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Hydrological structure of the Cretan Sea and adjacent regions in late winter 1994

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Abstract. Analysis of CTD data collected in the Cretan Sea and adjacent regions in late winter 1994 revealed the hydrological structure of their waters: Modified Atlantic Water (MAW) occurs in the south-eastern Ionian Sea and enters the Cretan Sea through the Antikithira Strait. Levantine Surface Water (LSW) spreads into the Cretan Sea across the Karpathos and Rhodos Straits. Surface waters of Black Sea origin (BSW) are identified in the north-western Cretan Sea. Levantine Intermediate Water (LIW) is present everywhere as a subsurface salinity maximum. Saline and warm Cretan Deep Water (CDW) occurs as a thick bottom layer in the Cretan Sea and also in the Antikithira and Kassos Straits; however, its influence is felt over the entire study area. Notable is the absence of the Eastern Mediterranean Deep Water (EMDW); instead, Eastern Mediterranean Transition Waters (EMTW) occupy thick layers beyond the Cretan Sea, whilst after intruding the latter, via the Antikithira, Kassos and Karpathos Straits, their signature is a pronounced salinity and temperature minimum layer.

1. Introduction

The Cretan Sea (Fig. 1a) occupies the southern and larger basin of the Aegean Sea in the Eastern Mediterranean. Its distinguishing bathymetric features are deep troughs, deeper than 1000 m in its western part and 2000 m in its eastern part, respectively (Fig. 1b). The Cretan Sea is delimited to the north by the Kiklades Plateau and to the south by the islands of the Cretan Arc. Through the straits of the latter (Fig. 1b) the Cretan Sea exchanges waters with the southeast Ionian Sea across the Straits of Elafonissos (sill depth 200 m; width 11 km) and Antikithira (sill depth 700 m; width 31 km), and with the northwest Levantine Sea via the Kassos Strait (sill depth 1000 m; width 67 km), the Karpathos Strait (sill depth 850 m; width 43 km), and the

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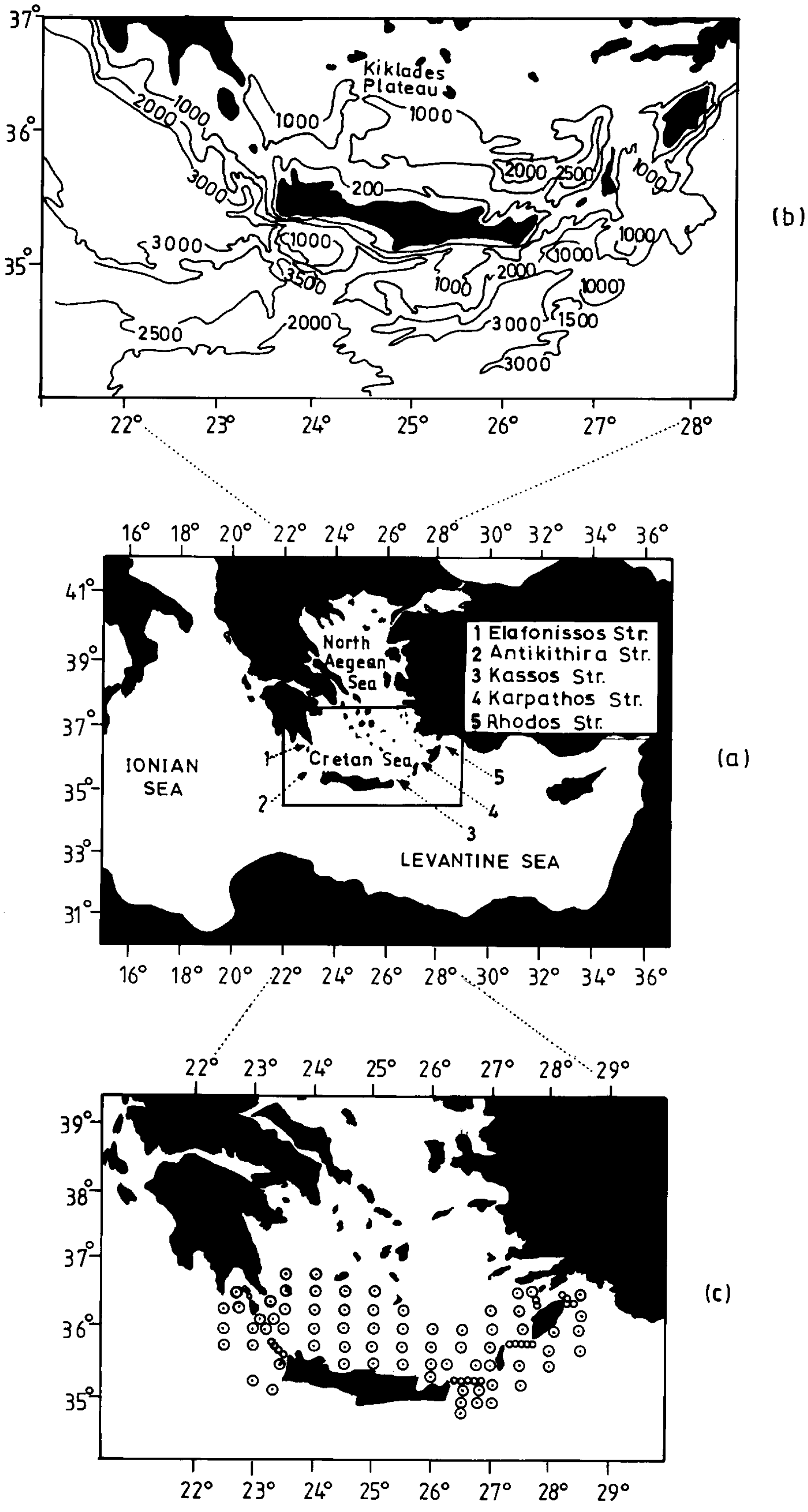

Fig. 1 - (a) The Cretan Sea and adjacent regions. (b) The bottom topography of the study area. (c) The locations of the CTD stations.

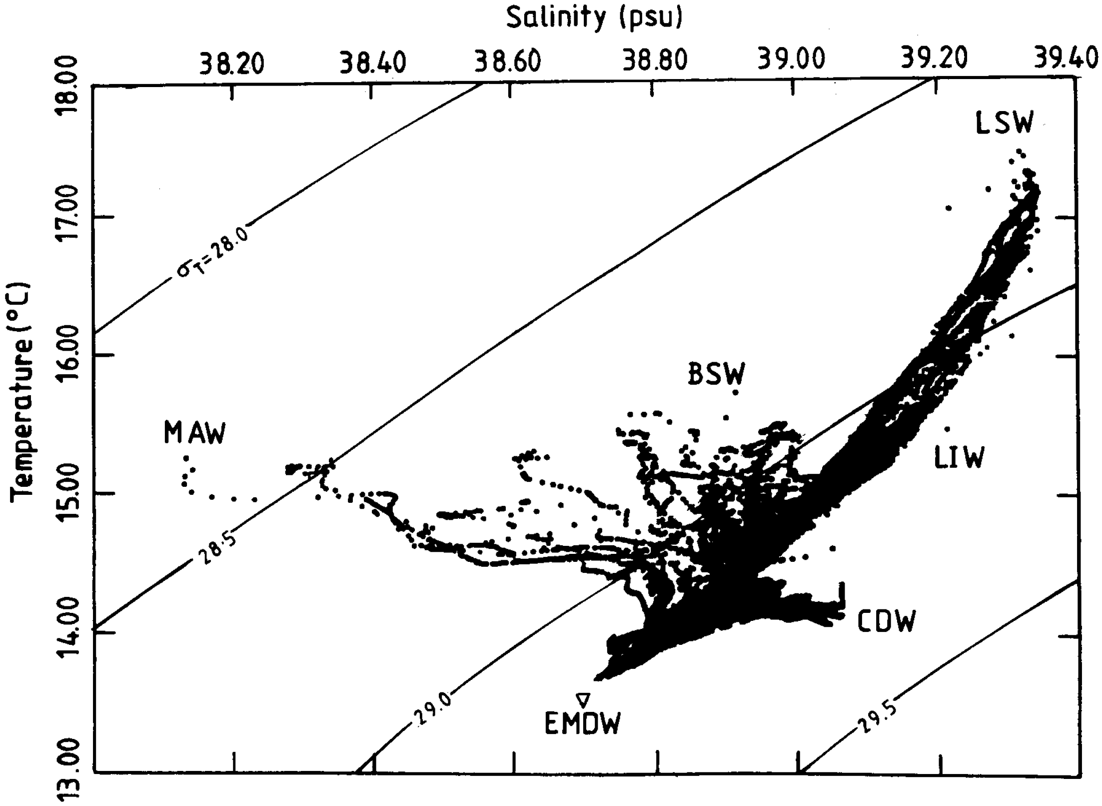

Fig. 2 - Composite T-S diagram for the PELAGOS-I-94 late winter cruise. MAW: Modified Atlantic Water; LSW: Levantine Surface Water; BSW: Black Sea Water; LIW: Levantine Intermediate Water; EMDW: Eastern Mediterranean Deep Water; CDW: Cretan Deep Water.

Rhodos Strait (sill depth 350 m; width 17 km).

The general features of the hydrology of the Cretan Sea and adjacent regions have been broadly known for some time (see, inter alia Hopkins, 1987; Rizzoli and Hecht, 1988). During the last decade, and particularly within the framework of the P.O.E.M (Physical Oceanography of the Eastern Mediterranean) Project, more detailed pictures of water-mass distributions and physical processes (Zodiatis, 1991; Theocharis et al., 1993) have emerged.

The surface layer of the study area is occupied mainly by three water masses with different thermohaline characteristics and sources. (1) The warm and saline (39.15-39.20) Levantine Surface Water (LSW) occurs in most eastern regions, entering the Cretan Sea through the eastern straits of the Cretan Arc (Zodiatis, 1991). In the Rhodos area, its salinity reaches very high values (~39.50) due to intense evaporation (Unluata, 1986). (2) The relatively low salinity (38.80-38.95) Black Sea Water (BSW) originating from the Black Sea and entering the Aegean Sea through the Straits of Dardanelles reaches the Cretan Sea through the northwest passages of the Kiklades Plateau. This water mass ultimately leaves the Aegean Sea through the straits of the western Cretan Arc (Zodiatis, 1993). (3) The occurrence of low salinity Modified Atlantic Water (MAW) in the southwesternmost part of the study area has been discussed in the literature (Manzella et

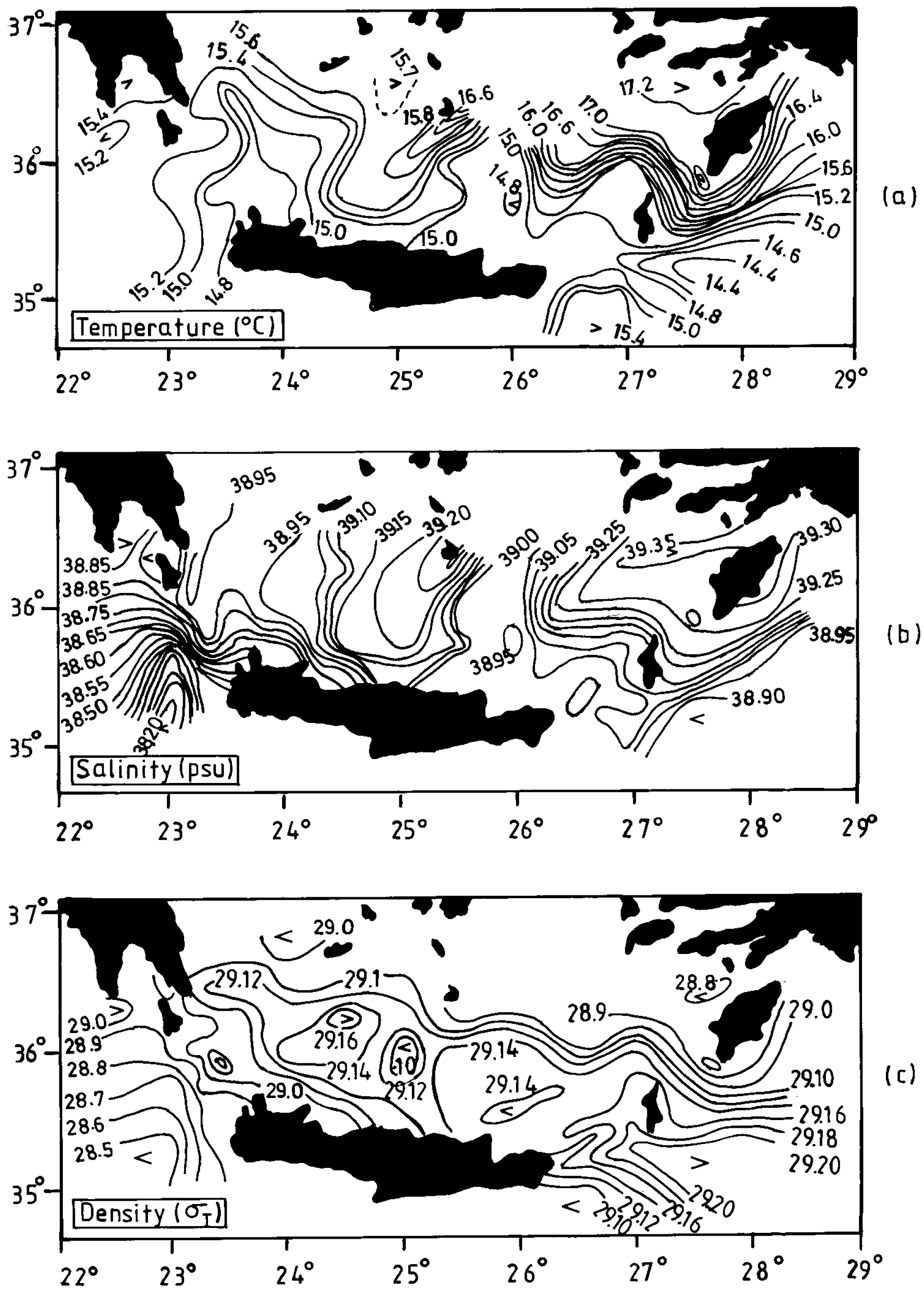

Fig. 3 - Distribution of (a) temperature (°C), (b) salinity, (c) density (σ_T) at the surface (2 dbar) in late winter 1994.

al., 1988; Theodorou, 1990). In the Cretan Sea, where its signature is a subsurface (≤ 200 m) salinity minimum (38.68-38.90), the MAW enters through the straits of the Cretan Arc (Theocharis et al., 1993).

The intermediate layer of the study area is dominated by the presence of the high salinity

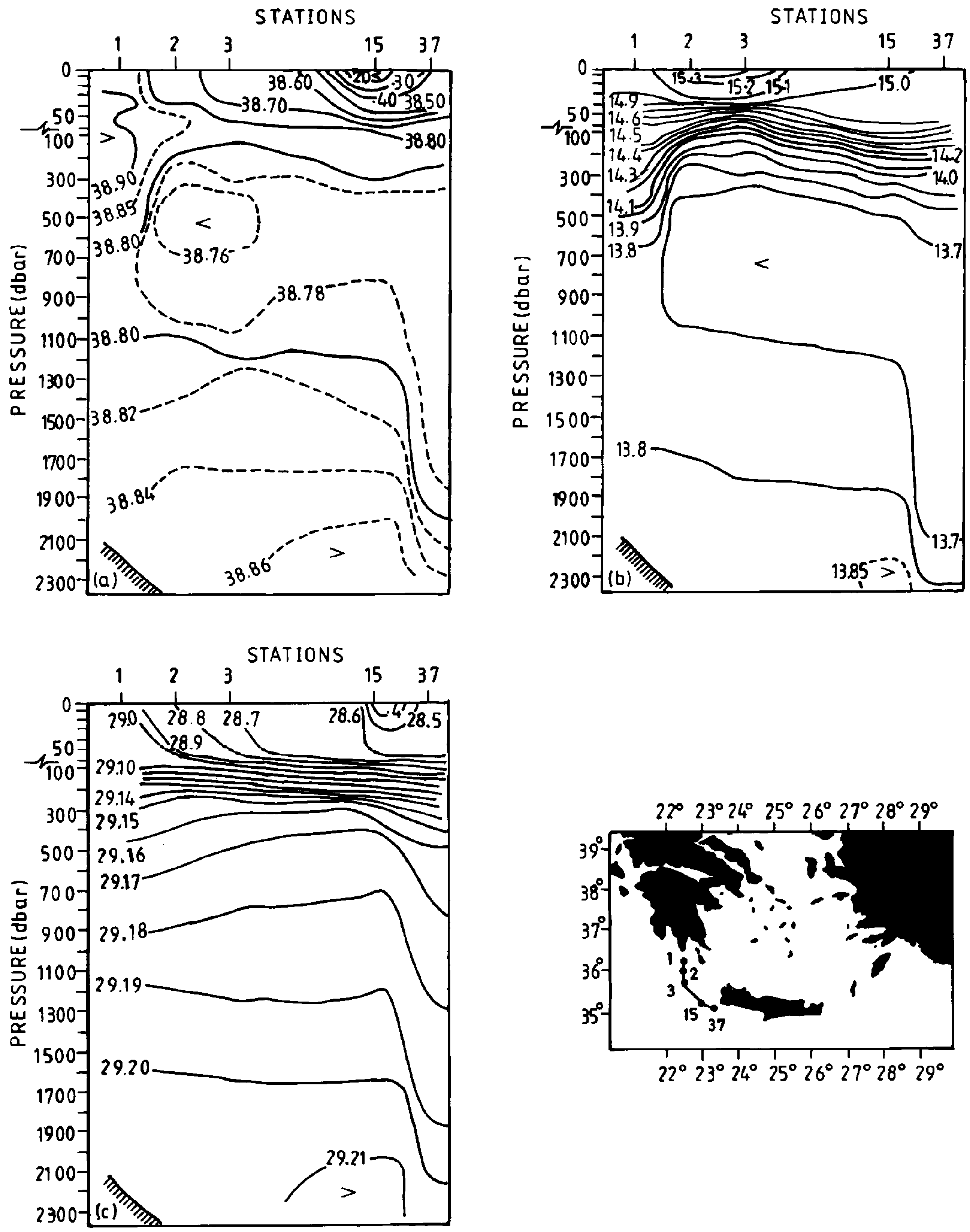

Fig. 4 - Vertical distributions of (a) salinity, (b) potential temperature (°C), and (c) potential density (σ_θ) along the section in the southeast Ionian Sea in late winter 1994 (see inset map for the location of the section within the study area).

(~39.1) Levantine Intermediate Water (LIW). This originates mainly at the surface at various places in the Levantine Sea (Nielsen, 1912; Wüst, 1961; Morcos, 1972; Ünlüata, 1986). However, intermediate water is also formed in the South Aegean Sea (Georgopoulos et al., 1989).

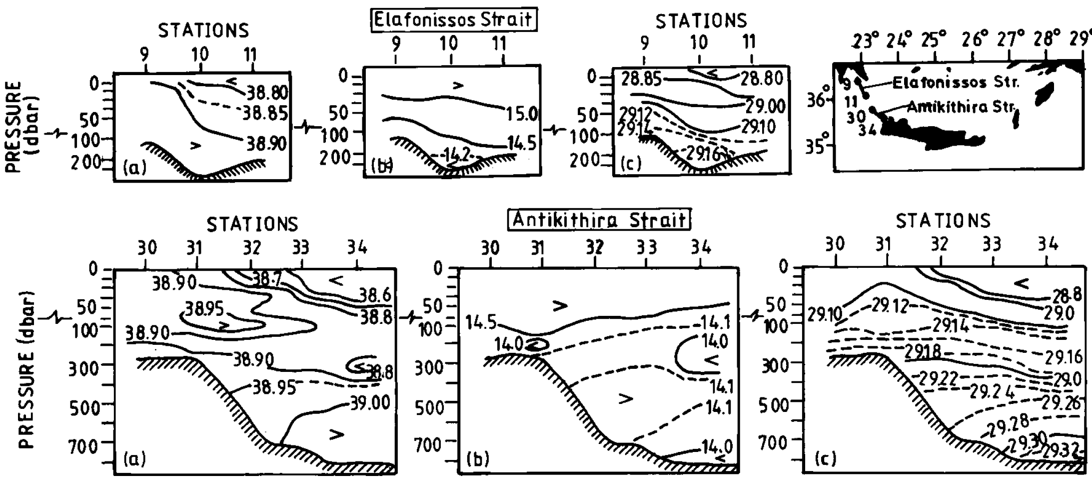

Fig. 5 - Vertical distributions of (a) salinity, (b) potential temperature (°C), and (c) potential density (σ_θ) along the sections in Elafonissos Strait (upper), and Antikithira Strait (lower) in late winter 1994 (see inset map for the locations of the sections within the study area).

In the deeper layers of the study area, two main water masses occur: (1) The relatively warm and saline Cretan Deep Water (CDW) originates at the centre of cyclonic gyres, mainly in the western part of the Cretan Sea during severe weather conditions (Gertman et al., 1990); but its formation is also influenced by the dense water sinking from the Kikladian shelf into the deep troughs of the Cretan Sea (Zodiatis, 1991a). (2) The consistently uniform (T=13.6 °C; S=38.70) Eastern Mediterranean Deep Water (EMDW) is produced in the Ionian Sea through the mixing of modified LIW, mainly with deep, cold and dense Adriatic Sea Water (Roether and Schlitzer, 1991) outflowing across the Otranto Strait (Theodorou, 1991a). The upper portion (700-1600 m) of the EMDW may be considered as a transitional water mass (Pollak, 1951) lying between the LIW and the EMDW.

In this paper CTD data are used to describe the hydrological structure in the Cretan Sea and adjacent regions during late winter 1994, and thus contribute to a better understanding of their regional oceanography.

2. Data and methods

To this end and within the framework of the PELAGOS-I Mediterranean Targeted Project (MTP), CTD data were acquired on board the R/V AEGAIO on a regular 0.5° (latitude and longitude) grid of 93 stations (Fig. 1c) in the Cretan Sea and adjacent southeastern Ionian and northwestern Levantine regions, between 14 March and 15 April 1994. A denser grid was employed in the Straits of the Cretan Arc. The observations were made using a Sea Bird Electronics (SBE) CTD profiler. The measurements were taken at a rate of 24 scans s^{-1} and they were averaged in situ over 1 s intervals, thereby providing measurements at about 0.7 dbar intervals. A three-point interpolation was used to obtain values at nominal depths of one decibar. No

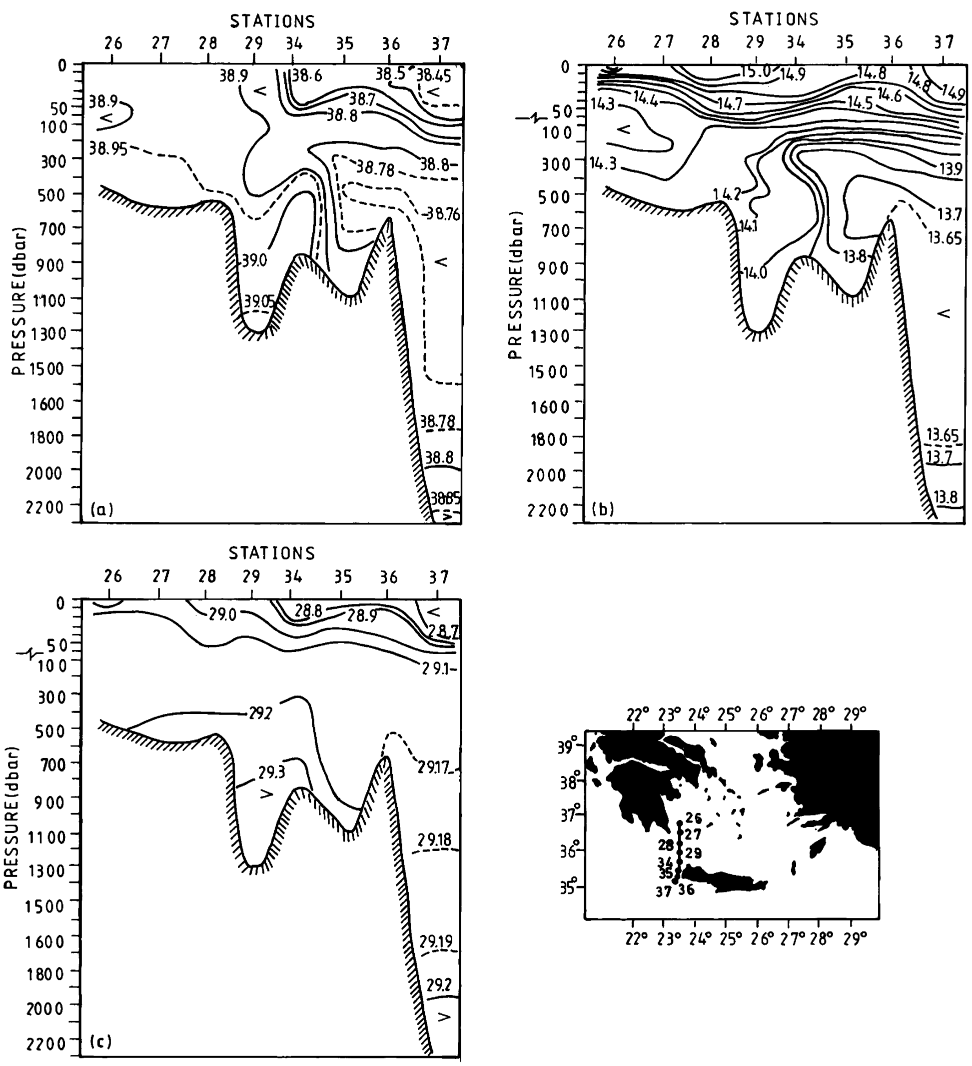

Fig. 6 - Vertical distributions of (a) salinity, (b) potential temperature (°C), and (c) potential density (σ_θ) along the section 23.5 °E in late winter 1994 (see inset map for the location of the section within the study area).

laboratory calibration of the SBE CTD was made before or after the cruise. The CTD salinity of PELAGOS-I dataset was calibrated against water sample salinity measured with an AUTOSAL salinometer. The practical salinity scale is used to determine salinity. During the subsequent processing the data were subjected to conventional methods of analysis.

3. Results and discussion

3.1. Water masses

Fig. 2 shows the composite T-S diagram of all the stations, and clearly demonstrates the pre-

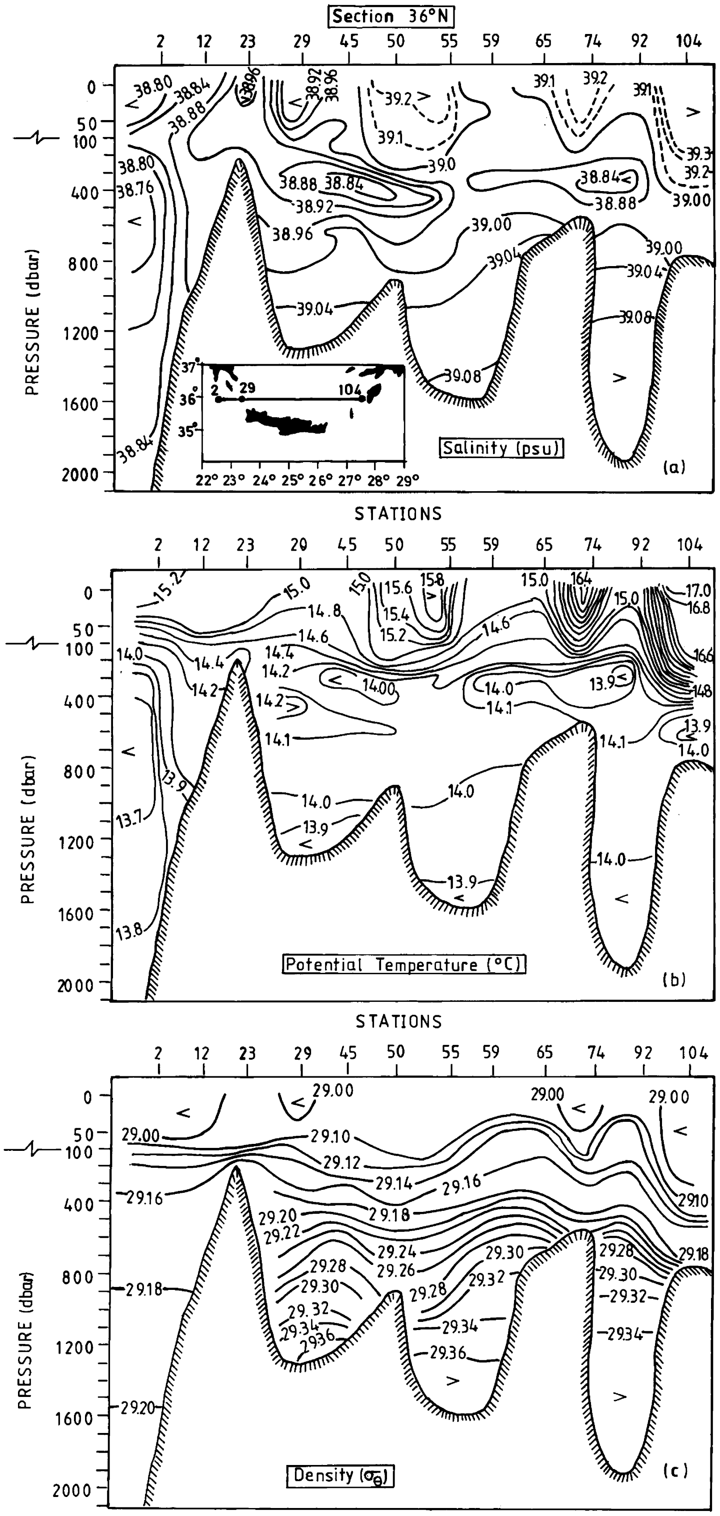

Fig. 7 - Vertical distributions of (a) salinity, (b) potential temperature (°C), and (c) potential density (σ_θ) along the section 36 °N in late winter 1994 (see inset map for the location of the section within the study area).

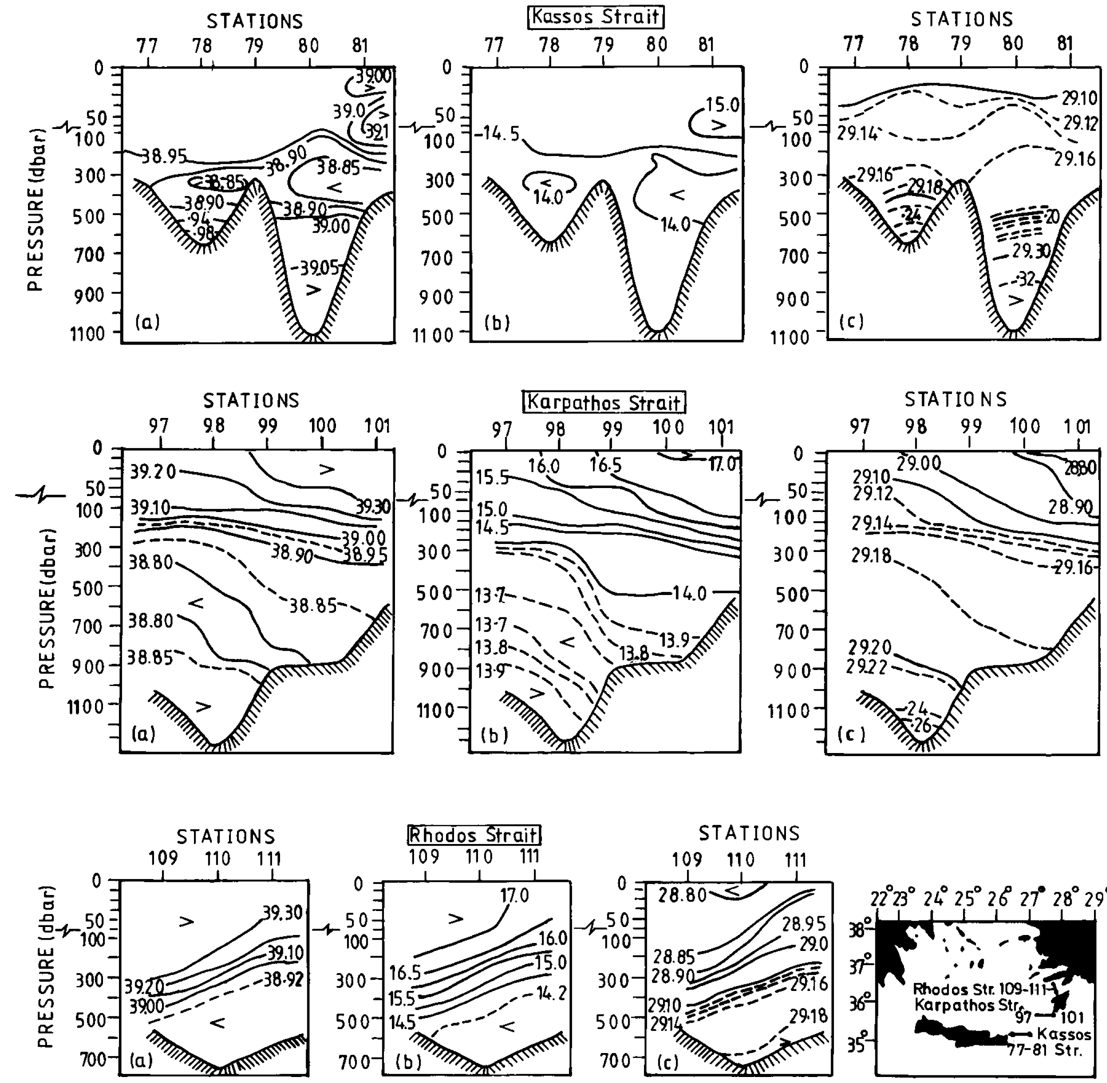

Fig. 8 - Vertical distributions of (a) salinity, (b) potential temperature (°C), and (c) potential density (σ_θ) along the sections in Kassos Strait (upper), Karpathos Strait (middle), and Rhodos Strait (lower) in late winter 1994 (see inset map for the locations of the sections within the study area).

sence of the following indigenous and in transit water masses: (i) Modified Atlantic Water (MAW) of low salinity (38.15-38.80); (ii) Levantine Surface Water (LSW) of high salinity (≤39.37) and warm (≤17.3 °C); (iii) Black Sea Water (BSW) of low salinity (~38.9); (iv) Levantine Intermediate Water (LIW) characterized by a subsurface (~200 dbar) salinity maximum (≥38.90 in the eastern areas and ≥38.85 in western areas); (v) Cretan Deep Water (CDW) highly saline (≥39.00) and warm (~14 °C); (vi) Eastern Mediterranean Transition Water (EMTW) prominent as an intermediate temperature and salinity minimum layer. The absence of the Eastern Mediterranean Deep Water (EMDW) from the study area even at great depths is notable.

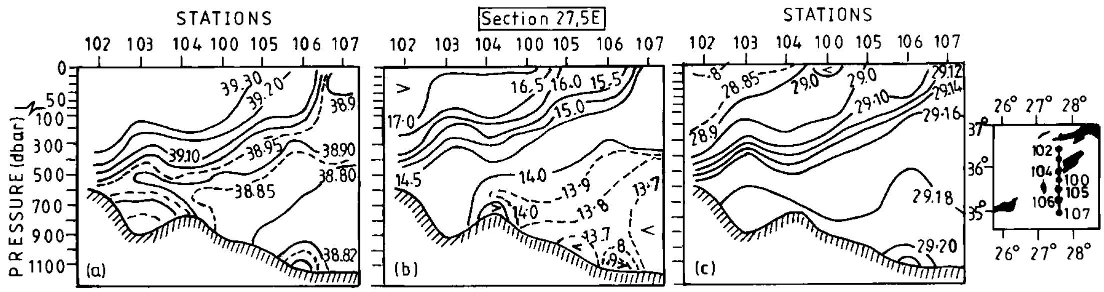

Fig. 9 - Vertical distributions of (a) salinity, (b) potential temperature (°C), and (c) potential density (σ_θ) along the section 27.5 °E, through Karpathos Strait, in late winter 1994 (see inset map for the location of the section within the study area).

3.2. Regional thermohaline structure and dynamic inferences

Owing to its bottom topography (Fig. 1a) the study area can be separated into a number of regions. Thus, the hydrological structure will be studied regionally on the basis of the distributions of salinity and potential temperature along selected vertical sections. Vertical sectional density (σ_θ) distributions will also be employed to derive dynamic inferences. Specifically, from the slope of σ_θ-isolines the direction of baroclinic shear-assuming geostrophy- and the presence of mesoscale disturbances can be deduced. Advection or decay of the latter has been shown in other oceanic areas to have much longer time scales than the quasi-synopticity of the sections (Bernstein and White, 1974), and hence these features will be considered as consistent.

SOUTHEASTERN IONIAN SEA AND WESTERN CRETAN ARC STRAITS. The surface salinity ranges from 38.152 in the southernmost part of this area to 38.872 in its northernmost part. This strong surface salinity gradient separates saline waters in the north and east from the relatively lower salinity MAW in the south (Fig. 3b). The core of the latter water mass, where the lightest water (σ_T =28.43) occurs, is flanked by heavier water (Fig. 3c) thereby indicating an anticyclonic feature, which presumably is a part of the so-called Pelops multicentered anticyclone (Robinson et al., 1991). A similar mesoscale anticyclonic feature was also observed during late winter 1986 (Theodorou, 1990, 1991b; Theocharis et al., 1993). The MAW, transported by the mid-Mediterranean current from the Western Mediterranean to the southeastern Ionian, occurs in the uppermost (0-50 dbar) layer in the southeasternmost Ionian, and its signal is a surface salinity minimum (Fig. 4a), whereas the saline Levantine waters, which occur in the northern part, extend from the surface down to about 500 dbar (Figs. 3b and 4a). There is an impressive, thick (200-1000 dbar) intermediate layer of minimum salinity and temperature, due to EMTW (Fig. 4). Below this, and even at great depths (~2300 dbar), no salinities pertinent to the EMDW (~38.70) are encountered; rather, water of relatively high salinity (>38.86) is evident (Fig. 4a), thereby implying the influence of the outflowing high salinity CDW.

The Antikithira Strait is dominated by a mesoscale cyclonic eddy, which seems to be centered on station 31 (lower Fig. 5c). The latter cyclonic eddy, in conjunction with the aforementio-

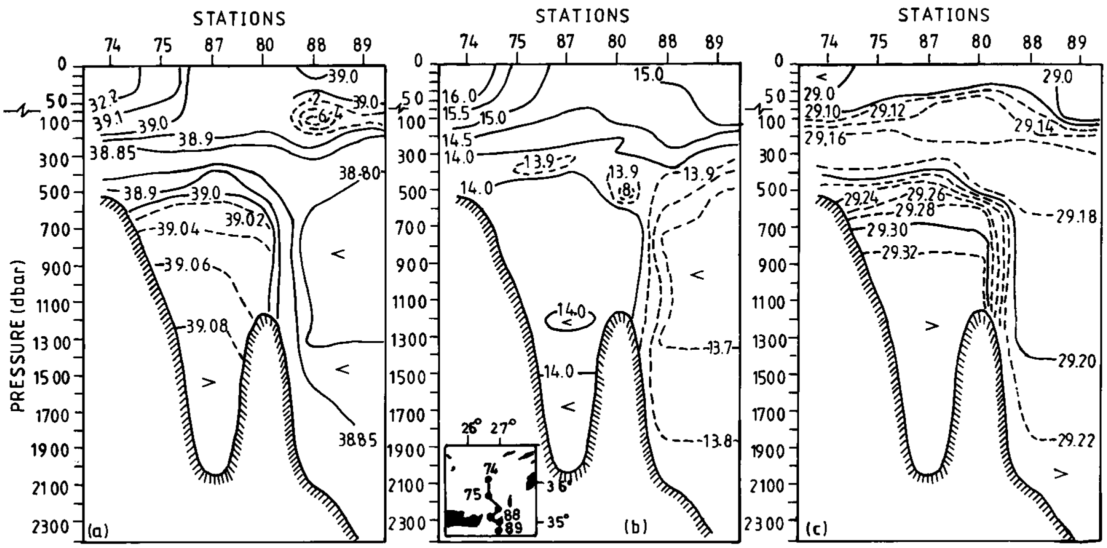

Fig. 10 - Vertical distributions of (a) salinity, (b) potential temperature (°C), and (c) potential density (σ_θ) along the section through Kassos Strait, in late winter 1994 (see inset map for the location of the section within the study area).

ned Ionian anticyclone, controls the water exchange through this strait. Thus, a surface layer (~ 50-100 dbar) of relatively cooler (<15 °C) and fresher (< 38.60) MAW appears to enter the western Cretan Sea through the eastern part of the Antikithira Strait (stations 34-37 in Figs. 6a and 6b), whereas Black Sea Water (BSW) occurs in its uppermost western part, presumably exiting from the Strait (lower Fig. 5). EMTW occupies the intermediate depths of this Strait, and enters the western Cretan Sea (stations 26-34 in Figs. 6a and 6b), whilst deeper than about 500 dbar, a relatively thick bottom layer of CDW is evident outflowing from the Antikithira Strait (lower Fig. 5). Although the CDW evidently influences considerably the hydrology of the deep southeastern Ionian Sea (Fig. 4), it only shows diluted characteristics offshore from the sill depth of Antikithira Strait (Figs. 6a and 6b). In the Elafonissos Strait, there is a surface inflow of MAW and a deeper outflow of higher salinity Levantine waters (upper Fig. 5).

CRETAN SEA. In the southwestern Cretan Sea MAW occurs in the near-surface layer inflowing through the eastern side of the Antikithira Strait (lower Fig. 5). As far as 24.5 °E, this MAW intrudes into the southwesternmost Cretan Sea; and, while spreading eastwards its salinity increases to about 38.6-38.7, due to its encounter with relatively more saline (~38.90) BSW spreading from the north Aegean (Fig. 3b). BSW occupies the upper 100 dbar or so layer in the northwestern Cretan Sea (stations 26-29 in Fig. 6). Fig. 7 vividly demonstrates the vertical thermohaline and dynamic structure of the Cretan Sea. The pattern of the σ_θ- isolines is indicative (Fig. 7c) of the juxtaposition of cyclonic and anticyclonic regions; in the former regions, intermediate waters (~ 250 dbar) are surfacing, whilst in the latter, relatively warm (14.2-16.0 °C) and saline (38.9-39.2) Levantine waters are trapped, and sinking takes place. However, the most

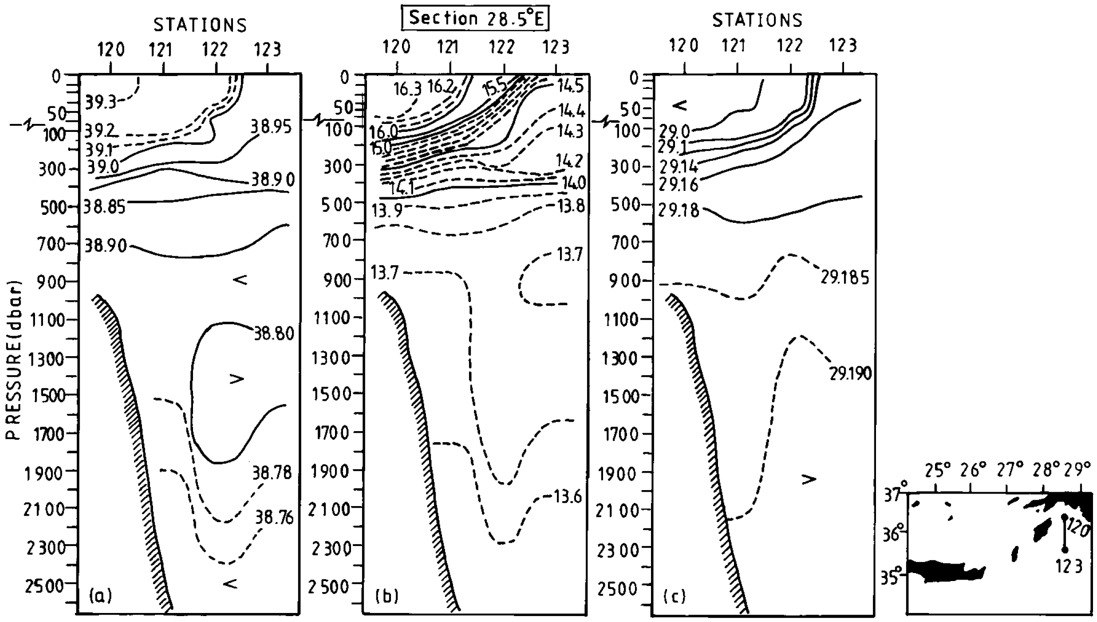

Fig. 11 - Vertical distributions of (a) salinity, (b) potential temperature (°C), and (c) potential density (σ_θ) along the section 28.5 °E in late winter 1994 (see inset map for the location of the section within the study area).

striking feature is the presence of an intermediate salinity (and temperature) minimum layer, which is present almost throughout the entire Cretan Sea. This layer consists of EMTW, and its vertical extent in the central Cretan Sea is about 200 dbar, whilst its core fluctuates between 300-400 dbar (Figs. 7a and 7b). EMTW enters the Cretan Sea through the Antikithira Strait (Fig. 6) as well as across the Kassos (Figs. 8 (top) and 10) and Karpathos Straits (Figs. 8 (middle) and 9). Below the EMTW, both salinity and temperature increase with depth, reaching values which are pertinent to CDW (Figs. 7a and 7b). The latter water mass is also the densest, with σ_θ greater than 29.36 (Fig. 7c). Our data clearly show that the thermohaline characteristics of the Cretan Sea deeper water masses have shifted towards higher values, probably due to dryness and deep convection processes owing to long term atmospheric forcing; thus, they confirm earlier results (Theocharis et al., 1993).

The eastern Cretan Sea is dominated by a surface thermal front separating the warmer (≤17.5 °C) and saline (≤39.50) Levantine Surface water (LSW) in the northeastern part from the colder (< 15°C) and relatively less saline (~39.00) waters in its southwestern part (Fig. 3a,b). The former warm saline waters are transported by a branch of the Asia Minor current (AMC) mainly through the western side of the Karpathos Strait (Figs. 8 (middle) and 9). Between Rhodos and Asia Minor, the highest surface salinities (~39.50) are observed (Fig. 3b); these salinities remain almost uniformly high in a thick layer extending from the surface down to about 400 dbar (Fig. 9a). This region is characterized by a strong anticyclonic flow (Fig. 9c). The influence of these high salinity Levantine waters is found as far as 26.5°E extending southwestwards into the Cretan Sea (Fig. 10).

NORTHWESTERN LEVANTINE SEA AND EASTERN CRETAN ARC STRAITS. In the northwestern Levantine Sea, relatively cold (T < 14.4 °C) and dense ($\sigma_\theta > 29.2$) surface water is flanked by lighter water, which fact is consistent with cyclonic movement; moreover, to the west of this cyclonic region, there is light water surrounded by heavier water, which implies anticyclonic flow (Figs. 3a and 3c). The former area corresponds to the northernmost part of the Rhodos gyre, which is a persistant feature of the northwest Levantine Basin (Ozsoy et al., 1989, 1991; Robinson et al., 1991; Zodiatis 1992, 1993; Theocharis et al., 1993) and is also the main area of LIW formation in the Easterm Mediterranean Sea during winter cooling of the sea surface; whilst the latter feature indicates the presence of the so-called Ierapetra anticyclone (Theocharis et al., 1993). Fig. 11 shows part of the vertical thermohaline structure of the Rhodos gyre dome. Within this, upwelling of relatively colder and fresher waters from the deeper layers (200-250 dbar) is evident. The Rhodos gyre weakens with depth, being stronger only in the upper 400 dbar, in agreement with earlier findings (Theocharis et al., 1993). Moreover, north of the Rhodos gyre, there is a strong horizontal temperature gradient, a result of the juxtaposition of the cooler/upwelled surface waters in the Rhodos gyre and the warmer surface waters transported by the AMC just south of Rhodos (Fig. 3a). LIW occurs in the northwest Levantine Sea in a relatively thin layer (100-200 dbar), which deepens within the anticyclonic flow regions (Fig. 11).

Temperature and salinity characteristics of the deeper layers of all sections, beyond the Cretan Sea, although decreasing, never reach values pertinent to the EMDW (T = 13.7 °C; S = 38.70). In contrast, waters with thermohaline characteristics of EMTW occur in the deeper layers (600-2600 dbar) in all regions outside the Straits of the Cretan Arc. EMTW originating in the Levantine, where it occupies a thick layer (Fig. 11), participates in the meandering flow, which occurs in the Kassos Strait (upper Fig. 8), and eventually enters the Cretan Sea (Fig. 10), as it does also across the western side of the Karpathos Strait (middle Fig. 8).

CDW also appears in the deeper parts of the Kassos Strait, presumably exiting from the South Aegean (upper Fig. 8), and contributes significantly to the hydrological structure of the waters, as is implied by the relatively higher temperatures and salinities of the deep layers of the northwest Levantine (Figs. 8 (top) and 10). CDW, although present near the bottom of the Kassos Strait, does not show its thermohaline characteristics in undiluted form beyond the sill of this Strait (Fig.10), presumably due to the intense diapycnal processes which occur there. Moreover, in the area of the Rhodos gyre, a thick layer (1000-1800 dbar) of relatively high salinity water (S > 38.8) is evident (Fig. 11), thereby indicating that the influence of CDW extends well into the area of the Rhodos gyre.

The upper 200 dbar or so layer of the eastern side of the Kassos Strait are occupied by saline Levantine waters, which overlie an intermediate layer of EMTW; both water masses seem to enter the Cretan Sea (upper Fig. 8). A strong pycnocline occurs between 500-600 dbar also in the eastern side of the Strait, presumably delineating the upper boundary of outflowing CDW (upper Fig. 8). Warm and saline waters of Levantine origin occupy the upper 300-400 dbar of the Karpathos Strait (middle Fig. 8), most likely entering the Cretan sea (middle Fig. 8c), whilst, in the remaining deeper parts of this Strait an inflow of EMTW occurs (middle Fig. 8). The entire Rhodos Strait is occupied by warm saline Levantine waters entering the South Aegean (lower Fig. 8), which are most likely transported by a strong branch of the AMC.

4. Conclusions

In the framework of the PELAGOS-I experiment, CTD data were collected on board the R/V AEGAIO in the Cretan Sea and adjacent regions between 14 March and 15 April 1994. The water mass analyses led to the following conclusions:

(1) Low salinity (38.15-38.80) Modified Atlantic Water (MAW) occurs mainly in the upper layer (0-100 dbar) in the south-eastern Ionian Sea, and tends to enter the Cretan Sea through the south-eastern part of the Antikithira Strait.

(2) High salinity (≤ 39.37) warm (≤ 17.3 °C) Levantine Surface Water (LSW) is transported by two intense Asia Minor Current (AMC) branches from the northern Levantine Basin through the Karpathos and Rhodos Straits, respectively in the central and eastern Cretan Sea.

(3) Low salinity (~ 38.9) surface waters of Black Sea origin (BSW) are identified in the north-western Cretan Sea.

(4) Levantine Intermediate Water (LIW) occurs throughout the area under study and is characterized by a subsurface (~200 dbar) salinity maximum (≥38.90 in the eastern areas and ≥38.85 in western areas).

(5) Saline (≥ 39.00) and warm (~14 °C) Cretan Deep Water (CDW) occupies a thick, near-bottom layer in the Cretan Sea and also at the sills of the Antikithira and Kassos Straits, but not offshore the latter. However, its influence is felt throughout study area, as is implied by the higher temperatures and salinities of the deeper water masses in both the southeastern Ionian and the northwestern Levantine Seas.

(6) The absence of Eastern Mediterranean Deep Water (EMDW) from the study area even at great depths was notable.

(7) The almost ubiquitous Eastern Mediterranean Transition Water (EMTW) occupies thick layers beyond the Cretan Sea. Whilst transported through the Antikithira and Kassos Strait within the latter, it was prominent as an intermediate temperature and salinity minimum layer, due to its intrusion into the saline and warm Cretan Sea water masses.

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