high salinity ($\sim$39.00) of the water mass found in the southern Cretan Sea and the winter meteorological conditions constitute a favourable background for convective mixing, especially over the easten part of the Cretan shelf. The homogenization of the entire water column over the shelf and the high density of the water near the surface caused, by strong cold and dry north winds, facilitate the sinking of dense water up to intermediate depths of 200-250 m. An anticyclonic eddy is present off the shelf area. The water formed over the shelf area and probably the waters formed within the surrounding cyclonic flow regions accumulate in the anticyclonic convergent region. There, final mixing occurs and an intermediate water mass, with 15.25-15.30°C temperature and 38.99-39.01 salinity, is generated.

The zone along the Cretan shelf may therefore be considered as a source area of Eastern Mediterranean, intermediate water, given favourable meteorological conditions.

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