Investigation of the Mediterranean water in the Strait of Istanbul (Bosphorus) and the Black Sea

Bosphorus
Blak sea
Sea of Marmara
Mediterranean water
Water exchange

Bosphore
Mer Noire
Mer de Marmara
Eau méditerranée
Échanges d'eau

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ABSTRACT

The spreading of Mediterranean water in the Strait of Istanbul and the Black Sea was investigated. Mediterranean water is observed as a well defined salt wedge along the Strait. Details of the spreading of Mediterranean water in the vicinity of the Strait of Istanbul and the Black Sea region were determined. It is shown that the northern sill does not prevent the Mediterranean water from entering the Black Sea, where it persistently takes a northeast route beyond the sill. A stable, equally persistent westward turn, almost at the same location, was observed. Data support the presence of a canyon or groove at or in the vicinity of the sill and adjacent shelf area.

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RÉSUMÉ

L'eau méditerranéenne dans le détroit du Bosphore et la mer Noire

L'eau d'origine méditerranéenne traverse le Bosphore en formant un courant profond et de salinité élevée tout au long du détroit. Le seuil situé au nord du détroit n'empêche pas l'eau méditerranéenne de pénétrer dans la mer Noire. La topographie du fond détermine son écoulement en un flux stable et permanent orienté d'abord vers le nord-est, puis vers le nord-ouest. Les données confirment la présence d'une fosse sur le plateau continental à proximité du seuil.

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INTRODUCTION

The Strait of Istanbul (Bosphorus), located between the Sea of Marmara and the Black Sea, forms part of the Turkish Strait System which consists of the Strait of Canakkale (Dardanelles), the Sea of Marmara and the Strait of Istanbul. This system, approximately 300 km in length, connects the Mediterranean Sea via the Aegean to the Black Sea. The Strait of Istanbul is located in its northern part. It has an important influence on oceanographic conditions in the Black Sea and the Sea of Marmara.

The Strait of Istanbul is a meandering strait some 31 km (20 miles) in length, with widths varying from 0.7 to 3.5 km (0.4 to 2.2 miles), averaging about 1.6 km (0.9 miles). Average and maximum depth are 35.8 and 110 m (Gunnerson *et al.*, 1972, Gunnerson, 1974). The bathymetry and the locations in the Strait, derived from Turkish Chart TR-2921, are shown in Figure 1.

Its bed is a drowned river channel, more than 50 m deep, extending beyond a sill of 32 to 34 m depth located at the southern entrance of the Strait, between Kabataş and Üsküdar (Fig. 1). The bottom of the strait deepens from approximately 40 to 70 m in the northern part. Another sill at a depth of 57 to 59 m is located at about 4 km from the northern entrance (Fig. 2).

One of the distinct characteristics of the Strait of Istanbul is a two layer current and density distribution. Less saline Black Sea surface water is carried into the Sea of Marmara at the surface, while underlying bottom water from the Sea of Marmara, which is originally from the Mediterranean, is carried in the opposite direction, towards the Black Sea. The surface current follows the Strait's meanderings and forms numerous small circulations in several bays on both sides. The bottom current follows the windings of the channel more closely.

Vertical stratification, the two-layer current system and the transportation of Mediterranean water with the bottom current have been investigated by many

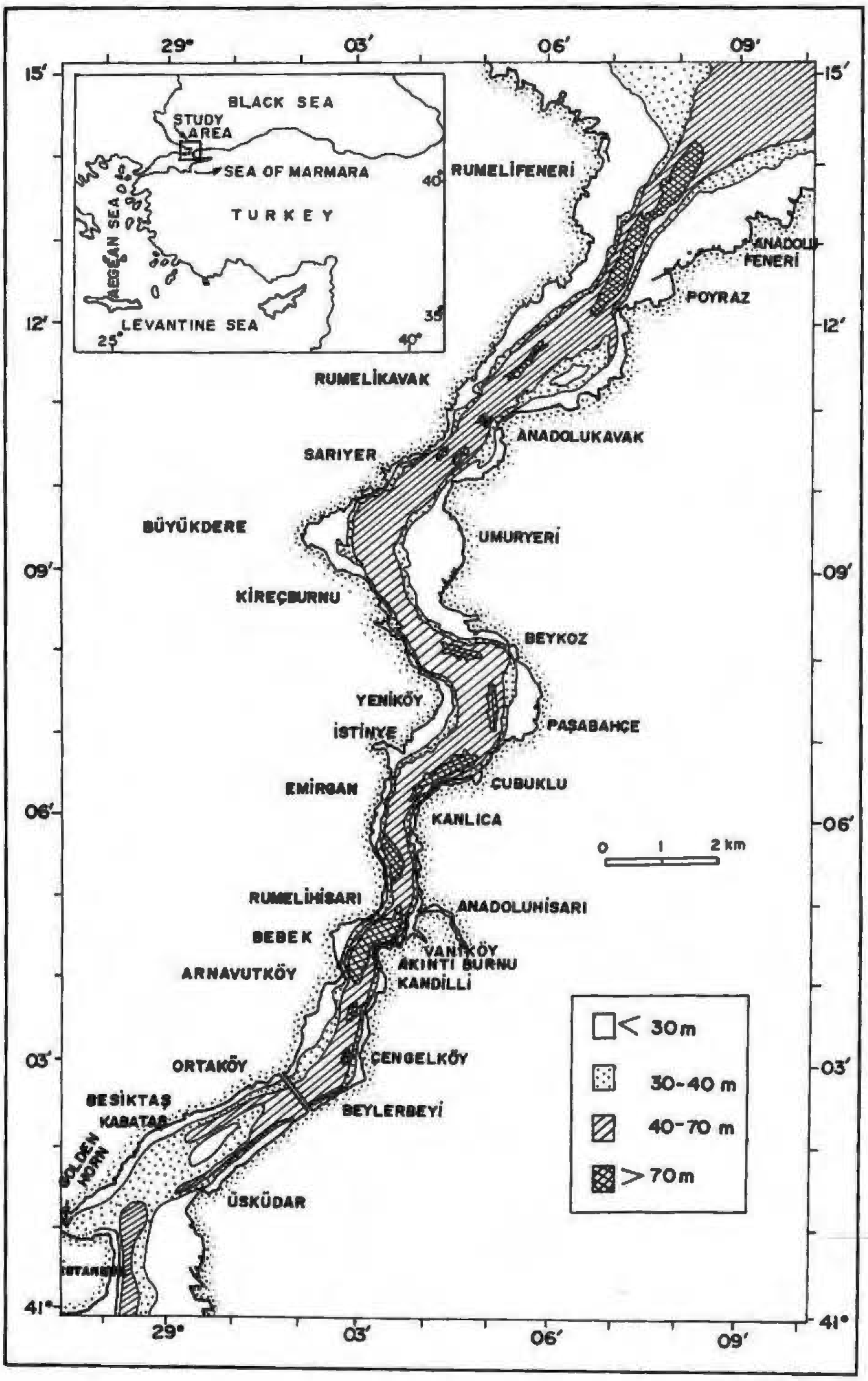

Figure 1
Strait of Istanbul bathymetry derived from Turkish chart (2921) *and location chart. The southern sill is located between Kabatas* and Üsküdar.

researchers, due to the important role of water exchange throughout the Strait of Istanbul in determining the oceanographic regime, especially in the western Black Sea and the Sea of Marmara. Studies of water exchange, vertical stratification and current characteristics conducted by English, Russian and German observers were first reported before the 1930's (Wharton, 1872; Makarov, 1885; Möller, 1928). Later scientific studies have led to both specific and general understanding of conditions along and at the Black Sea entrance to the Strait (Reference 1-9, 11-17, 19).

The general oceanographic conditions pertaining in the Strait of Istanbul are thus quite well documented, but detailed surveys and studies are still needed in order to define such features as the flow characteristics of the Mediterranean water into the Black Sea. Different hypotheses concerning the continuity of this flow have been proposed. Complete (Ulyot, Ilgaz 1946; Ulyot 1953), or partial (Pektas, 1953, 1956) blockage, and continuous flow (Makarov 1885; Bogdanova, 1961, 1965) have been the subject of discussion among oceanographers.

A well-documented review of the dynamics of the Strait of Istanbul and a summary of recent Turkish studies are given by Ünlüata, Oğuz (1983). Büyüközden *et al.* (1983 *a*, *b*, 1985) studied the distribution of Mediterranean water along the Strait of Istanbul and in the Black Sea based on historical data and data collected between 1983-1984, beginning at the end of 1982. Utilizing all available Soviet data collected from a programme initiated by V.A. Vodyanitsky (1948) and lasting more than 15 years (1959-1973), Tolmazin (1985) described the intrusion and spreading of Mediterranean water in the Black Sea. These studies, which are complementary to each other, reveal some previously unknown details of this spreading. Büyüközden *et al.* (1983 *b*, 1985) gave detailed information on the spreading of Mediterranean water along the Strait of Istanbul and in the Black Sea. This recent study covers the entire Strait, the sill and the region neighbouring the Strait of Istanbul, and in consequence extends from Turkish territorial waters outward, in contrast with Tolmazin's (1985) data which were collected beyond the outer limits of Turkish territorial waters. It is shown by both authors that the northern sill does not prevent Mediterranean water from entering the Black Sea and that this water persistently takes a northeast-northwest direction. The Mediterranean water in the Strait of Istanbul and the Black Sea is further investigated below, on the basis of a review, further elaboration and interpretation of Büyüközden *et al.* (1985) data and findings.

DATA COLLECTION AND ANALYSIS TECHNIQUES

The data used in the present study were collected from surveys conducted both in the Strait and in the Black Sea, and have been utilized earlier by Büyüközden *et al.* (1985). The distances between cross-sections and stations were 1.2 and 0.4 miles respectively in the Strait of Istanbul. In the Black Sea, a dense network of oceanographic stations, starting in the northern part of the Strait was set up along sections with respect to the strait exit and perpendicular to the coastline. The distance between individual cross-sections and stations was less than 2.0 miles close to the shore. Off shore (>5.0 miles), the distances between individual cross-sections and stations were approximately 4.2 and 3.5 miles respectively. At each station, Nansen bottle casts were performed from a drifting vessel at standard depths. At the Black Sea stations, water samples were also collected 2.0 and 4.0 m from the bottom, at both Nansen-cast and bottom water sampling stations located between cross-sectional Nansen-cast stations. To obtain bottom-water samples two Nansen bottles without reversing thermometers were connected 2 metres apart from one another and dead weight. Wire tension were carefully monitored and messenger was dropped when the weight hit the bottom. Two research cruises in the Strait and one in the Black Sea were conducted each month between 1983-1984, beginning at the end of 1982.

In the survey programme on which Tolmazin's (1985) work is based, there were virtually no continuous property measurements downstream and across the flow after it leaves the Strait, the circulation pattern south of the observation site.

The present study filled this gap: in addition to the strait stations, a dense network of stations, especially in Turkish territorial waters, which had not been occupied before, was established and covered by monthly research cruises.

RESULTS AND DISCUSSION

The sill, at a depth of 32-34 m at the southern entrance of the Istanbul Strait between Kabataş and Üsküdar (Fig. 1), does not prevent Mediterranean water from entering the strait. This is because the Mediterranean water is found at a depth of approximately 20 metres close to the sill. Since the depth of the southern sill does not exceed 40 m, the Mediterranean water drawn

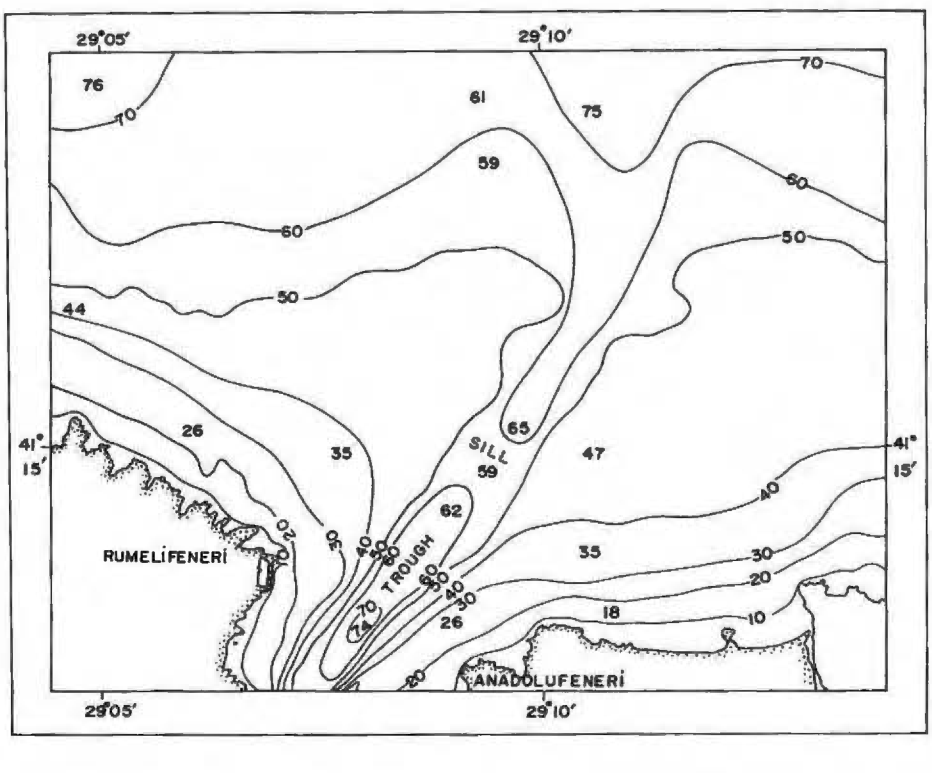

Figure 2
Bathymetry of the Strait of Istanbul-Black Sea junction derived from Turkish Chart TR 1811.

into the Strait by the undercurrent penetrates with a maximum depth of 40 m.

The Mediterranean water can be traced from the salinity, which is an appropriate trace parameter due to the high contrast along the Strait of Istanbul and in the Black Sea. Highly saline Mediterranean water observed in the bottom layer throughout the entire length of the Strait during research cruises conducted in 1983-1984 beginning at the end of 1982. In these surveys, only the thickness of this layer varies, depending upon the water level difference, prevailing winds and location along the Strait. Surface water temperatures increase from north to south during winter and decrease in summer due to mixing of the surface water with the cold intermediate Black Sea water which is observed in the Strait during the warm season. This cold intermediate water becomes shallower towards the south, as in the case of the Black Sea surface water in the Strait (Fig. 3 *a*). This shoaling, with the upwelling of Mediterranean water at the southern part, which is

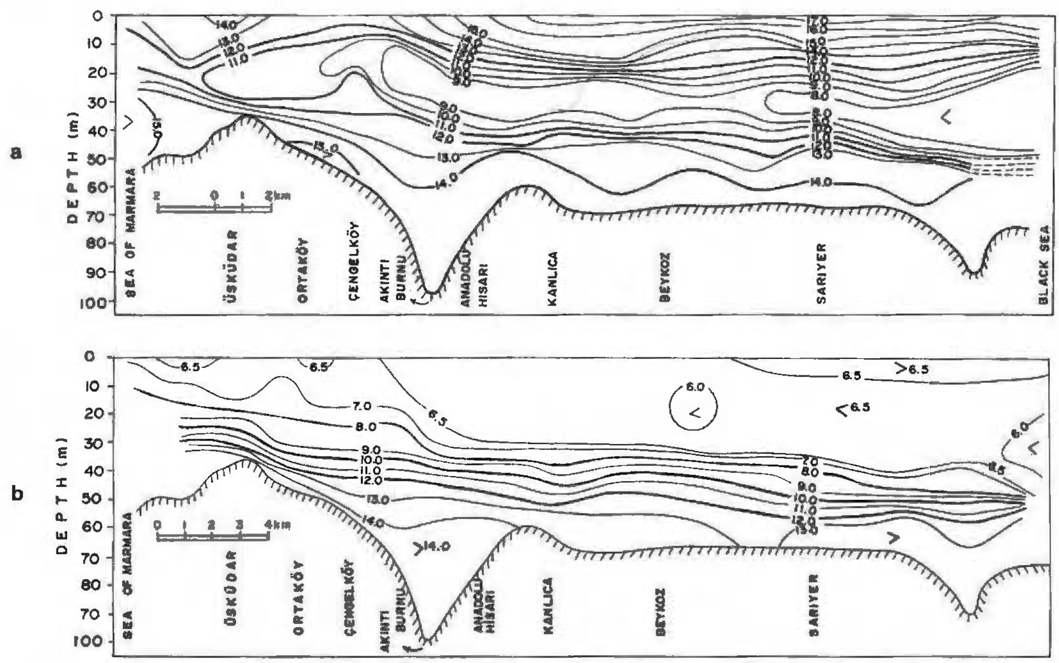

Figure 3

Temperature section along the Strait of Istanbul during (a) late winter-March data (b) early summer-June data.

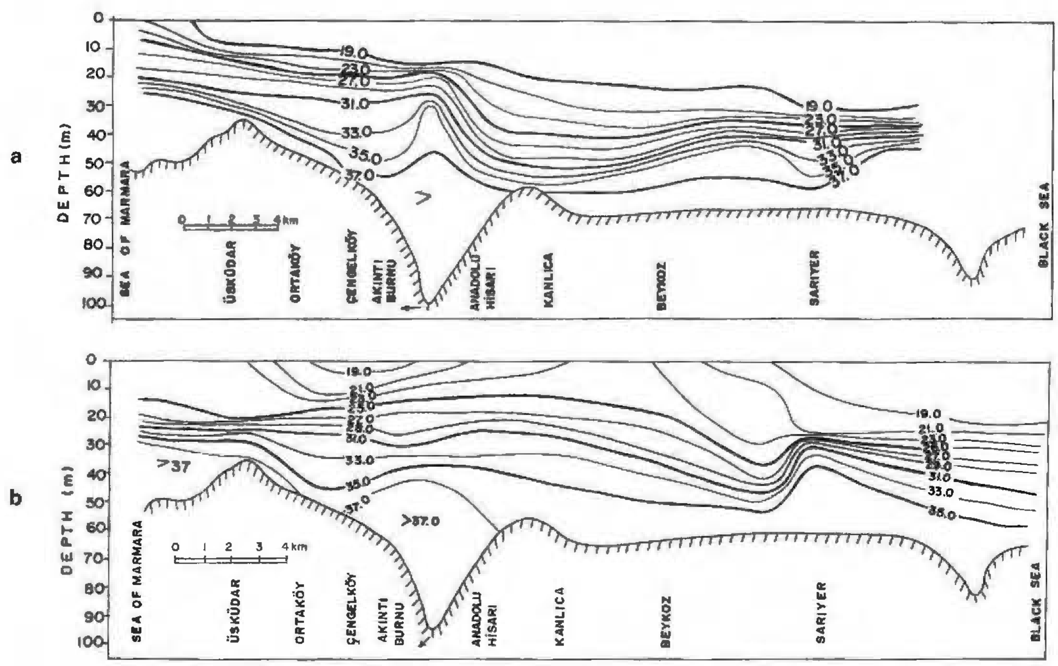

Figure 4

Salinity section along the Strait of Istanbul (a) October data-calm weather (b) November data when southerly winds dominate.

colder than the surface water due to high summer surface temperatures, causes surface temperatures to drop from north to south (Fig. 3 *a*). In winter, due to mixing with Mediterranean water, the temperature of the Black Sea surface water increases from north to south (Fig. 3 *b*). Bottom water temperatures do not show large seasonal variations. A salt wedge is observed in all of the cruises; below that, Mediterranean water with a temperature 15.5°C and high salinity (>30) is observed.

Bottom water salinity has a value of 38.0-38.5 at the entrance to the Sea of Marmara and 35.5-36.5 in the northern part of the Strait, namely at the Black Sea exit. Surface water salinity increases from north to south. Southerly winds are mainly observed during the period November through January and cause the surface current to decrease; or if they are strong enough, and time permits, a reversal of surface current, which os generally southbound, may occur. Wind-driven current reversals bring relatively high salinity water to the surface. The meandering structure and bathymetry of the Strait play important roles in controlling the surface and bottom currents. This effect is more pronounced on the Mediterranean water at the bottom, which follows the bottom topography and the meanderings of the Strait more closely. At the corner near Akinti Burnu (Fig. 1) this effect is strongly pronounced due to the morphological effects, especially when southerly winds exist. This difference can be seen in Figure 4, where Figure 4 *a* concerns calm weather and Figure 4 *b* southerly winds under whose influence surfacing of highly saline bottom water is evident. As already stated, the Strait of Istanbul is a meandering strait; beyond the Mediterranean water meeting-point at the headland of Akıntı Burnu, the coast turns westward (Fig. 1) forcing the Mediterranean water to press against this barrier and itself turn west. As a consequence, upwelling of the bottom water is observed in the vicinity of this point. At Akıntı Burnu, strong surface currents prevail. Along the direction of the flow between Akıntı Burnu and Beylerbeyi, however the core of the bottom currents is further from the Asiatic shoreline. The left-hand side of this current is very weak, almost nonexistent; thus the body of water is relatively stagnant. This current regime is partly due to the westward extension of the coastline, which forces the upwelling of the bottom waters and diminishes surface current effects; as a result, the current is very weak almost nonexistent.

Mediterranean water was encountered at the northern exit of the Strait during all the surveys. Cross-sections of the 30.0 isohaline in the northern part of the Strait, between Rumeli Feneri and Anadolu Feneri, for different months, are shown in Figure 5. Approximately 8.0 m of variation in the 30 isohaline depth are observed. At the northern exit, the bottom layer generally reaches its minimum thickness in the spring and increases during autumn and winter (Büyüközden *et al.*, 1985).

Mediterranean water is observed towards the Black Sea as a well defined salt wedge. It can also be identified from temperature and dissolved oxygen sections with its higher temperature and lower dissolved oxygen values. Salt wedge intrusion of Mediterranean water into the Black Sea and bathymetric channeling of the outflow plume can be easily seen in longitudinal and cross-sectional salinity temperature and diffolved oxygen distributions (Fig. 6).

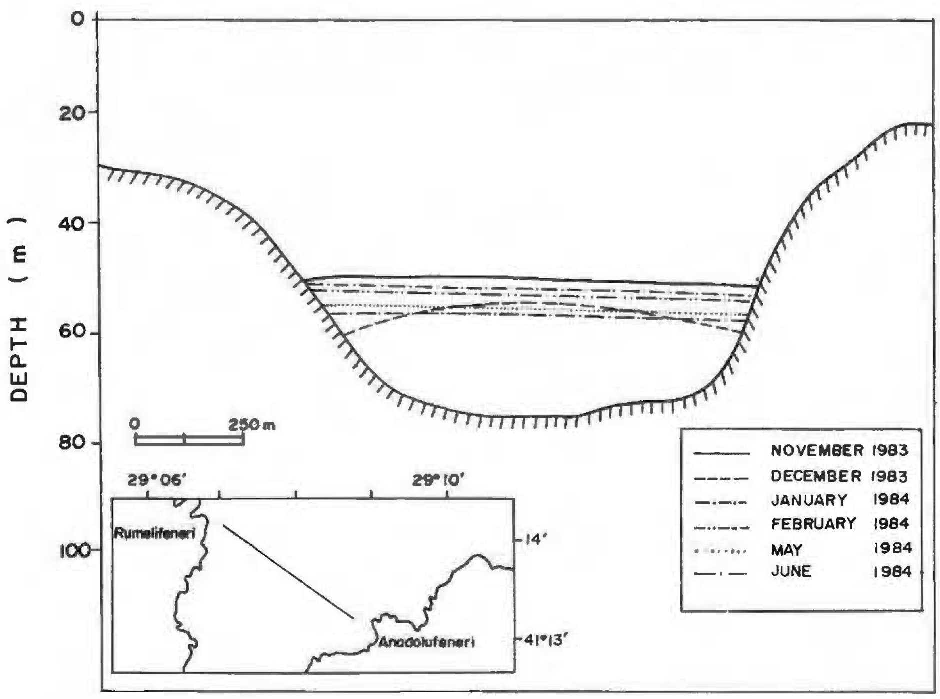

Figure 5

Boundary layer between the surface and the bottom water based upon the 30.0 *isohaline taken as the upper limit of Mediterranean water at the northern Black Sea entrance of the Strait* (1983-1984 *data, After Büyüközden et al.,* 1985).

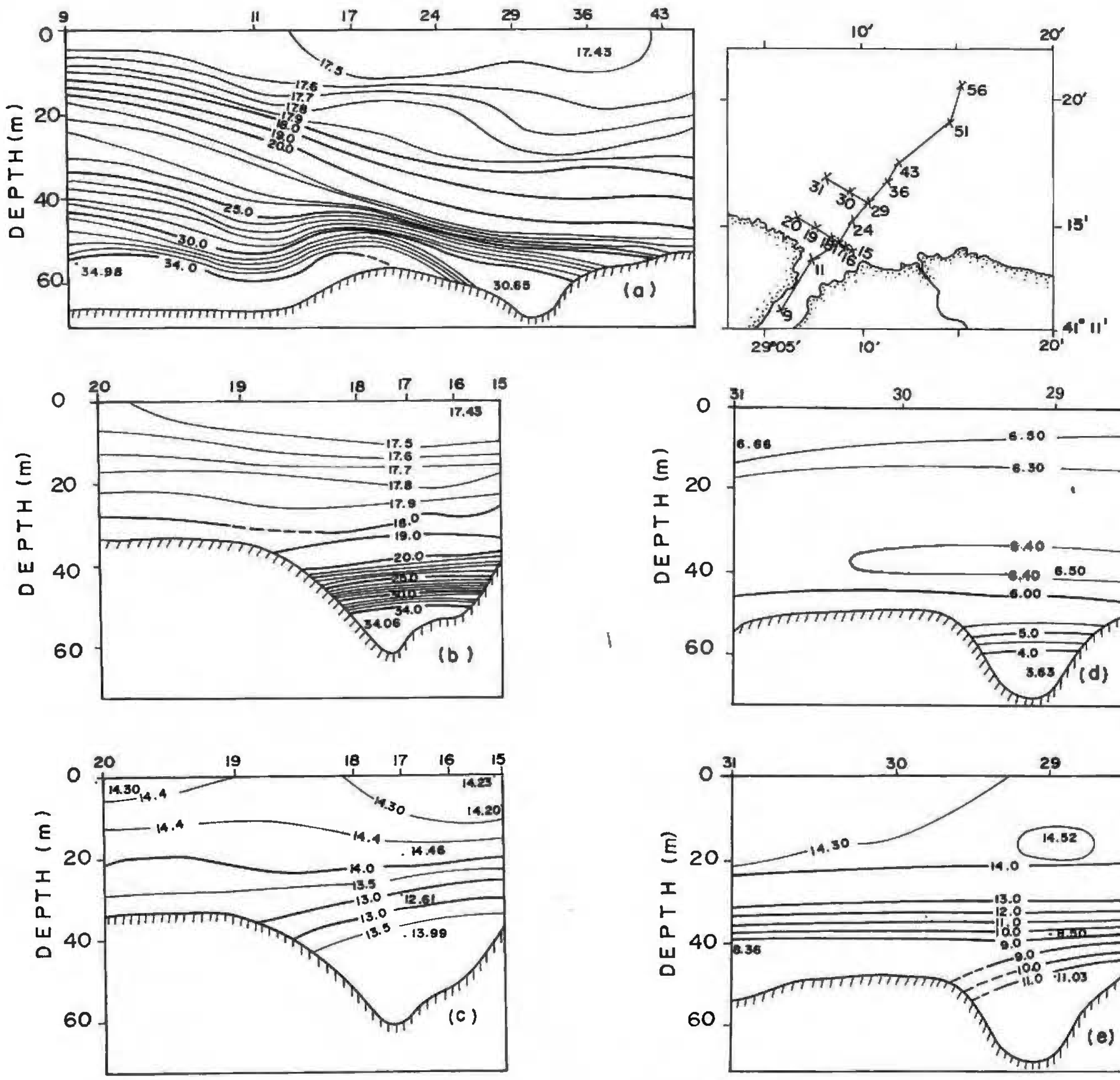

Figure 6
(a) Salinity section along the Strait of Istanbul extension toward the Black Sea; (b) salinity; (c) temperature; (d) dissolved oxygen (ml/l); and (e) temperature section perpendicular to the flow direction (b, c, e after yüce, 1988).

The salt wedge observed along the Strait, extends for 4.34 miles (9.0 km) away from the Strait exit into the Black Sea, directed by a bottom topography which is evident in sections perpendicular to flow direction (Fig. 6 *b-d*). At this distance, a salinity value of 30.6 was observed 8.0 m from the bottom temperature. Salinity, sections, perpendicular to the flow-direction higher (34.06) salinity value was observed 10 m from the bottom (Fig. 6 *b*) associated with low dissolved oxygen (< 5.46 ml/l) and higher temperature (> 13.99°C) within cold intermediate water of the Black Sea. Directed by the bottom topography this water extends notheast. Low oxygen content (3.63 ml/l) and higher temperature (> 11°C) below a cold transition layer indicate the presence of Mediterranean water further away from the northern sill (Fig. 6 *c*, station 29). Using a simple model Yüce (1989) calculated that Mediterranean water extends 4.84 miles (9.0 km) beyond the northern sill which is located 2.16 miles (4.0 km) from the northern exit of the Strait. These values are close to the Büyüközden *et al.* (1983 *b*) calculations that Mediterranean water may extend 4.84 miles (9.0 km) into the Black Sea after the Strait northern exit. During the 1983-1984 surveys, Mediterranean water was encountered in the Black Sea beyond the sill. This salt wedge observed in all of the cruises supports the above-mentioned results. The bottom water may extend for approximately 5-7 miles (9.0-13.0 km) into the Black Sea after passing through the Rumeli Feneri-Anadolu Feneri line and spreads in a northeasterly direction under the influence of bathymetric channeling, driven by density differences and "suck-in" effect of the lateral coastal bottom current system in the Black Sea. Even if this water is blocked at the Black Sea exit, with the aid of the local coastal bottom current system and frictionless control of the trough, transport across the sill is still a possibility, while with the aid of bottom topography this northeast flowing Mediterranean water plume spreads towards the northwest. Mediterranean water spreading path characteristics can be investigated by means of bottom salinity distributions based on data collected from systematic surveys in the Black Sea approach to the Strait. Spreading of Mediterranean water in a northwesterly direction is evident from bottom salinity distributions, which are shown in Figure 7 for different months. The discontinuity observed in these figures (Fig. 7 *a-c-e-f*) between high salinity areas which are located in the northwestern part and in

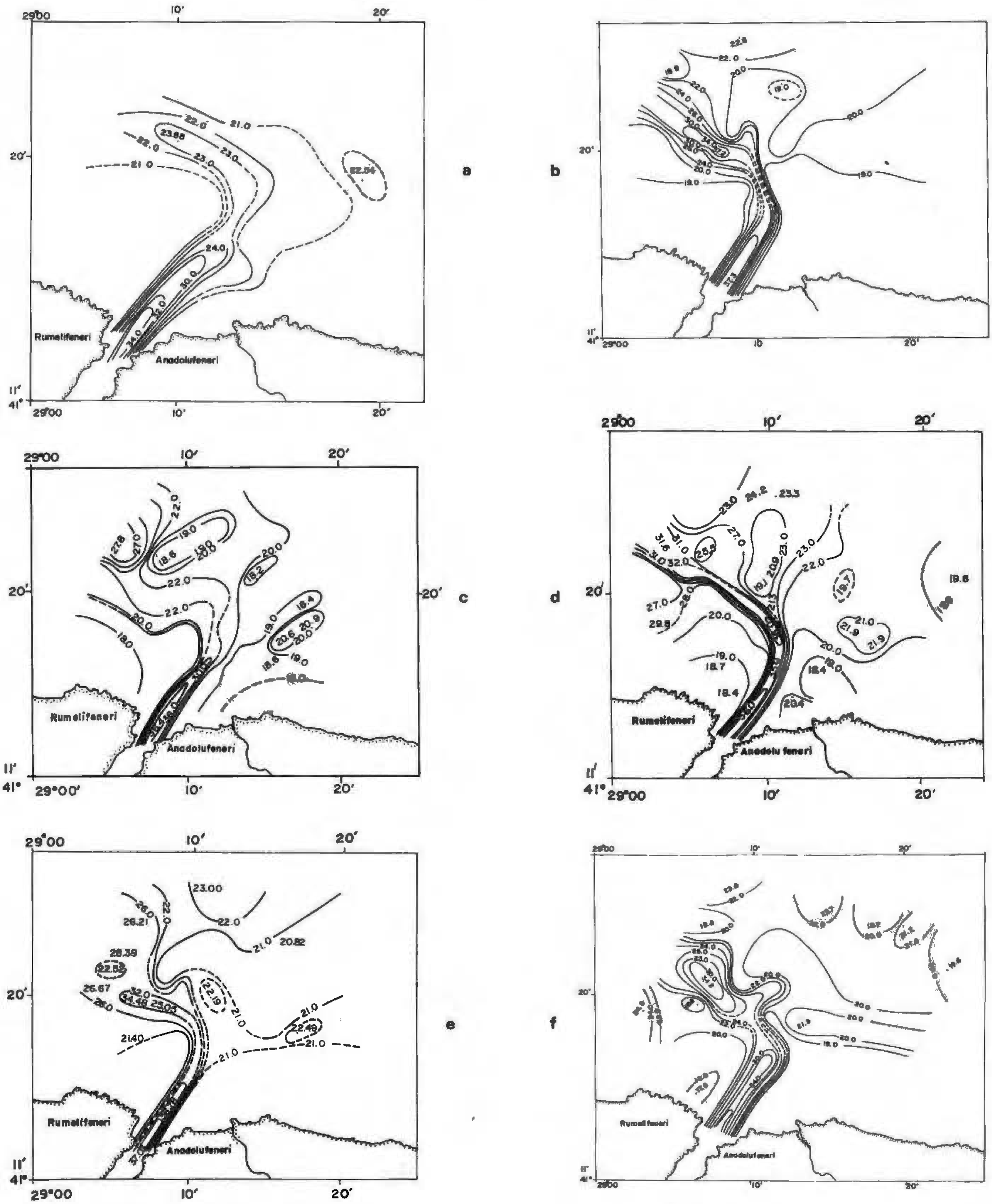

Figure 7

Bottom salinity distribution in the Black Sea exit of the Strait of Istanbul for different months (a) June 1983; *(b) June* 1984; *(c) July* 1983; *(d) September* 1984; *(e) October* 1982; *(f) November* 1982.

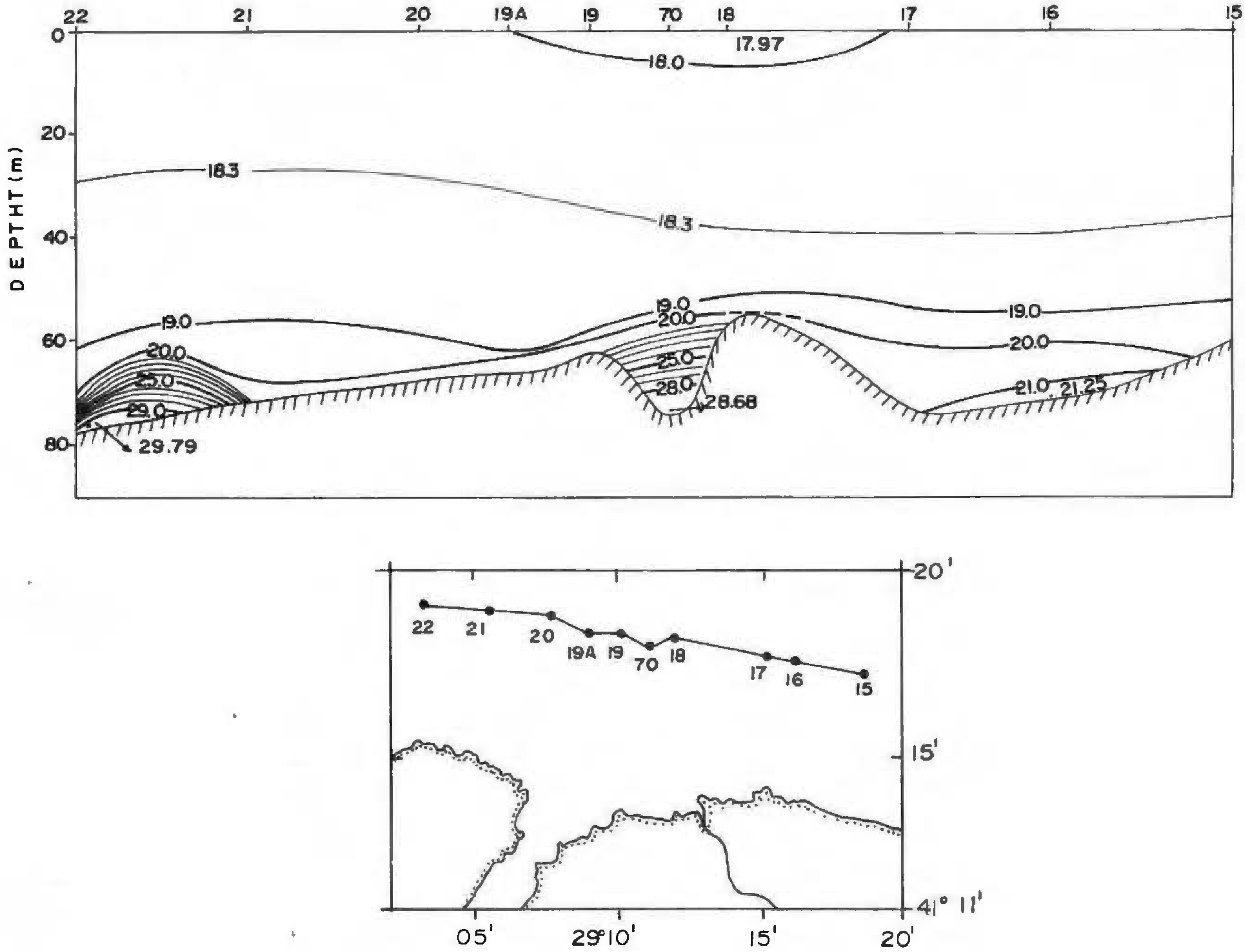

Figure 8
Salinity section parallel to the Strait of Istanbul coastline (September 1984 data).

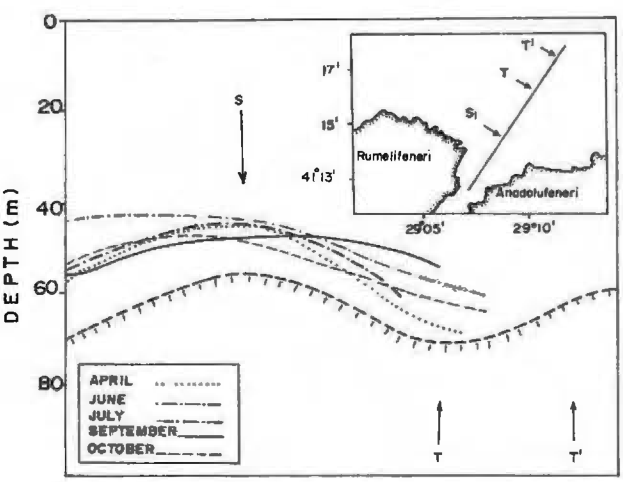

Figure 9
Strait of Istanbul Black Sea exit 30.0 *isohalines for different months* (1983-1984 *data*)*; bottom is schematic.*

the vicinity of the Straits is due to the passage of Mediterranean water which remains undetected because of its spatial distribution.

This was demonstrated by adding a new station between 18 and 19. At this newly established station 70, Mediterranean water was detected, and a higher water depth compared to the neighbouring stations was observed during the September 1984 cruise (Fig. 8, Fig. 7 *d*). Following the maximum salinity core layer of the Mediterranean water, the spreading path of Mediterranean water towards the Black Sea in a northwesterly direction was determined. After the still, its main route is at first towards the northeast; it then turns northwest and flows into the Black Sea. This is why early investigators who looked to east and not closely to the west beyond the sill depth failed to detect the Mediterranean water. The Mediterranean water flow path is almost straight and laterally it is not

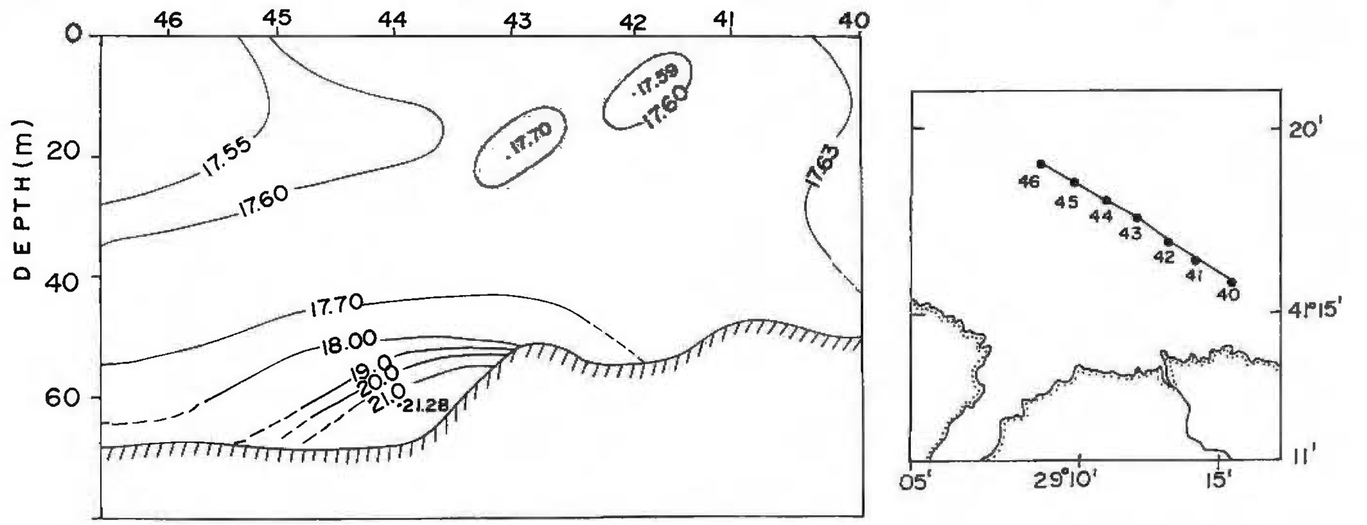

Figure 10
Salinity section parallel to the Strait of Istanbul coastline (December 1982 data).

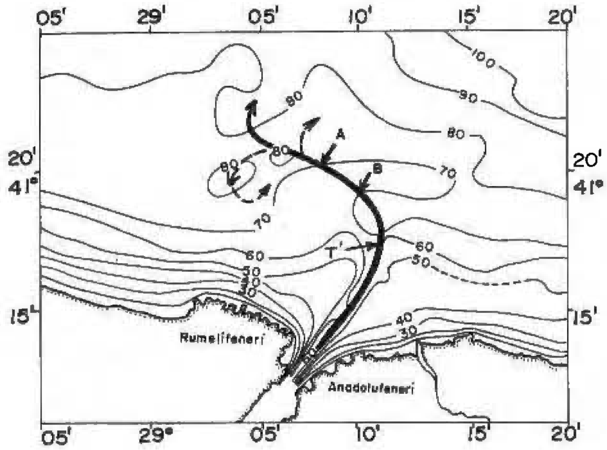

Figure 11
Bathymetry in the vicinity of Strait of Istanbul Black Sea exit and Mediterranean water flow path.

variable. Initially it extends in a northeasterly direction in the direction of the Strait up to a point which is the same almost every month. Beyond this point, it turns westward. This turning-point coincides with the location of point T' which is shown in Figure 9. Intrusion of Mediterranean water into the Black Sea can be easily explained by utilizing the 30.0 isohaline in the Black Sea. This provides an indication of the extent of the Mediterranean water and of the mechanism whereby it spreads out further, as mentioned previously. Although the bottom is schematic in this figure, there is a trough (T), with a shoal (T') beyond. This is due to the encounter with the westward extension of the 60 m depth contour as shown in Figure 11. Water presses up against the western part of point T' and turns westwards following the topography to the east (Fig. 10, station 44 and Fig. 9, point T'). This reveals a deepening of the bathymetry towards the northwest.

The most probable route of the Mediterranean water is determined by following the core layer with its high salinity values for different months (Fig. 11). This figure clearly supports the above-mentioned findings. Following the Strait extension and directed by the bathymetry, Mediterranean water extends in a northeast direction, and then turns westwards at point T' under the influence of the bathymetry on the eastern flank. Bathymetry drawn using available Turkish charts clearly depicts the deepening on the western part of point T', but additional bathymetric data are needed beyond this point and should be studied further The northwesterly flow direction of the Mediterranean water in the vicinity of point T' and the limited nature of the lateral migration of the path perpendicular to the flow direction testify to the presence of a canyon or a groove lying in a northwesterly direction, especially between the line A-B, beginning beyond the still and passing at point T'. Beyond approximately point A, branching is observed. This is due to the cessation of the bathymetric control.

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