Circulation in the Cretan Sea and adjacent regions in late winter 1994

Neutral surfaces
Circulation
Mediterranean Sea
Cretan Sea
Hydrology

Surfaces neutres
Circulation océanique
Mer Méditerranée
Mer de Crète
Hydrologie

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ABSTRACT

This paper presents the qualitative circulation patterns of the "upper" and "deeper" layers in the Cretan Sea and its environs in late winter 1994. The qualitative aspects of the flow field were determined primarily by the distribution of salinity on appropriate neutral surfaces and were supported by dynamic inferences. Water circulation presented a complex pattern, characterized by various sub-basin and mesoscale cylonic and anticyclonic gyres and smaller-scale eddies. An interesting finding was the presence of an eastward current meandering north of Crete, in the South Aegean Sea. Another interesting finding was the spreading in the opposite direction - westward - of the high-salinity Cretan Deep Water. The latter appeared to follow broadly the bottom bathymetric contours in its westward spreading from the presumed area of its formation in the deepest part of the Cretan Sea, where it also attained maximum thickness. The water exchanges between the Aegean Sea and the eastern Mediterranean Sea were influenced by their bottom topography and were also affected by the existence of permanent and/or recurrent circulation features and their variability.

RÉSUMÉ

Circulation dans la Mer de Crète en hiver 1994.

Ce travail présente le schéma de circulation des eaux dans la Mer de Crète en hiver 1994. Il a été déterminé par la répartition de la salinité sur les surfaces neutres et a été confirmé par des calculs géostrophiques. La circulation des eaux est complexe, avec des tourbillons cycloniques et anticycloniques à différentes échelles. Un résultat intéressant est la présence d'un courant vers l'est serpentant au nord de la Crète. En sens opposé, de l'eau de fond salée s'écoule vers l'ouest en suivant les contours bathymétriques, à partir de la zone probable de sa formation dans la partie la plus profonde de la Mer de Crète, où elle atteint son épaisseur maximale. Les échanges d'eaux entre la Mer de Crète et la Méditerranée orientale sont influencés par la topographie du fond, par les caractéristiques permanentes ou temporaires de la circulation et par leur variabilité.

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INTRODUCTION

The Cretan Sea (South Aegean Sea) constitutes the southern and larger basin of the Aegean Sea in the Eastern Mediterranean (Fig. 1*a*). The bathymetry is characterized by troughs which reach depths greater than 1000 m in its western part, and as much as 2500 m in its eastern part (Fig. 1*b*). Bounded to the north by the Cyclades Plateau and to the south by the islands of the Cretan Arc (Fig. 1*b*), the Cretan Sea exchanges waters with the southeast Ionian Sea across the Straits of Elafonissos (sill depth: 200 m; width: 11 km), Kithira (sill depth: 160 m; width: 67 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 Rhodos Strait (sill depth: 350 m; width: 17 km) (Hopkins, 1978).

The surface circulation and its seasonal variability in the Cretan Sea have been broadly known for some time (*see, inter alios*, Malanotte-Rizzoli and Hecht, 1988). Thus, in summer, the surface circulation consists of two flow regions: one cyclonic in the west, and the other anticyclonic in the east (Lacombe *et al.*, 1958); in winter, a broad cyclonic circulation prevails (Ozturgut, 1976; Ovchinnikov *et al.*, 1976). During the past decade and mainly within the framework of the POEM (Physical Oceanography of the Eastern Mediterranean) Programme, a more detailed and complex general circulation pattern, incorporating basin, sub-basin and mesoscale features, has emerged (Theocharis *et al.*, 1993). Thus, during winter, a number of small-scale gyres with the main current meandering from east to west occur; whilst in late summer, cyclonic and anticyclonic flow regions with a meandering flow from the northwest to the east prevail (Theocharis 1989; Zodiatis 1991). This observed seasonal variability in the Cretan Sea circulation has been attributed to the seasonal influence of the main current in the northwestern Levantine Sea, and to the influence of the wind fields (Malanotte-Rizzoli and Bergamasco, 1989).

Water exchanges across the straits of the Cretan Arc have been studied, mainly on the basis of TS analysis or the geostrophic approximation method, and various patterns have been suggested (Nielsen, 1912; Pollak, 1951; Bruce and Charnock, 1965; Burman and Oren, 1970; Lacombe *et al.*, 1958; Ozturgut, 1976; Ovchinnikov, 1966; Mosetti *et al.*, 1972). In the course of the POEM Programme, dynamic calculations of the geostrophic flow, together with current-meter measurements, have revealed a strong flow of water entering the South Aegean Sea through the Rhodos Strait (Theocharis *et al.*, 1987; Zodiatis, 1991).

The northwest Levantine Basin is dominated by the sub-basin multilobe cyclonic Rhodes gyre, which is flanked to the north by the westward-meandering Asia Minor Current (AMC) (Ozsoy *et al.*, 1989; Theocharis *et al.*, 1993). Bordering the latter, two persistent features are the mesoscale anticyclonic eddies which develop along the coast of Asia Minor and the islands of the Cretan Arc. The Rhodes gyre extends westward near Crete in winter, whilst it is restricted eastwards during the warm period of the year. Branches of the AMC intrude into the southeast Aegean through the eastern Cretan Arc straits. Other important features within the study area are: (i) the Ierapetra anticyclone to the southeast of Crete; (ii) the Pelops anticyclone in the southeastern Ionian Sea; and (iii) the Cretan cyclone in the northwestern part of the Cretan Passage (POEM Group, 1992; Theocharis *et al.*, 1993). The eastward-meandering Mid-Mediterranean Jet (MMJ) (Robinson *et al.*, 1991; POEM Group, 1992) recirculates in the Ionian along the Cretan cyclone's meandering boundary and eventually reaches the western straits of the Cretan Arc.

In this paper, CTD data collected within the framework of the PELAGOS Project are used to describe the water mass circulation in the Cretan Sea and adjacent regions during late winter 1994 and thereby contribute to a better understanding of their regional oceanography. The main objective is to infer the general qualitative circulation patterns of the study area. To this end, neutral surface

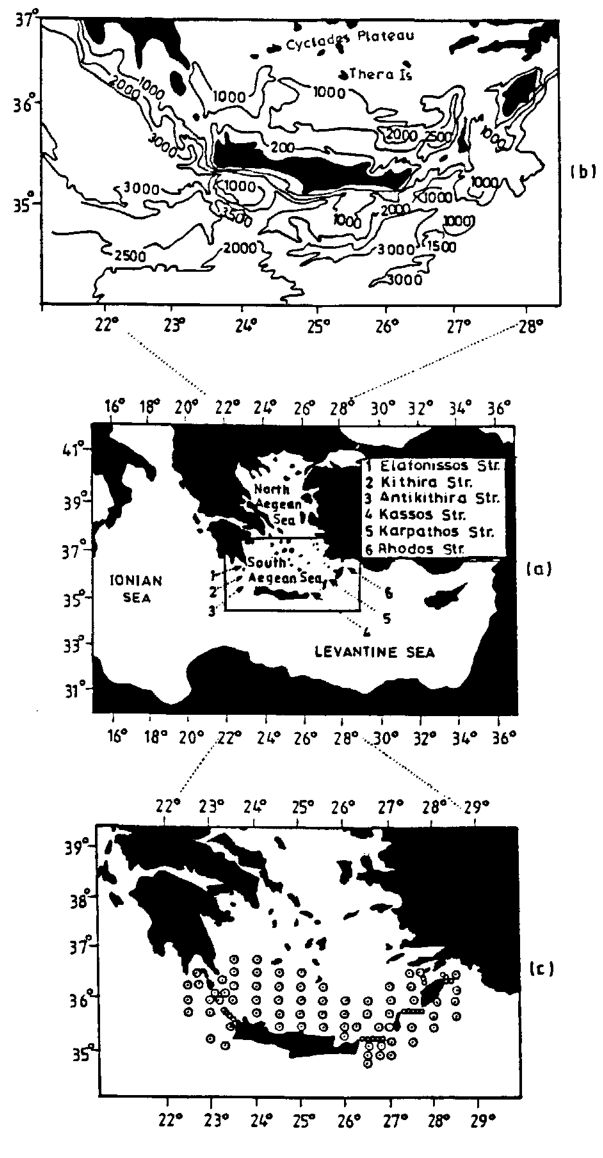

Figure 1

The study area (a); its bathymetry; (b) locations of CTD stations (c).

analysis (Theodorou, 1991), a technique used to infer the qualitative features of a flow pattern on the basis of hydrographic data, was applied. For an understanding of the hydrological structure of the study area during PELAGOS-1, the reader is referred to Theodorou *et al.* (1995).

MATERIALS AND METHODS

Within the framework of the PELAGOS-1 Mediterranean Targeted Project (MTP), CTD data were acquired on board R/V *Aegaio* on a regular 0.5° (latitude and longitude) grid of 93 stations (Fig. 1*c*) in the Cretan Sea and the adjacent southeastern Ionian and northwestern Levantine regions, between 14 March and 15 April 1994. A denser grid was established in the straits of the Cretan Arc. Observations were obtained by means of a Sea Bird Electronics (SBE) CTD profiler. Measurements were taken at a rate of 24 scans s^{-1} and 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 laboratory calibration of the SBE CTD was done either before or after the cruise. CTD salinity figures from the PELAGOS-1 data set were calibrated against water sample salinity measured by an AUTOSAL salinometer.

Neutral surface analysis is a versatile technique for inferring the qualitative aspects of a flow field on the basis of hydrographic data. The reader is referred to Theodorou (1991) for a detailed presentation of this

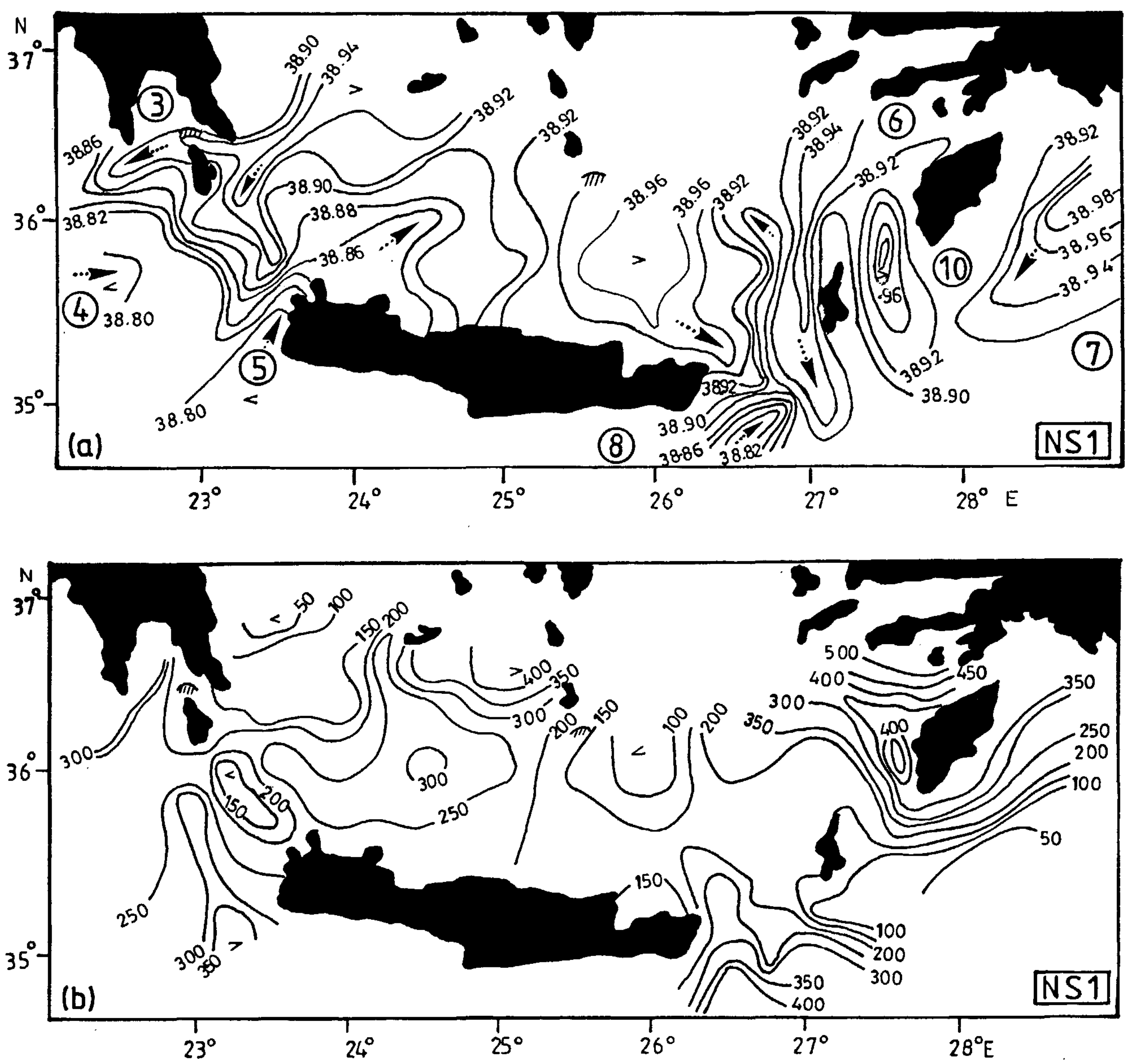

Figure 2

Salinity (a) and pressure (b) of the neutral surface NS1 delineated from a parcel defined by T = 14.628 °C, S = 39.001 at pressure 100 dbar of the reference station 95. The encircled numbers in part (a) refer to comments identified by the same numbers in the text.

technique, as well as its differences and significance *vis-a-vis* isopycnal analysis. On all eight neutral surfaces to be discussed below, the potential temperature distribution follows closely that of salinity, and hence is not shown here. All eight neutral surfaces have been chosen to cover spatially the entire range of all water masses present within the study area; they will be referred to by Arabic numerals, starting with 1 for the uppermost.

RESULTS

Proceeding from the uppermost (NS1) to the deeper ones, three groups of neutral surfaces can be distinguished: upper (NS1 and NS2); intermediate (NS3 to NS5); and deeper (NS6 to NS8). Figures 2 and 3 depict the salinity distribution (a) and the topographies (b) of neutral surfaces NS1 and NS2. Many features of the salinity distribution on the two uppermost neutral surfaces stand out clearly, as listed below.

(1) In the northwestern part of the Cretan Sea, plumes of relatively saline water (> 38.94), spreading from the northeast, interpenetrate with fresher ones (< 38.86) emanating from the southwest, thereby implying a cyclonic mesoscale feature (Figs. 2*a*, 3*a*).

(2) Also in the Cretan Sea, eastwards of the aforementioned cyclonic feature, the pattern of the isohalines indicates the presence of an anticyclonic and, further to the east, of another yet cyclonic feature (Fig. 3*a*). Interconnected with this succession of mesoscale features, a meandering "current", flowing eastwards from the north-westernmost

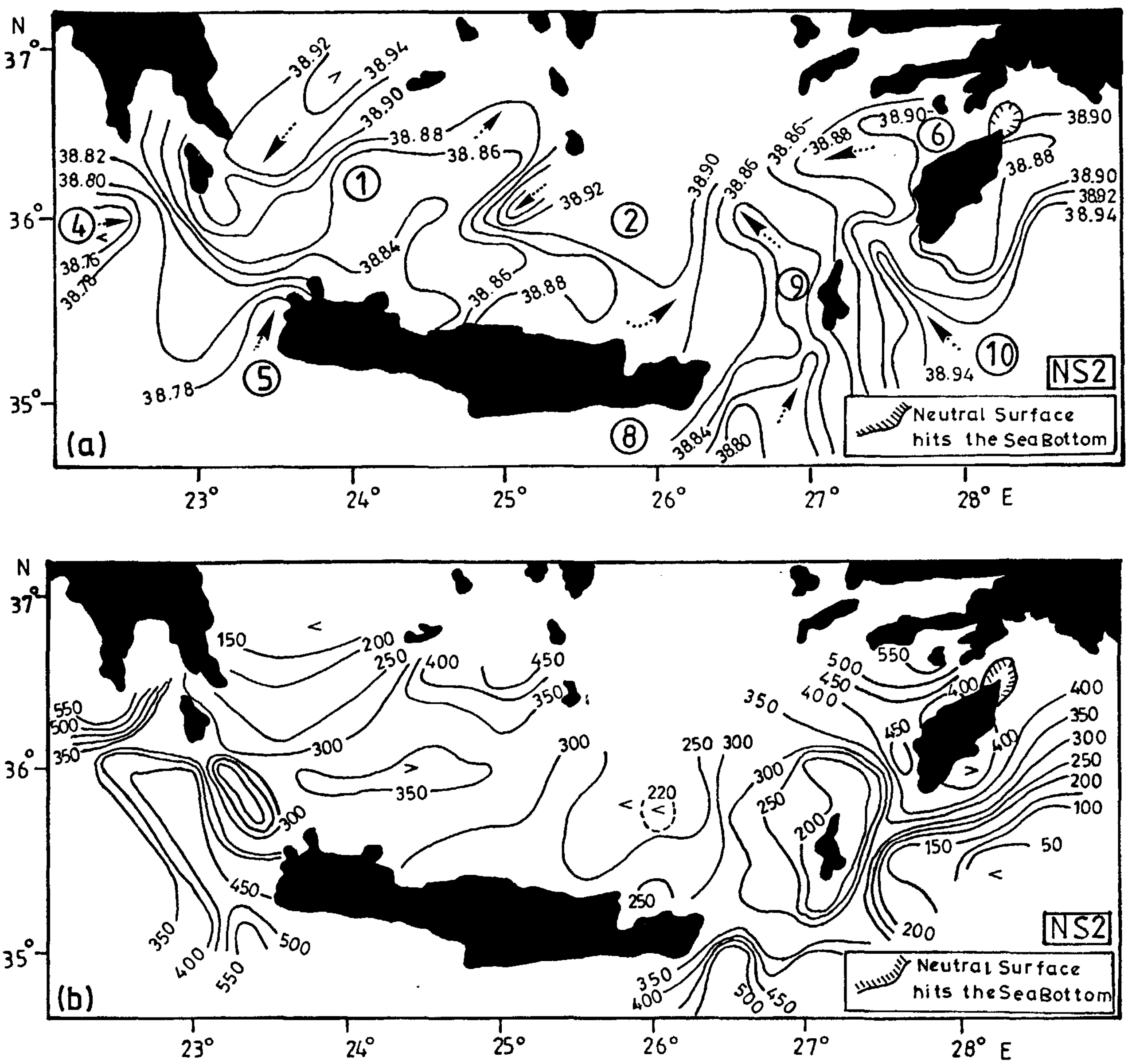

Figure 3

Salinity (a) and pressure (b) of the neutral surface NS2 delineated from a parcel defined by T = 13.674 °C, S = 38.732 at pressure 418 dbar of the reference station 2. The encircled numbers in part (a) refer to comments identified by the same numbers in the text.

part of the study area, may be inferred. To the north of Kassos Strait, this meandering flow presumably turns northwards (Fig. 3*a*).

(3) Tongues of relatively saline water (> 38.90) exit through the Elafonnisos and Antikithira Straits (Fig. 2*a*).

(4) In the southeastern Ionian Sea, a lower salinity tongue (< 38.76) spreads from the west in an anticyclonic direction (Figs. 2*a*, 3*a*).

(5) From this tongue, a plume of fresher water (< 38.80) enters the Cretan Sea through the eastern part of the Antikithira Strait (Figs. 2*a*, 3*a*).

(6) In the Rhodos Strait, a saline plume (> 38.98) enters the Aegean Sea from the east (Figs. 2*a*, 3*a*).

(7) To the south of Rhodos island, in the northwest Levantine Sea, a saline tongue (> 38.98) spreads in an anticlockwise manner (Fig. 2*a*).

(8) Just south of Kassos Strait, and to the west of the aforementioned cyclone, a relatively lower salinity plume (< 38.80) spreads in a clockwise direction (Figs. 2*a*, 3*a*).

(9) From the aforementioned anticyclone, a tongue of lower salinity water enters the Cretan Sea through the central part of Kassos Strait (Fig. 3*a*). This lower salinity intrusion is flanked on each side by tongues of higher salinity water, which appear to exit from the Cretan Sea through the western and eastern parts of Kassos Strait (Fig. 2*a*).

(10) In the Karpathos Strait, a cyclonic, eddy-like feature with a saline core, is evident on NS1, whilst on NS2, an intrusion of saline water (> 38.94) occurs in the Cretan Sea (Figs. 2*a*, 3*a*).

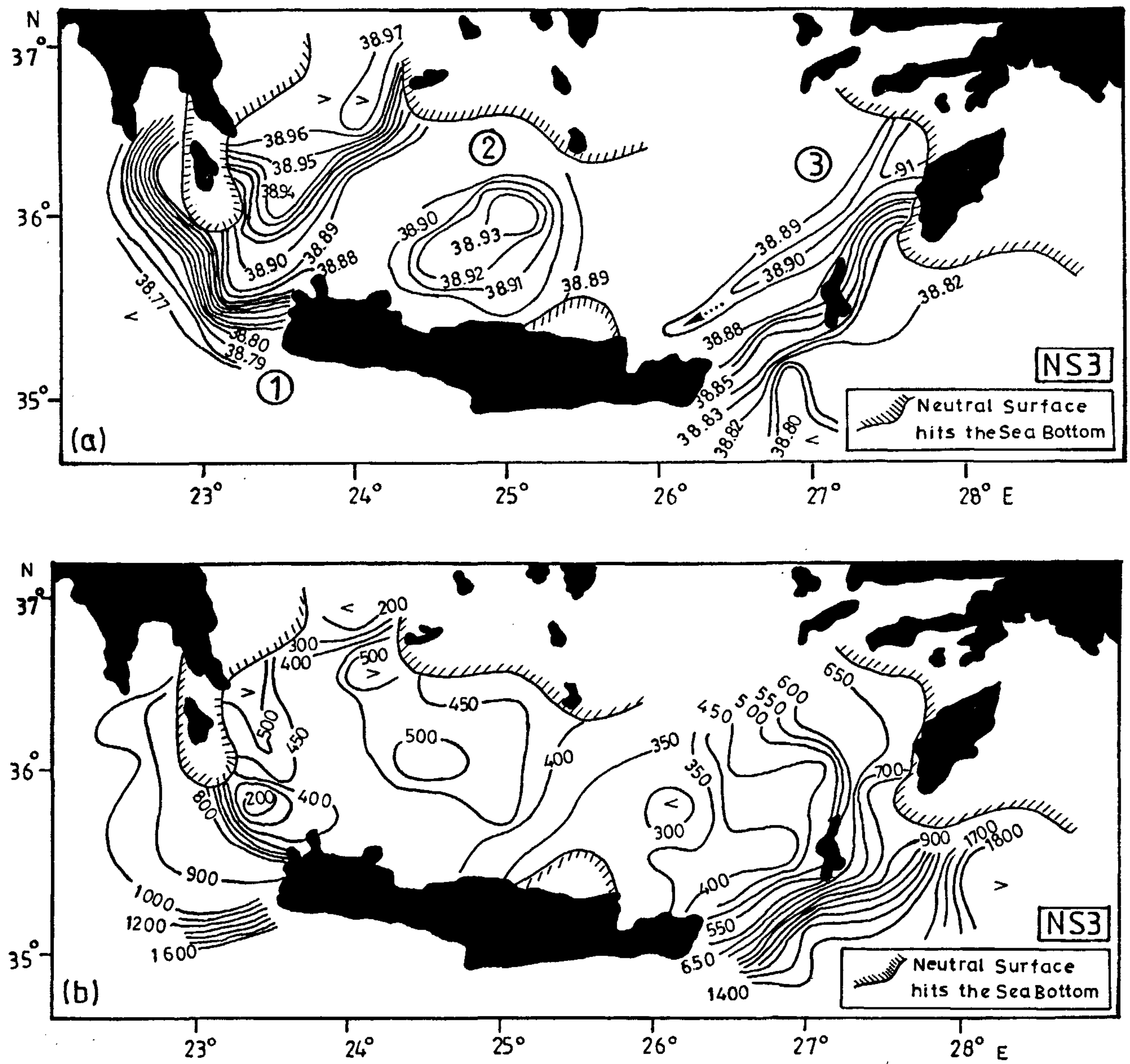

Figure 4

Salinity (a) and pressure (b) of the neutral surface NS3 delineated from a parcel defined by T = 13.828 °C, S = 38.776 at pressure 1023 dbar of the reference station 2. The encircled numbers in part (a) refer to comments identified by the same numbers in the text.

The topographies of the upper two neutral surfaces support the results obtained from the salinity distribution, assuming geostrophy relative to the "deeper" water. Thus, for instance, the neutral surface isobaths in the Rhodos Strait slope in a manner indicative of a westward inflow through this strait (Figs. 2*b*, 3*b*).

The next three neutral surfaces show an increasing isolation of the Cretan Sea (Figs. 4, 5, 6). Examining the salinity distribution on the neutral surfaces 3, 4, and 5 we find a number of noteworthy features, viz.

(1) In the vicinity of the western Cretan Sea Arc straits (Elafonissios, Antikithira), a strong haline front is evident on NS3, due to the encounter of low salinity waters of the southeastern Ionian Sea with the saline waters originating in the South Aegean Sea. This front runs roughly in the direction of the bottom isobaths.

(2) Also, on NS3, a high-salinity cyclonic mesoscale feature (Fig. 4*a*, 4*b*) stands out, occupying the central part of the Cretan Sea.

(3) An interesting feature on NS3, NS4, and NS5 is a saline tongue spreading south-westwards from the easternmost part of the South Aegean Sea, where this saline tongue is the dominant feature. Also, the salinity signal of this feature grows stronger from NS3 to NS5.

(4) From the latter feature, two saline tongues appear to descend abruptly, extending out through Kassos and Karpathos straits respectively, thereby creating strong haline fronts, due to their encounter with ambient relatively fresher water masses (Figs. 5*a*, 6*a*).

(5) Just south of the Cyclades Plateau (Thera island), another tongue of relatively high salinity (> 38.98) water

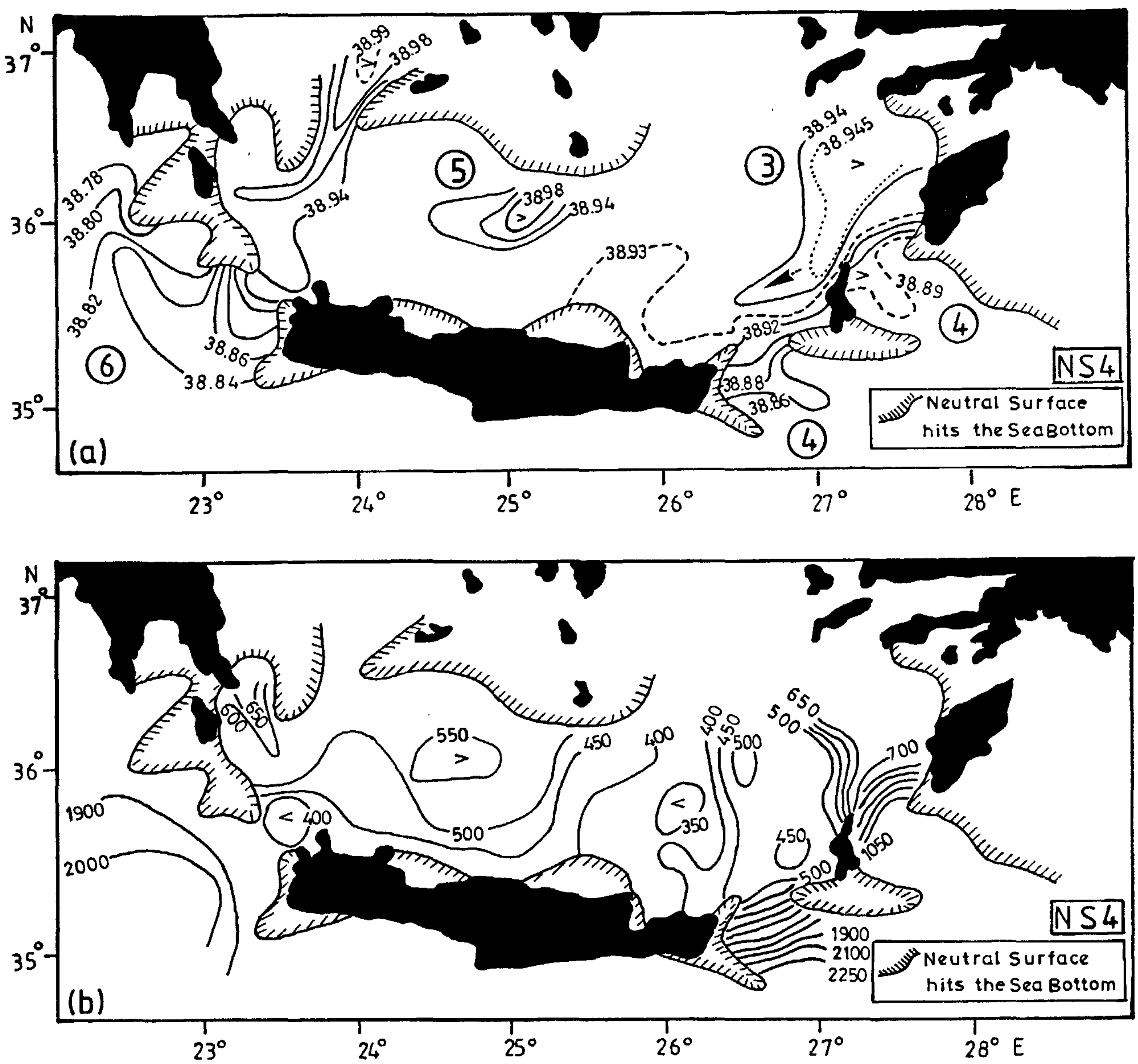

Figure 5

Salinity (a) and pressure (b) of the neutral surface NS4 delineated from a parcel defined by T = 13.722 °C, S = 38.780 at pressure 800 dbar of the reference station 1. The encircled numbers in part (a) refer to comments identified by the same numbers in the text.

is evident on NS4 and NS5 (Figs. 5*a*, 6*a*). Its salinity signal increases in the deeper neutral surfaces (Figs. 7, 8, 9), thereby presumably indicating a source of a saline (and warm) water mass.

(6) On NS4 (Fig. 5*a*), a saline tongue occurs in the southwesternmost part of the study area, spilling over the Antikithira Strait, and spreading in an anticlockwise manner, at 1900-2000 dbar; its salinity decreases in the direction of spreading. Support for the last inference is provided by the corresponding pressure distribution (Fig. 5*b*). Indeed, on NS4, assuming geostrophy relative to the "upper" water, a cyclonic flow is evident in the southwesternmost part of the study area, in the Ionian Sea (Fig. 5*a*). In general, the pressure distribution on all three intermediate neutral surfaces (Figs. 4*b*, 5*b*, 6*b*) corroborates the inferences obtained from the respective salinity distributions. On NS5, no communication exits between the Cretan Sea and the southeastern Ionian Sea, as well as the greater part of the northern Aegean Sea. In NS6 and NS7, the Cretan Sea retains its communication with the northern Aegean Sea with an opening at its northeasternmost part (Figs. 7, 8); whilst, on NS8 (Fig. 9), the Cretan Sea appears to be totally isolated, without any communication with the surrounding seas. Also, on NS8, assuming geostrophy relative to the "upper" water, a meandering westward "flow" occurs over the deeper parts of the Cretan Sea (Fig. 9*b*).

However, regarding the deeper water, the most conspicuous feature on the deeper neutral surfaces (Figs. 7*a*, 8*a*, 9*a*) is the westward spreading of a high salinity (and relatively warm) water mass. The latter appears to spread initially southwestward. But on the deeper surfaces, its direction of

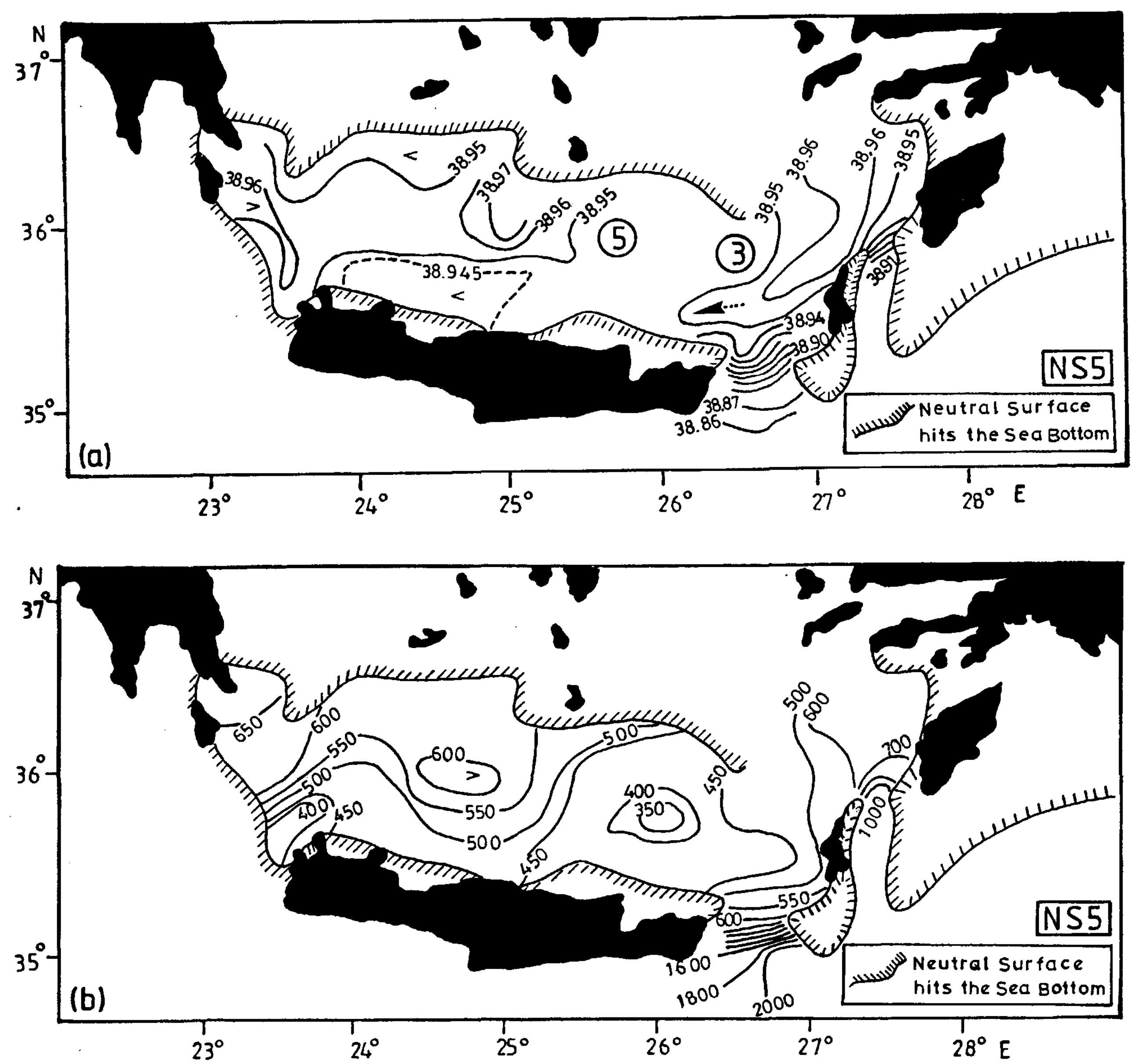

Figure 6

Salinity (a) and pressure (b) of the neutral surface NS5 delineated from a parcel defined by T = 14.101 °C, S = 38.860 at pressure 1850 dbar of the reference station 163. The encircled numbers in part (a) refer to comments identified by the same numbers in the text.

spreading veers in an clockwise manner, and on the deepest neutral surface (Fig. 9*a*) spreads due west. Support for this inference is provided by the respective topography of this neutral surface (Fig. 9*b*), assuming geostrophy relative to the "upper" water. This saline (S > 39.00) water mass appears to follow broadly the bottom bathymetric contours, in its westward spreading, from the presumed area of its formation, where an anticyclone seems to be tied with the deepest part of the Cretan Sea, in the easternmost part of the study area. At the latter location, this water mass attains its maximum thickness. Figure 10*a* presents the distribution of thickness of the Cretan Deep Water (CDW) (S> 39.00; Fig. 10*b*), and shows that the latter covers the greater part of the Cretan Sea *per se*, as a near bottom layer, with thickness varying between 10 and 1800 m. The CDW, although present as a bottom layer both at Antikithira and also at Kassos Straits, it does not appear in its undiluted thermohaline characteristics beyond the sills of these straits, due to the intense diapycnal processes which presumably occur there. However, the contribution of Cretan Deep Water to the hydrography of the Eastern Mediterranean is most important, affecting the water column in the adjacent areas down to great depths (~ 2600 dbar), as it is implied by the higher salinities and temperatures of the deeper water masses of both the southeastern Ionian Sea and the also northwestern Levantine Sea (Theodorou *et al.*, 1995).

DISCUSSION AND CONCLUSIONS

The purpose of this paper has been to establish the qualitative circulation patterns of the "upper" and "deeper"

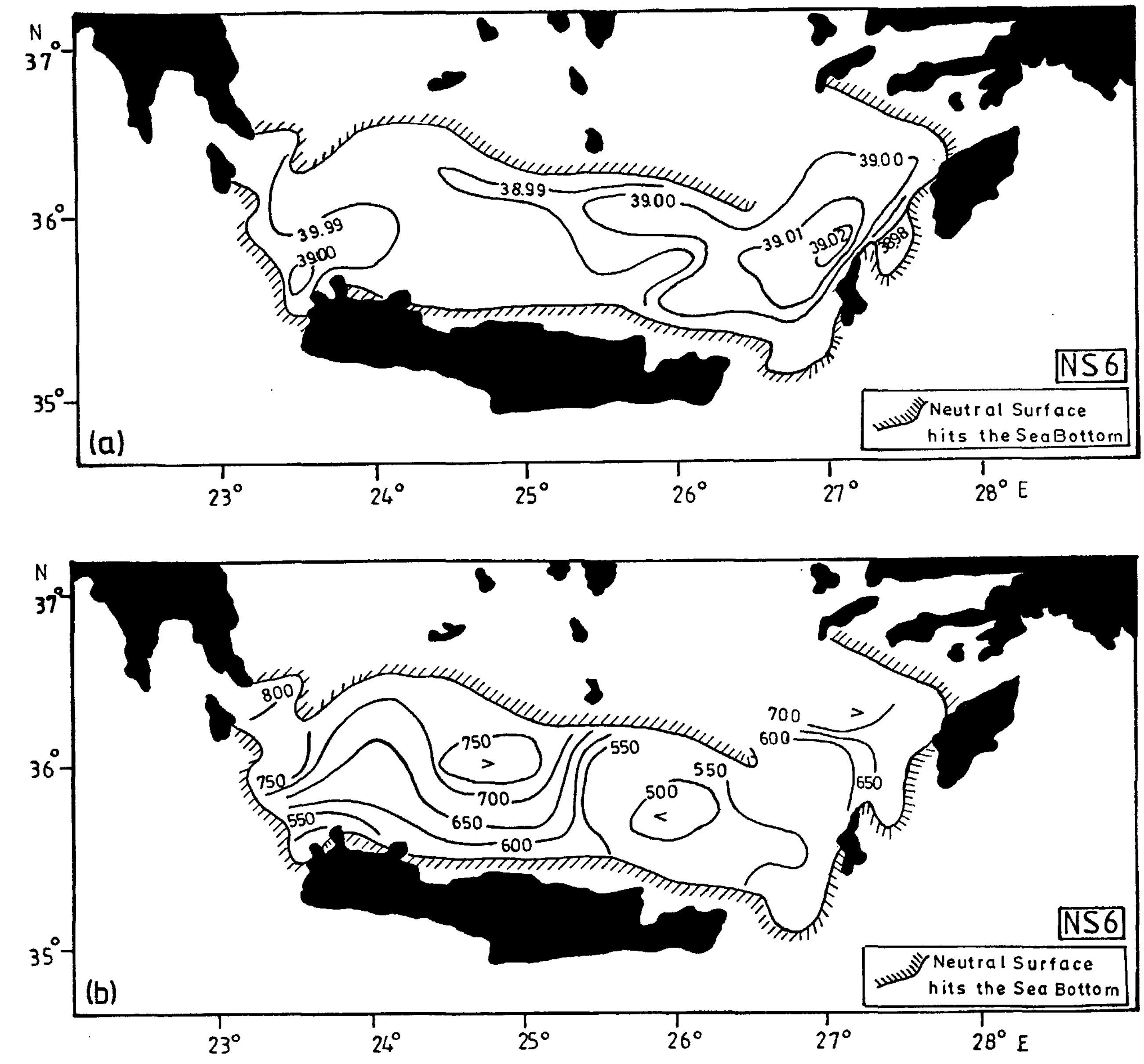

Figure 7

Salinity (a) and pressure (b) of the neutral surface NS6 delineated from a parcel defined by T = 14.159 °C, S = 38.961 at pressure 1185 dbar of the reference station 98. The encircled numbers in part (a) refer to comments identified by the same numbers in the text.

layers in the Cretan sea and its environs during late winter 1994. The qualitative aspects of the "flow" field, determined primarily by the distribution of salinity on appropriate neutral surfaces and supported by dynamic inferences, based on the geostrophic assumption, are summarized below.

In the northwestern part of the Cretan Sea, plumes of relatively saline water, spreading from the northeast, interpenetrate with fresher ones, emanating from the southwest, thereby implying a cyclonic mesoscale feature. In the Antikithira Strait, an inflow-outflow system occurs in the upper layer, whilst in the deeper layer a tongue of saline water exits through this strait. In the southeastern Ionian Sea, a lower salinity tongue spreads from the west in an anticyclonic direction. From the latter, a plume of fresher water enters the Cretan Sea through the western part of the Antikithira Strait. The encounter of low salinity waters in the region of this anticyclone with the more saline waters originating from the Cretan Sea creates a strong haline front, which runs roughly in the direction of the bottom isobaths of the western Cretan Sea Arc islands. In the Cretan Sea, eastwards of the aforementioned cyclonic feature and based on the pattern of the isohalines, the presence of an anticyclone and, further to the east, of another cyclone were inferred. The succession of these mesoscale features implies the presence of a meandering "current", flowing eastwards from the northwesternmost part of the study area. To the north of Kassos Strait, this meandering flow presumably turns northwards. In the Rhodos Strait, a saline plume enters the Aegean Sea from

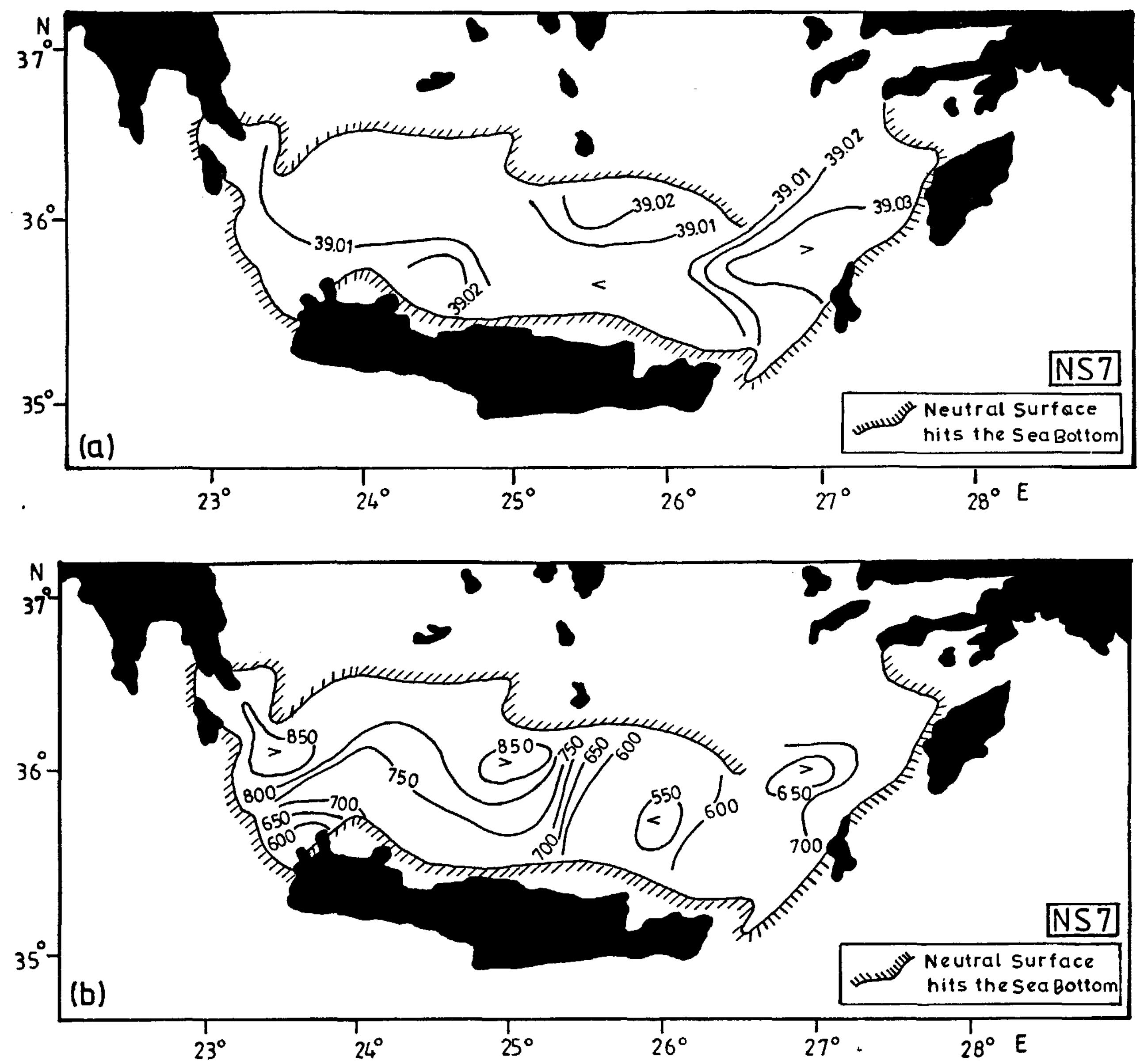

Figure 8

Salinity (a) and pressure (b) of the neutral surface NS7 delineated from a parcel defined by T = 14.167 °C, S = 39.006 at pressure 800 dbar of the reference station 49.

the east. South of Rhodos, a saline tongue spreads in an anticlockwise manner. Just south of Kassos Strait, and to the west of the aforementioned cyclone, a relatively lower salinity plume spreads in a clockwise direction. From the aforementioned anticyclone, a meandering flow of lower salinity water enters the Cretan Sea through the Kassos Strait, whilst in the deeper layer of the same strait a saline tongue seems to outflow. In the Karpathos Strait, an anticyclonic, eddy-like feature occurs; associated with this feature is an intrusion of saline water. By combining the above results, we show in Figure 11 a schematic qualitative circulation pattern for the "upper" layer water. Especially noteworthly is the flow reversal reflected in the data of the late winter 1986 (11 March - 24 April 1986) POEM-2 cruise and the late winter 1994 PELAGOS-1 cruise: during the latter, an eastward "current" meandered north of Crete, in the South Aegean Sea; whereas during the former, a general cyclonic circulation pattern occupied most of the South Aegean Sea (Theocharis *et al.*, 1993). Another interesting finding of the PELAGOS-1 cruise, and also the most conspicuous feature on the three deeper surfaces (NS6 to NS8), was the westward spreading of the high salinity Cretan Deep Water (CDW). Support for this inference was provided by the topographies of these neutral surfaces, assuming geostrophy relative to the "upper" water. Thus, the CDW appears to follow broadly the bottom bathymetric contours in its westward spreading from the presumed area of its formation in the deepest part of the Cretan Sea, in the easternmost part of the study area, where it also attains its maximum thickness, occupying a layer extending about

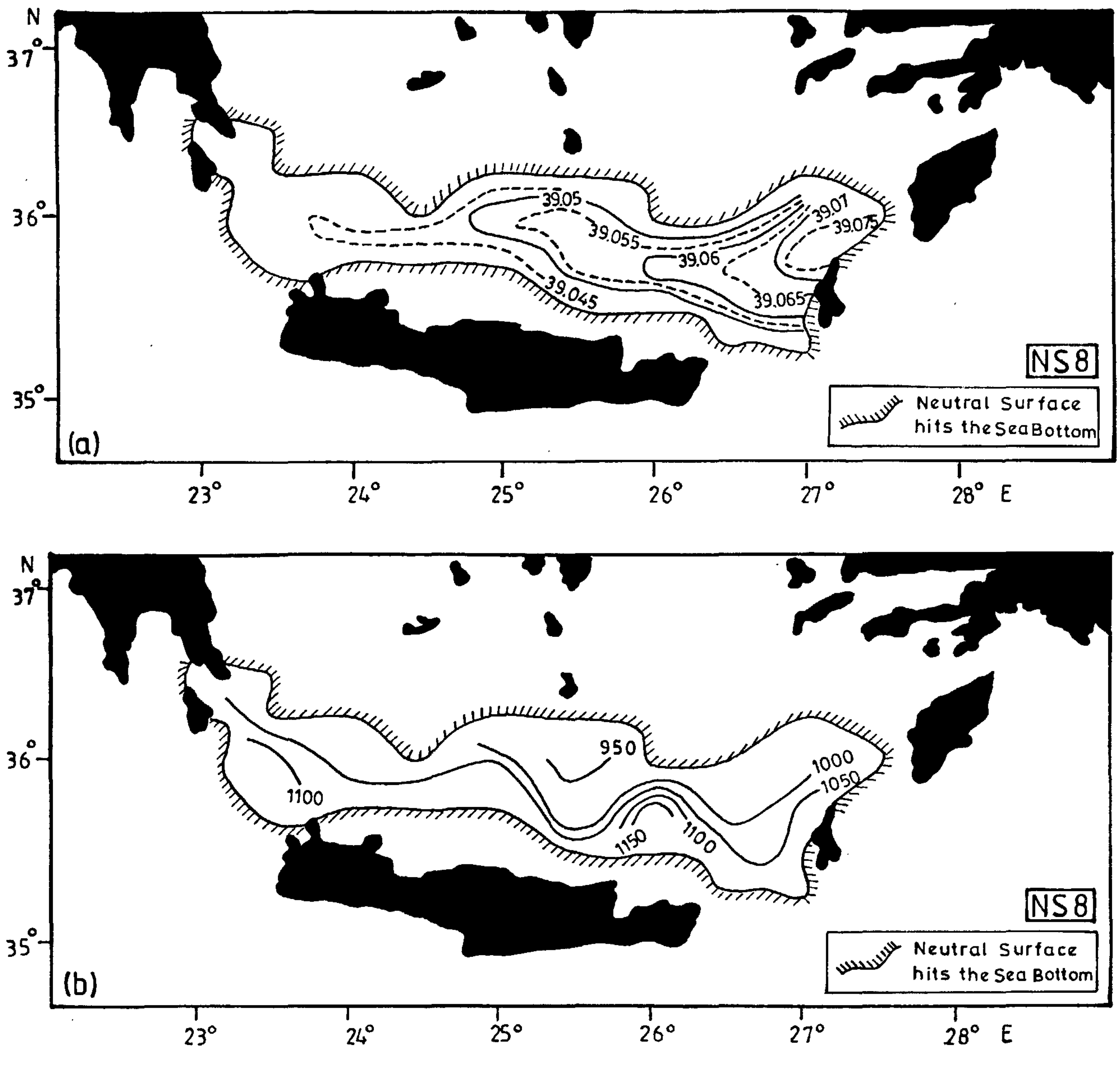

Figure 9

Salinity (a) and pressure (b) of the neutral surface NS8 delineated from a parcel defined by T = 14.144 °C, S = 39.056 at pressure 980 dbar of the reference station 60.

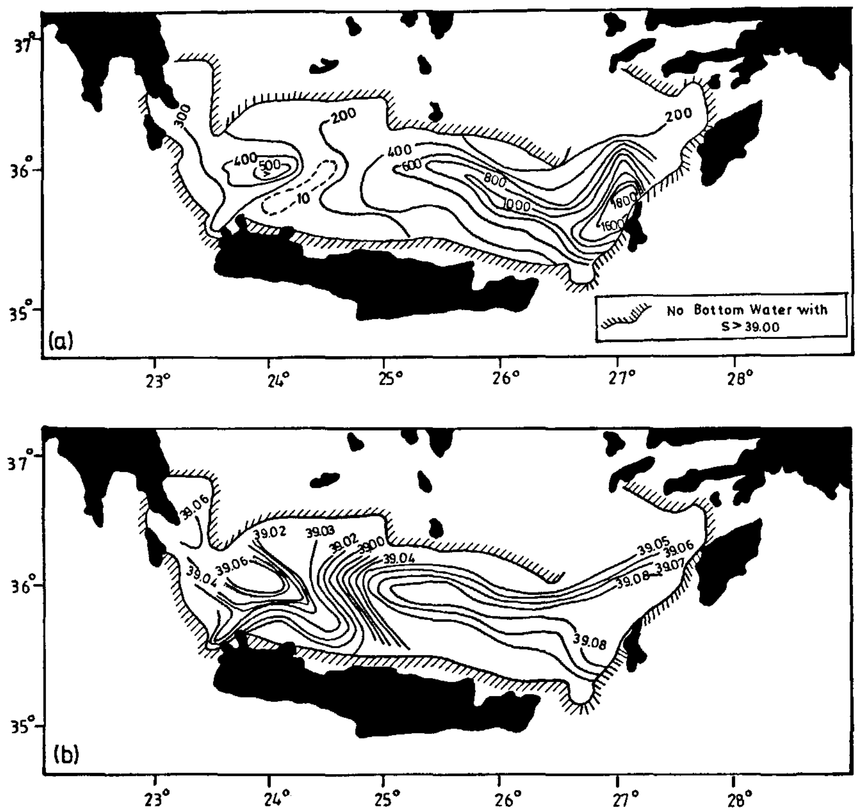

Figure 10

Thickness in m (a) and maximum salinity in psu (b) of the layer of Cretan Deep Water.

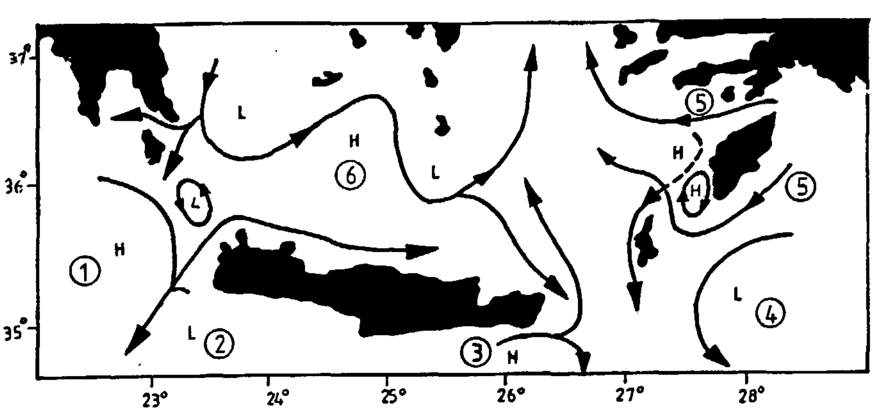

Figure 11

Schematic qualitative circulation pattern for the "upper" layer. (1) Pelops anticyclonic gyre; (2) Cretan cyclonic gyre; (3) Ierapetra anticyclonic gyre; (4) Rhodes cyclonic gyre; (5) Asia Minor Current; (6) South Aegean Sea eddies and jet.

1800 m above the bottom. This saline water outflows from the Cretan into the Ionian and Levantine Seas; this finding is both interesting and important, in that it fits nicely with the newly emerging evidence indicating that the salinity of the Eastern Mediterranean Deep Water (EMDW) has increased over the past few years and the source of EMDW has recently been shifted from the Adriatic (Schlitzer *et al.*, 1991) to the South Aegean (Roether *et al.*, 1996).

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