Characteristics of the Mediterranean underflow in the southwestern Black Sea continental shelf/slope region

Mediterranean underflow
Black sea
Continental shelf/slope
Sinking
Intrusion

Eau méditerranéenne
Mer Noire
Plateau/talus continental
Plongée
Intrusion

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ABSTRACT

Hydrographic observations obtained during the period 6-13 August 1989 are used to illustrate characteristics of the dense water of the Mediterranean underflow in the southwestern Black Sea shelf/slope region. The inflowing warmer and saltier Mediterranean water is observed to spread north-northwestward of the channel-canyon axis along the bottom of the shelf. As the inflowing water crosses the shelf it becomes gradually cooler, fresher and thus less dense by mixing continually with the waters of the Cold Intermediate Layer (CIL). Beyond the shelf break, the slightly denser water of the Mediterranean underflow interacts with the thermocline waters of the ambient environment and is finally interleaved in the form of a neutrally buoyant, relatively colder plume in or beneath the halocline. Observations show multiple interleaving layers with thicknesses less than 50 m and temperature differences of about 0.1°C at depths of 200-300 m. At depths of 400-500 m, intrusions may be distinguished from the ambient environment by temperature differences of the order of 0.01°C.

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RÉSUMÉ

Caractéristiques du flux d'eau méditerranéenne sur le plateau continental du sud-ouest de la Mer Noire

Le flux d'eau dense méditerranéenne entrant dans le sud-ouest de la Mer Noire a été étudié sur le plateau et le talus continental à partir des caractéristiques hydrologiques mesurées du 6 au 13 août 1989. L'eau méditerranéenne chaude et salée s'écoule vers le nord-nord-ouest en suivant l'axe du canyon. En traversant le plateau, elle se refroidit et se dilue et sa densité diminue progressivement par mélange avec les eaux de la couche intermédiaire froide (CIL). Au-delà du plateau continental, les eaux méditerranéennes rencontrent les eaux de la thermocline et forment un panache relativement froid dans l'halocline ou au-dessous. Une stratification est observée avec des couches d'épaisseurs inférieures à 50 m présentant des différences de température d'environ 0,1°C à des profondeurs de 200 à 300 m. Aux profondeurs de 400 à 500 m, les intrusions se distinguent de l'eau environnante par des écarts de température de l'ordre de 0,01°C.

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INTRODUCTION

The continental shelf/slope region of the southwestern Black Sea (Fig. 1), adjacent to the Bosphorus Strait, serves as a junction region for the exchange of relatively fresh surface waters of the Black Sea with the underlying saltier and denser bottom waters of Mediterranean origin. The surface waters flow southward through the Turkish Straits System and ultimately reach the Aegean Sea. The bottom waters flow in the opposite direction into the Black Sea and are modified considerably by mixing with the Black Sea waters as

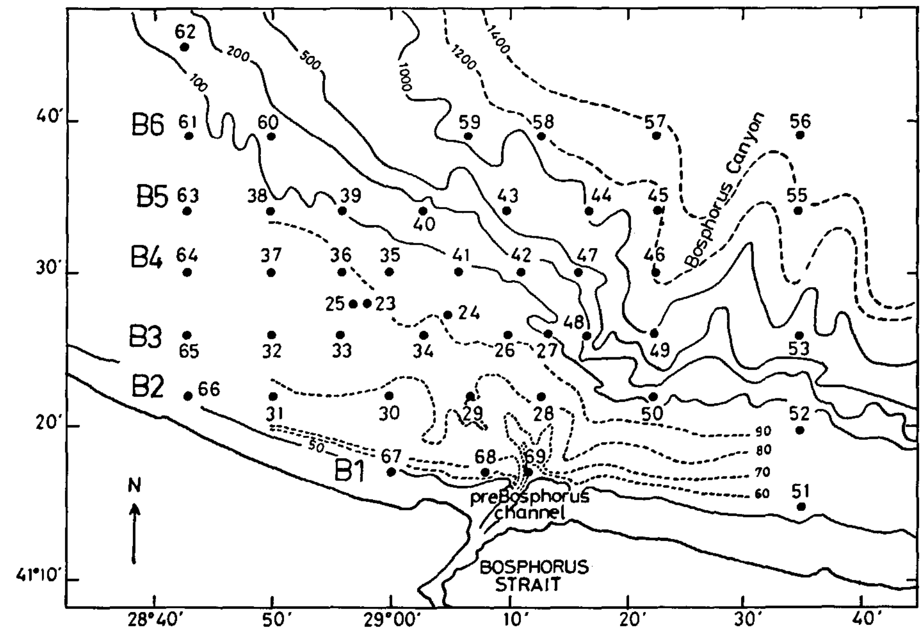

Figure 1
Study area, its regional bathymetry and locations of hydrographic stations.

they spread over the shelf region. They ultimately form the subhalocline waters of the basin's interior.

On recent decades, various observational studies have investigated the way in which the Bosphorus underflow enters the Black Sea, is dispersed within the shelf and eventually sinks along the continental slope toward the deeper levels. Analyzing the available hydrographic observations carried out up to the beginning of the 1960's, Bogdanova (1963; 1965) documented the inflow conditions of Mediterranean water exiting from the Bosphorus Strait into the Black Sea and recognized the persistency of the inflow throughout the year. More recently, the results of various field studies reported by Tolmazin (1985), Yuce (1990) and Latif *et al.* (1991), have confirmed the continuous inflow of Mediterranean water into the shelf in the form of a distinct patch of salty water, even in the case of unfavourable conditions of strong northerly winds. The effluent was shown to follow persistently a north-northwest track within the shelf and then deflect eastward in the direction of the Main Black Sea current system on its way to the interior of the basin. Tolmazin (1985), utilizing data collected by Soviet oceanographers during the 1959-1973 period, provided the spreading characteristics of the effluent in the deeper parts of the shelf region, beyond the Turkish territorial waters (approximately to the north of latitude 41°25'N). A distinct patch of salty and warmer water was always observed at the bottom of the outer shelf region throughout the field experiments, but a firm explanation for the north-northwestern deflection of the effluent could not be given.

Yuce (1990) provided complementary data taken during 1983-1984 immediately outside the Bosphorus, but mostly in Turkish territorial waters. He noted that the earlier investigations had misplaced the Bosphorus northern sill' (see *e.g.* Fig. 3 in Tolmazin, 1985). According to the topography given in the Turkish hydrographic chart TR-1811, he showed that the sill, with a depth of 57-59 m, was actually located 4 km outside the strait's exit. The Mediterranean water was observed to flow continuously over the sill, proceed a few kilometres in a northeasterly direction and then turn north-northwestward almost at the same location, indicating the possible role of bathymetry on the initial path of the underflow.

Latif *et al.* (1991) pointed out, by documenting the details of the regional topography, that the Bosphorus linked the shelf through the narrow, so-called pre-Bosphorus channel which has a width of 500-1 000 m (Fig. 1). This channel, with a length of about 8.0 km, is first oriented along the strait's axis in a northeasterly direction and then turns north and continues for another 2 km to carry the effluent toward the north-western part of the shelf. The Bosphorus northern sill, with a depth of 60 m and a length of about 3.5 km, is found to be located within this channel immediately outside the Bosphorus exist. A brief description of the work given in Latif *et al.* (1991) was also provided by Unluata *et al.* (1990) in a review of the physical oceanographic characteristics of the Turkish Straits System. In relation with the internal hydralic characteristics of the Bosphorus exchange flow, the outflow conditions of the dense Mediterranean water from the northern exit of the Bosphorus into the Black Sea were further studied by Oguz *et al.* (1990 *a*).

Understanding of the sinking and subsequent spreading characteristics of the Mediterranean effluent within the Black Sea is of considerable interest in explaining a series of subtle processes associated with the mixing and renewal of intermediate and deep waters. Observational studies on the subject are, however, scarce and by no means give a satisfactory description of the sinking process. The measurements reported in Yuce (1990) and Latif *et al.* (1991) were mainly restricted to the shelf region and did not cover the fate of effluent beyond the shelf break. Continuing efforts made during the long-term field studies described in Tolmazin (1985) were not successful in tracing the warm and salty waters of the Mediterranean plume as it sinks toward the deeper levels. This was claimed by Tolmazin (1985) to be primarily due to the equipment limitations and the relatively coarse vertical sampling done by Nansen-bottle casts.

As part of the characterization of the general hydrography and circulation of the southern Black Sea, Oguz *et al.* (1991) recently showed the presence of colder and slightly less saline quasi-horizontal injections in the subhalocline levels of the southwestern Black Sea offshore waters. It is pointed out that such intrusions might be associated with the sinking plume of the Mediterranean effluent. It was noted that the effluent was modified along its path to the interior of the basin and was no longer characterized by warm and salty patches beyond the shelf break. Further observational support for such features of cold intrusion waters came from the R/V *Knorr* cruises carried out in 1988 (Ozsoy *et al.*, 1991; Buesseler *et al.*, 1991). In an analysis of hydrographic data obtained in Leg 4 of the R/V *Knorr* cruises, Ozsoy *et al.*, (1991) also observed cold anomalies at intermediate depths at several deep stations in the southwestern Black Sea region. They further emphasized the role of a double-diffusive environment in the Black Sea on the mixing of the apparently transformed Mediterranean underflow with the ambient waters. Buesseler *et al.* (1991) noted the distinct role of the Mediterranean underflow in the quasi-horizontal spreading of Chernobyl cesium into the interior of the basin. However, these studies are based on spatially limited data and therefore do not provide a detailed and systematic description either of the sinking and spreading characteristics of the Mediterranean underflow, or of the processes related to the ventilation and renewal of anoxic subhalocline waters.

In the present paper, we describe a hydrographic data set which enables us for the first time to trace the Mediterranean underflow systematically from its origin (*i.e.* immediately outside the Bosphorus northern exit) to the subhalocline waters in the continental slope region of the southwestern Black Sea, until its properties can barely be detected with available instrumentation. The observational findings were obtained by the Soviet-Turkish expedition carried out on 6-13 August 1989 on board R/V *Professor Vodyanitksy*. The hydrographic measurements were performed at 47 closely-spaced stations (Fig. 1) by using the Soviet-made ISTOK-CTD profiling instrument. The CTD probe was calibrated by laboratory analyses of bottle samples and had an accuracy better than ±0.01 for both temperature and salinity. It sampled 14 data points per second as it was lowered into the water column.

Findings reported in this work essentially complement those given by Tolmazin (1985), Yuce (1990) and Latif *et al.* (1991) and form a bridge between these studies and the those given by Oguz *et al.* (1991) and Ozsoy *et al.* (1991). The remaining part of the paper is organized as follows: we first present a brief outline of regional bathymetry, vertical thermohaline structure and regional circulation in the second section in order to substantiate the discussion given in the third section. Here we describe observational findings related to the properties of the Mediterranean effluent as it traverses the shelf region and sinks along the continental slope. A summary and discussion are given in the last section.

GENERAL CHARACTERISTICS

Regional topography

The continental shelf region outside the Bosphorus exit essentially forms a continuation of the wider northwestern Black Sea shelf to the south. It is divided into two parts by the Bosphorus Canyon, which is a deep, V-shaped cleft extending along a northeasterly axis, its head being located approximately 15-20 km outside the exit of the pre-Bosphorus channel (Fig. 1). The shelf becomes gradually wider to the northwest of the channel-canyon axis and has an approximate width of 30-40 km, and an average bottom slope of the order of 10^{-3}. It is this part of the shelf that plays a major role on the distribution of the dense Mediterranean underflow. The shelf is connected to the interior of the basin through a narrow continental slope oriented in a NW-SE direction, with a width of approximately 10 km between the 100 m and 1000 m isobaths. The continental slope is often intersected by various small-scale canyons which seem to have an important role in the mixing characteristics of the sinking plume.

Thermohaline structure

The general stratification and water mass characteristics of the Black Sea were given by Murray (1991) and Oguz *et al.* (1991). Using the present data set, a brief description of the principal features of the regional thermohaline structure is also included here, however, to complement the discussion given in the following section. Figure 2 shows the temperature, salinity and density profiles for station 59, being representative of water characteristics at the outermost part of the study region, away from any direct influence of the Mediterranean effluent. The profiles are shown for only the upper 500 m, below which the Black Sea waters are known to possess only slight vertical gradients (Murray *et al.*, 1991).

The temperature profile shows that the uppermost 25 m of the water column is formed by warm and brackish surface waters with $T \simeq 23.0$°C, $S \simeq 17.5$-18.0 and $\sigma_t \simeq 10.5$-11.0, separated from waters of the Cold Intermediate layer (CIL) by the seasonal thermocline at 25-35 m. The CIL is notable for the rapid decrease in temperature to values less than 8°C, the minimum

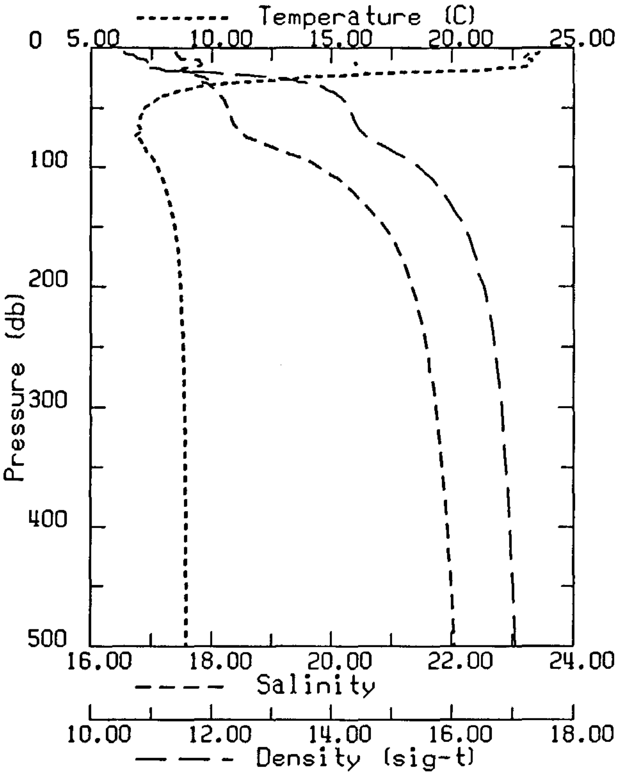

Figure 2
Temperature, salinity and density profiles for station 59.

temperature being slightly below 7°C at depths of about 70-80 m. The CIL is further signified by gradual changes in salinity, which increases to the value of 18.5 ppt at depths of 70-80 m. The lower limit of the CIL is generally defined by the 8°C isotherm, which is located at the depth of 120 m for the profile we consider here. The lower half of the CIL is therefore characterized by a temperature increase of almost 1°C through a distance of about 40 m. It also constitutes a part of the permanent thermocline zone extending to a depth of 150 m where the temperature increases to approximately 8.5°C. The vertical extension and thickness of the CIL, however, vary by about 30 m at stations along the continental slope. As shown by the 8°C isotherm map in Figure 3, changes in the thickness of the CIL follow closely the isobaths (*cf.* Fig. 1) and the CIL becomes shallower towards the continental shelf. At deeper levels, the temperature varies insignificantly and becomes 8.8°C at 250 m and 8.9°C at 500 m.

Salinity, which has typical values of 18.0 ± 0.5 within the uppermost 70-80 m, undergoes considerable changes within the permanent thermocline zone, the implication being that it also forms the permanent halocline; it increases in this region from 18.6 at 75 m to approximately 20.0 at 100 m and 21.0 at 150 m. Salinity of the subhalocline waters becomes 21.6 at 250 m and 22.0 at 500 m. The vertical density profile follows closely that of salinity except above the seasonal thermocline where the large temperature variations are reflected in the density profile. The pynocline, between the depths of 75 m and 150 m, is identified by the sigma-theta values of 14.5 and 16.2, respectively. Below the pycnocline, the density becomes 16.7 at 250 m and 17.0 at 500 m.

In terms of the spreading and mixing characteristics of the Mediterranean effluent, the hydrographic profiles and the 8°C isotherm map shown in Figures 2 and 3, respectively, imply the following properties of the water column:

– the Mediterranean underflow interacts with the Cold Intermediate Water during its passage through

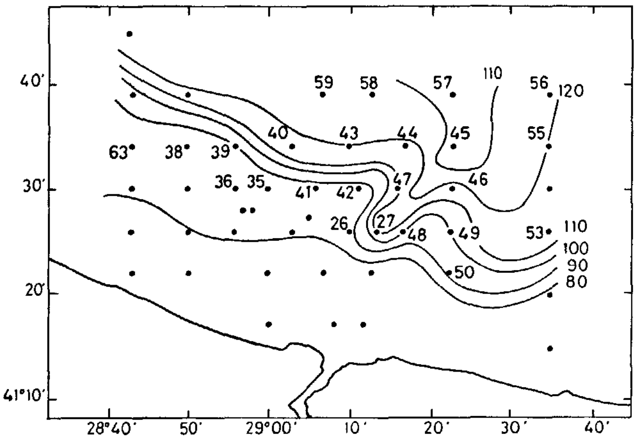

Figure 3
Distribution of the depth of 8°C isotherm at the base of the Cold Intermediate Layer.

the shelf. As we shall see in the following section, this interaction gives rise to the cooling of the Mediterranean effluent;

– within the upper continental slope region immediately outside the shelf break (*i.e.* at depths between 100 m and 500 m), the Mediterranean underflow interacts with the interfacial (thermocline-halocline) waters of the ambient environment. This interaction is expected to provide further changes in water mass properties of the underflow;

– the ambient Black Sea waters have typically T ≃ 8°C and S ≃ 20 at the depth of 100 m. This implies that the water mass characterized by higher temperature and salinity values at the bottom of the shelf (*i.e.* at depths shallower than 100 m) must represent the dense water of the Mediterranean underflow. An example is given in Figure 4 by the temperature and salinity profiles for two stations, one located in the shelf (station 34, depth ≃ 84 m) with the signature of Mediterranean underwater at the bottom, and the other (station 59, depth ≃ 1 065 m) signifying the ambient conditions.

Regional circulation

As a part of the large-scale general circulation of the southern Black Sea, the circulation of the Bosphorus exit region was studied by Oguz *et al.* (1990*b*; 1991) using satellite imagery and the hydrographic data collected during several recent cruises of the research vessel Bilim of the METU-Institute of Marine Sciences. It has been shown that the regional circulation possesses

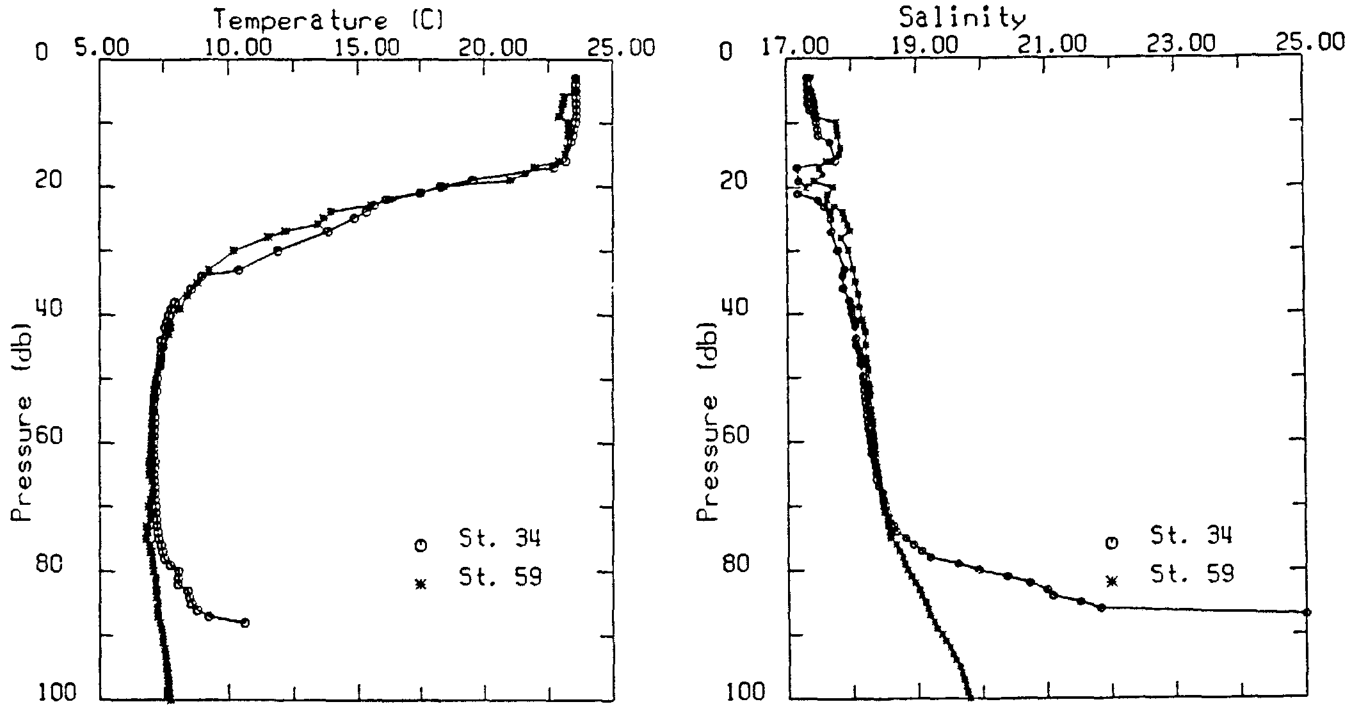

Figure 4

Temperature and salinity profiles for stations 34 *and* 59 (*for station* 59, *only upper* 100 *m is shown*).

certain distinct quasi-permanent features. The flow, being a part of the Main Black Sea Current System, comes from the northwestern Black Sea basin by following the regional topography and splits into two parts outside the Bosphorus. A part of the flow continues toward east and forms the peripheral current system along the entire Turkish coast of the Black Sea. The other part of the flow interacts with the Bosphorus Canyon, is deflected towards the south and enters partially into the Bosphorus Strait. This southerly flow also contributes to the formation of an anticyclonic eddy along the northwestern coast. This eddy was observed in all the satellite imagery examined for the 1989-1990 period (Oguz *et al.*, 1990*b*) and in all the geostrophic velocity fields obtained from the hydrographic data (Oguz *et al.*, 1991). Its northern extension was also observed in the Bulgarian shelf in field studies reported by Trukhchev *et al.* (1985).

Similar flow structure may also be inferred in the present observations from the horizontal distribution of density at a depth of 70 m (Fig. 5). This density level is chosen because it is close to the bottom of the shelf and may therefore represent a more realistic local flow structure in regard to its interaction with the Mediterranean underflow found at the bottom of the shelf. It is evident from Figure 5 that the form of the isopycnals suggests a typical topographically-driven flow case. The southeasterly flowing rim current seems to be confined mainly to the continental slope and, upon reaching the Bosphorus Canyon region, it interacts with the canyon topography and gives rise to a complex flow pattern immediately outside the Bosphorus. A part of the flow acquires an anticyclonic tendency in the shelf region which generates a coastal

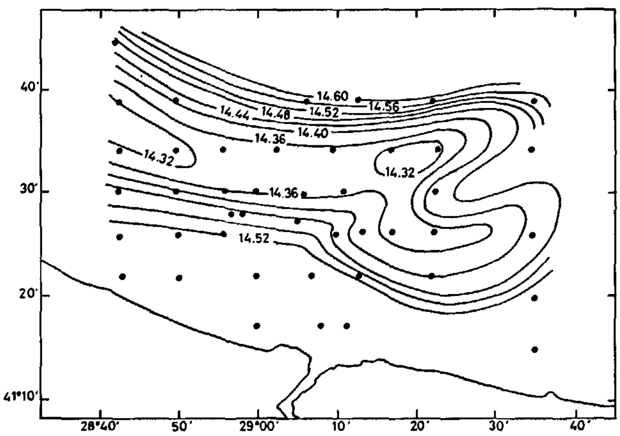

Figure 5

Distribution of the density (*sigma-theta*) *at depth of* 70 *m.*

counter-current in the northwestern direction. We note that confinement of the flow to the local topography along the continental slope is also suggested by the 8°C isotherm map shown in Figure 3.

DISTRIBUTION OF THE MEDITERRANEAN EFFLUENT

The distribution of deep Mediterranean waters in the study region is described by five vertical temperature and salinity cross-sections (*see* Fig. 1 for their locations). These are oriented in an E-W direction and identified consecutively by the section numbers B1 to B6 with B1 indicating that nearest to the Bosphorus exit. The underflow within the Bosphorus and the adjacent pre-Bosphorus channel has only been followed by echosounder.

The transects along the section B1 (Fig. 6 *a*, *b*) consists of three stations, one of which (station 69) is located immediately outside the channel exit. The other two

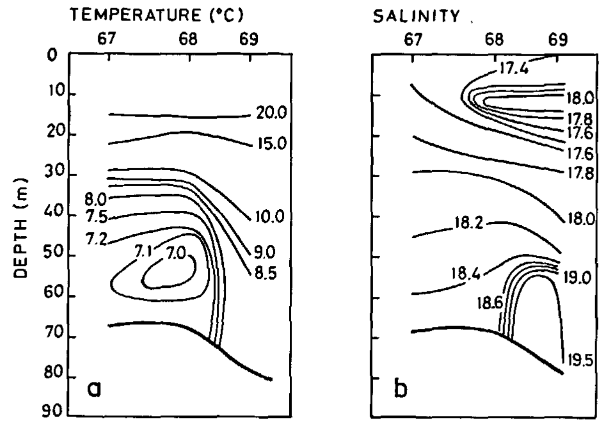

Figure 6
(a) Temperature, (b) salinity transects for section B1.

stations 67 and 68 are situated further west of the exit and reveal the sole presence of CIL waters near the bottom characterized by T≃7.0-7.5°C and S≃18.6. At station 69 the bottom waters have slightly higher temperature (T≃8.3°C) and salinity (S≃19.5) values, indicative of the presence of the effluent. Given the near-bottom temperature and salinity values at station 29 of the following section B2 (Fig. 7 *a*, *b*) and also referring to Yuce (1990) and Latif *et al.* (1991), the core of the effluent should attain T > 12°C, S > 30 at the

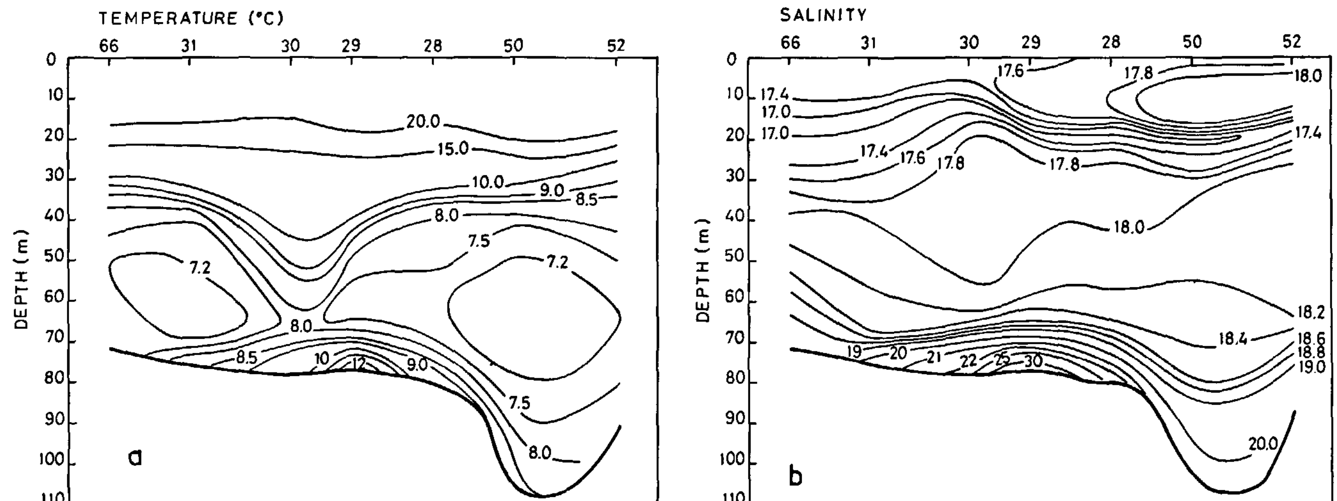

Figure 7
(a) Temperature, (b) salinity transects for section B2.

the exit section of the channel. The efflux should therefore essentially transit slightly west of station 69. Unfortunately, station spacing was not fine enough to capture the core of the underflow exiting from the bottom conduit.

After the effluent enters the shelf region, its core is identified at station 29 (along section B2) by maximum T and S values of 12°C and 29 ppt (Fig. 7 *a*, *b*). The effluent covers essentially the region between stations 31 and 28 to the north of the pre-Bosphorus channel exit. Near station 30, the isotherms and isohalines slope downward below 40 m suggesting increased vertical mixing and subsequent dilution of the effluent with the CIL waters. The effluent may also be traced to the east of station 28 as may be indicated by slight increases in the near-bottom (≃100 m) temperature and salinity values at station 50.

Figures 8 *a*, *b* imply that the core of the effluent continues to flow in a northwesterly direction and is identified along the section B3 by the salinity and temperature values of 30 ppt and 12°C, respectively, at station 33. A part of the effluent is mixed and diluted as it moves along the shelf and then sinks eventually in the form of a plume along the continental slope covered by stations 26, 27 and 48 to the east of station 33. As seen from Figure 8 *a*, bottom waters with temperature values of 8.0-8.3°C are involved in the sinking process at depths of 100-110 m near the shelf break. At deeper levels, down to 250 m, the sinking water is identified by the deepening of isotherms along the continental slope (station 48) relative to their position at station 49. Features related to the process of plume sinking are also evident in the salinity transect shown in Figure 8 *b*.

The temperature transect in Figure 8 *a* also shows the presence of a relatively warm lens of Mediterranean water with T≃8.5-8.7°C between the depths of 140-150 m at station 49. Given that station 49 is located near the head of the Bosphorus Canyon about 20 km outside the exit of the pre-Bosphorus channel, the warm spot indicates a partial leakage of the underflow directly into the canyon by flowing along the channel-canyon axis. This feature was indicated earlier as occuring between stations 28 and 50 in Figure 7 *a*, but could not be resolved fully due to the lack of sufficiently

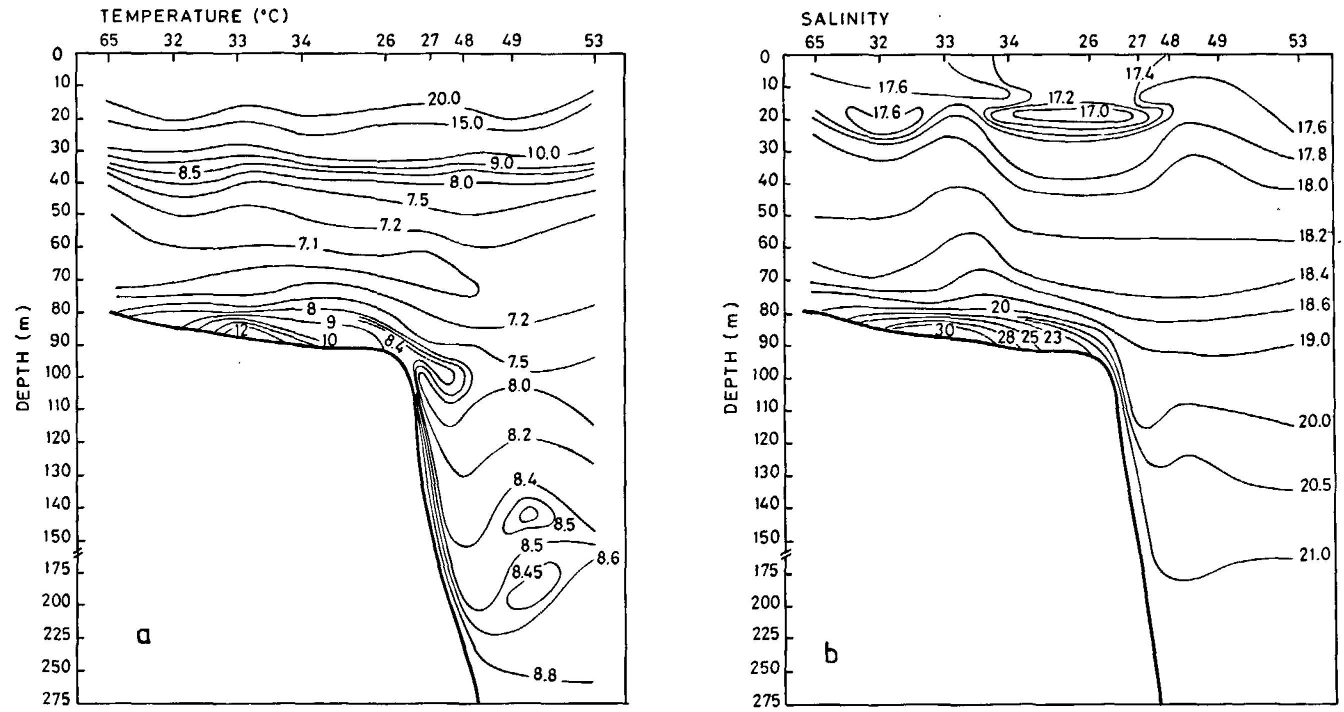

Figure 8
(a) Temperature, (b) salinity transects for section B3.

close station spacing. Such slightly warmer and saltier modified Mediterranean waters are also found at two nearby stations 48 and 27 located to the west of station 49. They are, however, not observed further into the interior of the canyon (*e.g.* at stations 46, 45), which implies that they cannot preserve the distinction of being warmer and saltier than the ambient environment any further, due to complex sinking and mixing processes which apparently take place within the canyon (Bignami *et al.*, 1990).

Station 49 also presents a lens of cold water characterized by the minimum temperature value of 8.47°C at depths of 180-200 m. This relatively cold patch of water is possibly advected from west-northwest and, as we shall discuss below, represents the sinking plume of the modified Mediterranean water. These warm and cold lenses are further displayed by the T-S curves in Figures 11 and 12.

Along section B4 (Fig. 9 *a, b*), the core of the effluent is confined between stations 36 and 41, indicating its north-northeastward deflection toward the shelf break by the southeasterly flowing rim current described previously. As a result of continuous dilution of the effluent through horizontal and vertical mixing, the thickness as well as the temperature and salinity of the core are reduced to about 5 m (as measured by the elevation of 8°C isotherm above the bottom), 11°C and 26, respectively. Sinking toward the deeper levels along the continental slope is seen to take place near station 47 where a patch of cold water exists at depths between 110-120 m with a minimum temperature of 8.05°C against the background value of 8.12°C.

Transects along the section B5 (Fig. 10 *a, b*) show no clear evidence of the effluent in the shelf region to the west of station 39. This implies that most of the sinking process takes place along the shelf break between sections B3 and B4 due to the deflection of effluent by southeasterly currents in the outer shelf and slope regions and, therefore, the effluent can no longer be traced in the shelf further north-northwest. Station 40, which is situated with a total depth of 210 m at the upper continental slope to the east of station 39, shows anomalous water characteristics at the base of CIL describing a sinking event associated possibly with the plume approaching the region from station 35. The anomaly is observed between 135-160 m with a minimum temperature value of 8.14°C at 145 m against the ambient value of 8.24°C.

Further details of the intrusion characteristics beyond the shelf break are given in Figure 11 by the temperature profiles acquired at some of the locations given in Figure 1. As we noted earlier, because seawater density is dominated by salinity, water temperature can be viewed as a tracer permitting the identification of separate water masses. It is seen from Figure 11 that the profiles at stations 59 and 56, which are located more than 15-20 km away from the shelf break, are representative of smooth variations of temperature with depth. The remaining temperature profiles are, on the other hand, jagged and reveal a series of anomalous features indicative of interleaving water masses at various depth levels below the CIL. These anomalies, apparently signifying the Mediterranean underflow beyond the shelf break, generally start immediately below the depth of 100 m, first in the form of relatively warmer lenses and

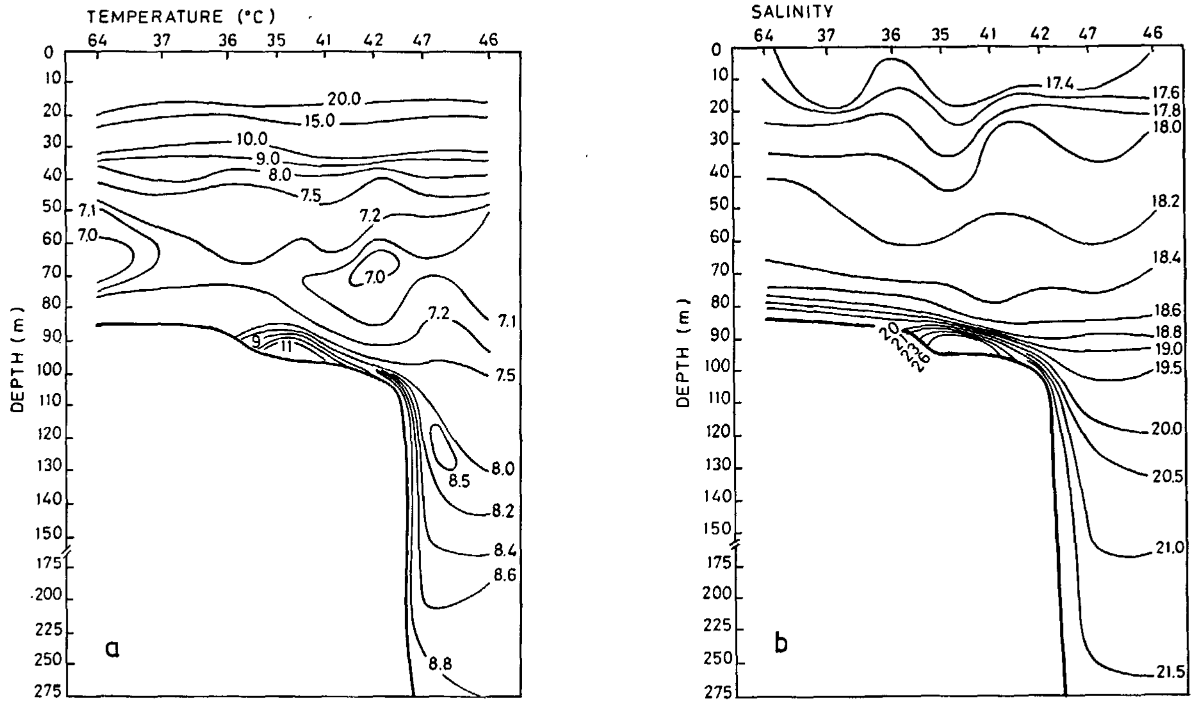

Figure 9
(*a*) *Temperature*, (*b*) *salinity transects for section B4.*

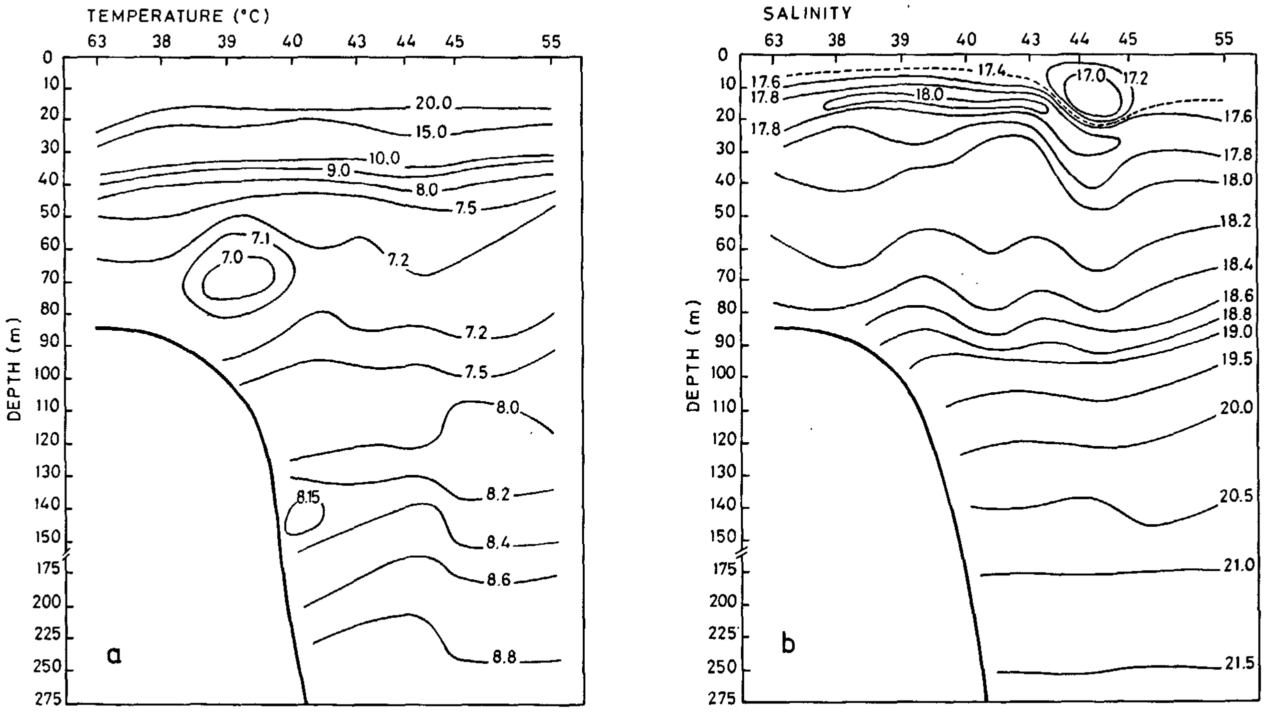

Figure 10
(*a*) *Temperature*, (*b*) *salinity transects for section B5.*

relatively warmer lenses and then followed by a series of cold spots toward deeper levels.

The warm spots are traced at stations 27, 47, 48, and 49 which have the total depths of 140 m, 470 m, 190 m, and 620 m, respectively, and are located near the head of the Bosphorus Canyon. The warm spot is also observed at station 45, located further offshore to the north of this group of stations. At station 27, the Mediterranean underflow is traced at depths between 95-100 m by $T \simeq 8.36$°C, $S \simeq 19.73$ and $\sigma_t \simeq 15.32$, being warmer and saltier than the surrounding waters of the CIL by about 0.6°C and 0.1. At station 48 the underflow is found near the depth of 110 m corresponding to the base of the CIL and attains the values of $T \simeq 8.26$°C, $S \simeq 20.20$ and $\sigma_t \simeq 15.70$, being greater than the ambient values by approximately 0.2°C and 0.05. At stations

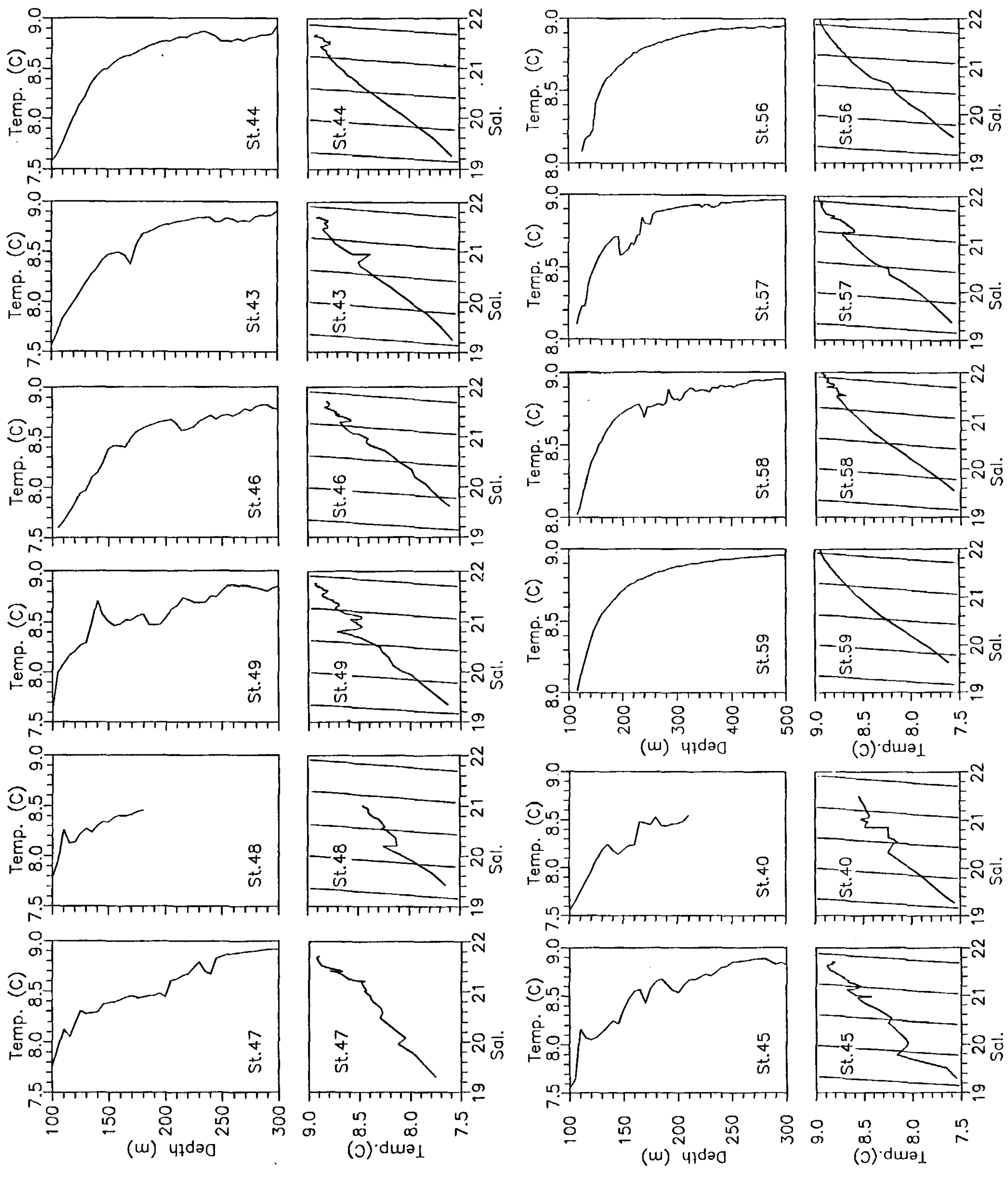

Figure 11
Temperature profiles and T-S plots displaying intrusions at various stations beyond the shelf break.

47 and 45, it is also observed immediately below the CIL at the depth of 110 m with slightly lower values in comparison with those at station 48 ($T \simeq 8.12$°C, $S \simeq 19.90$, $\sigma_t \simeq 15.40$). The warm spot is, however, relatively thicker at station 49 located within the Bosphorus Canyon. It is identified at depths of 135-150 m by the temperature, salinity and density values of $T \simeq 8.70$°C, $S \simeq 20.81$ and $\sigma_t \simeq 16.12$.

The temperature of the surrounding ambient waters at this level is approximately 8.45-8.50°C. An expanded form of the T-S curves showing the warm spots at stations 27, 48 and 49 is presented in Figure 12.

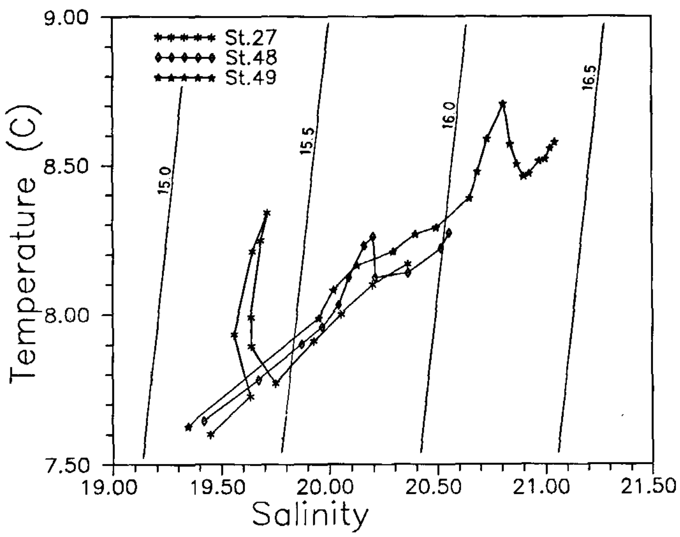

Figure 12
T-S plots for stations 27, 48 and 49 showing the warm lenses of the Mediterranean underwater at the base of the Cold Intermediate Layer.

A warm spot of the Mediterranean effluent was not, however, observed at station 40, further away from the main core of the effluent dispersing near the shelf break. On the contrary, a cold spot, having a temperature difference of about 0.1°C, exists at depths of approximately 140-160 m identified by T≃8.14°C, S≃20.50 and $\sigma_t \simeq 16.00$. The background temperatures at corresponding depth levels change between 8.25-8.45°C. Similar cold anomalies are observed at slightly deeper levels (165-175 m) at station 43, further offshore of station 40. The effluent was identified by T≃8.35-8.45°C, S≃20.95, $\sigma_t \simeq 16.27$ and was also cooler by about 0.1°C than the ambient values. Cold lenses observed immediately below CIL further southeast at stations near the head of the Bosphorus Canyon are, on the other hand, generally characterized by temperatures values of 8.20-8.30°C at depth levels of 130-140 m, the only exception being station 49 where the cold anomaly was found at deeper levels (185-195 m) with T≃8.45-8.50°C.

The special thermohaline structure of the ambient Black Sea waters makes the sinking plume of the Mediterranean effluent to show up in the form of cold intrusions further below the base of the CIL. As we discuss in section 2 and as it is shown in Figures 2 and 11, the temperature of thermocline waters increases almost linearly by about 0.5-0.6°C immediately below the CIL to the depth of about 150-175 m. Therefore, while the temperature and salinity of the ambient environment increases gradually and exceeds approximately 8.2°C, the sinking plume appears to be in the form of slightly colder and less saline lenses at depths below 120-130 m. Such intrusions are clearly depicted at most of the offshore stations at various depths and with varying thicknesses (Fig. 11). At 200-300 m depth levels, the intrusions may have a thickness of about 50 m and a temperature difference of about 0.1°C (*e.g.* station 57). Below 400 m, their signature may be identified by temperature differences of the order of 0.01°C (*e.g.* stations 57, 58).

Cold intrusions appear to be more pronounced at offshore stations 40, 43, 44, 57 in comparison with those near the head of the Bosphorus Canyon (*i.e.* stations 48, 49, 47, 46, 45). The cold anomalies observed within the first group of stations originate from the underflow which follows a longer path within the shelf by deflecting first northwestward and then southeastward. This allows for more interaction of the effluent with the CIL waters within the shelf and therefore gives rise to a somewhat cooler and denser Mediterranean underflow as compared to that moving along the channel-canyon axis. The difference in the water mass characteristics between these two types of anomalies is further reinforced by the mixing exerted by the Bosphorus Canyon topography immediately outside the Bosphorus exit. It is well known from observational studies (*e.g.* Shepard *et al.*, 1979) and theoretical models (*e.g.* Klinck, 1988) that submarine canyons generate a variety of motions including high frequency oscillations with periods shorter than the inertial period. These oscillatory currents, together with those generated by internal waves, edge waves, turbidity currents, etc., produce considerable mixing within the water column over the canyon.

The transects along sections B1-B5 also exhibit several structural details observed near the surface. Salinity transects along B1, B2 and B3 imply the presence of a saltier waters mass with S≃17.8-18 in the upper 10-15 m. This tongue of surface water appears to protrude southwestward from the eastern edge of the analysis region as a narrow layer approximately 15 m thick. The surface layer also presents a different, relatively less saline water mass with S≃17.0-17.2. This water mass appears to be associated with the colder and less saline Danube waters entering the region from the northwestern shelf region. Below the seasonal thermocline, the CIL is observed with minimum temperatures of 7.0°C at the cross-section beyond the shelf (*i.e.* section B5 and B4). The minimum temperature is however increased to 7.1°C at section B3 and to 7.2°C at section B2 as a result of increased mixing with the bottom waters of Mediterranean origin.

SUMMARY AND DISCUSSION

The flow and stratification characteristics of the southwestern Black Sea continental shelf/slope region outside the Bosphorus Strait have been studied by means of hydrographic observations carried out during the period 6-13 August 1989. Particular emphasis has been given to identifying the characteristics of the Mediterranean effluent as it spreads and sinks along the continental slope.

It is found that the Mediterranean effluent undergoes considerable modification as it travels from the exit of the Bosphorus Strait to the subhalocline waters of the Black Sea. The physical characteristics of the underflow, including its volume, velocity, temperature and salinity, evolve along its trajectory to the final, neutrally buoyant state at some level in or below the pycnocline. On its way, in the form of a thin layer along the bottom of the shelf, the effluent is diluted by entrainment of relatively colder and less saline ambient waters of CIL origin. Subsequently, the volume of the underflow increases and its temperature, salinity and thus density decrease as it moves downslope.

The main part of the effluent proceeds north-northwestward within the shelf. The northwesterly coastal current associated with the quasi-permanent anticyclonic eddy over the shelf is expected to participate in the northwestward deflection of the underflow. Penetrating further into the shelf, the effluent tends to be deflected east-southeastward by the Main Black Sea Current system, continues to be diluted and becomes less dense by entrainment of surrounding water and ultimately protrudes into the subhalocline waters of the Black Sea. The role of the Earth's rotation cannot be discounted as helping to determine the eastward deflection of the flow. Beyond the shelf break, the flow appears to be geostrophic and follows the isobaths. Within the shelf, ageostrophic processes such as friction and nonlinear advection should be important dynamic effects.

The temperature values typical of the sinking plume are 8.0-8.2°C near the shelf break at depths of 100-120 m. Such values are greater than the ambient value and the effluent may be identified as warmer and more saline bottom waters within the shelf. Beyond the shelf break, below depths of 140-150 m, as the temperature of the ambient waters exceeds 8.5°C, the intruding plume becomes cooler than the environment and is identified by relatively colder and slightly less saline patches down to the depth of 500 m. Recalling that the subhalocline waters of the Black Sea are anoxic, the sinking of the relatively oxygen-rich plume provides an interesting mechanism for the partial ventilation and renewal of the subhalocline waters.

Although the growing number of observations are leading to a better understanding of the processes controlling the motion of dense bottom currents in the southwestern Black Sea, the scientific study of their sinking and spreading characteristics is still in its infancy. Further observation and modelling will provide a more detailed and quantitative description of the flow field that conveys the dense underwater found on the shelf to the interleaved layers offshore. At present, existing mathematical models are generally limited in their scope and follow the so-called « stream tube » approach in which all physical variables are averaged across the face of the intruding plume (Smith, 1975; Killworth, 1977; Hamblin and Carmack, 1978). A slightly different model is also given by Stigebrant (1987) for describing the evolution of a rotating, dense bottom current of constant width in the Baltic Sea. All these models, however, have only limited success and applicability (*e.g.* Melling and Lewis, 1982; Artegianni and Salusti, 1987). The processes are complex and involve a wide variety of spatial and temporal scales that make modelling formulation quite difficult. The dynamics should incorporate the combined effects of stratification, rotation, topography, and three-dimensional field of motion, as well as a modern and fairly sophisticated turbulence parametrization scheme to deal with the various types of mixing processes taking place between the ambient water mass and the Mediterranean underwater.

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