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THE SOURCES OF THE DEEP WATER OF THE EASTERN MEDITERRANEAN SEA[1]

By

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ABSTRACT

The deep water in the two basins of the eastern Mediterranean Sea, the Levant and the Ionian Sea, is identical in temperature and salinity though differing slightly in oxygen content. Contrary to Nielsen's thesis, none of this water is formed in the southern Aegean Sea. The latter, connected with the Mediterranean by a number of straits, has consistently higher salinities and oxygen values in the vicinity of the sill depths than are found at equal or greater depths on the Mediterranean side of these channels. The effluent from the Strait of Sicily is also eliminated as a source of the deep water since it is separated from the latter by an intervening layer of maximal salinity. The Adriatic Sea has extremely variable water characteristics because of its shallow average depth and consequent susceptibility to fluctuations of the prevailing weather regime. In its southern half, considerable mixing takes place between relatively fresh water from the north and more saline water from the upper few hundred meters of the Ionian Sea. This mixed water sinks and then flows sporadically along the bottom into the Mediterranean Sea, where it circulates counterclockwise. This flow is confirmed by the distribution of oxygen values in the deep layers of the entire eastern Mediterranean.

INTRODUCTION

In his outstanding treatise on the hydrography of the Mediterranean Sea, Nielsen (1912) makes the following statement about the sources of the deep water in the Levantine and Ionian basins:

> We have seen, further, that a uniform layer of water from surface to bottom occurs in the southern part of the Adriatic and in the Aegean Sea north of the Cyclades—possibly also in the deep water north of Crete—and that this layer is colder and heavier than the masses of water, which are found at the same level in the Levant and Ionian Sea. These masses of water will then move towards the south, in the extent to which the depths permit, and after reaching the Ionian Sea and Levant will flow down its northern slopes to the greatest depths. During this movement they will become partially mixed with the bottom-water and be distributed by horizontal currents in the bottom-layer over the whole of the eastern basin.

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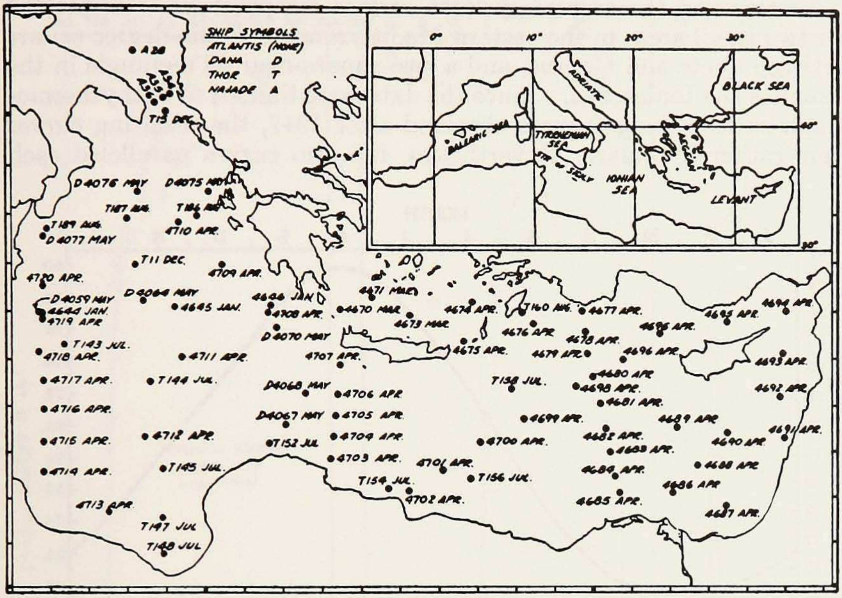

Figure 1. Station positions in the eastern Mediterranean Sea.

Schott (1915), in a paper which is largely a review of Nielsen's work, agrees with the above statement but doubts that enough water flows out of the Aegean Sea to fill the Levantine Basin.

The present paper will attempt to show that the deep water is formed only in the Adriatic Sea and that the Aegean Sea cannot contribute to this bottom water mass.

The serial observations of temperature, salinity and oxygen obtained by the Research Vessel ATLANTIS of the Woods Hole Oceanographic Institution during the winter and spring of 1948 form the main source of data for this discussion of the eastern Mediterranean. Earlier stations in the area were also used, with the exception of POLA data which were obtained in the days before the present standards of accuracy were achieved in oceanographic observations. Fig. 1 shows the outlines of the area under discussion and the positions of all stations used.

Vertical convection currents which can cause a complete overturning of the entire water column and can thus be an important factor in the formation of subsurface water characteristics are most likely to occur during periods of minimum surface temperatures. Therefore it becomes important to establish a criterion for comparison of stations taken at different times of the year.

To this end the annual cycle of surface temperatures was plotted for two small areas in the eastern Mediterranean: A one-degree square between Crete and Cyprus, and a two-square-degrees rectangle in the center of the Ionian Sea. Since the data were limited to bathythermograph surface temperatures obtained after 1947, the resulting curves were rather irregular. Nevertheless, the two curves paralleled each other closely, the Ionian Sea temperatures being about 1.5° C. colder than corresponding temperatures from the Levantine area. As a check on these data, averaged monthly surface temperatures obtained by British ships between 1900 and 1914 (Meteorological Committee, Air Ministry, London, 1930) were plotted on the same diagrams. Good agreement was found. Since relative rather than absolute temperatures were the feature sought, these different sets of surface data were combined into a mean curve (Fig. 2).

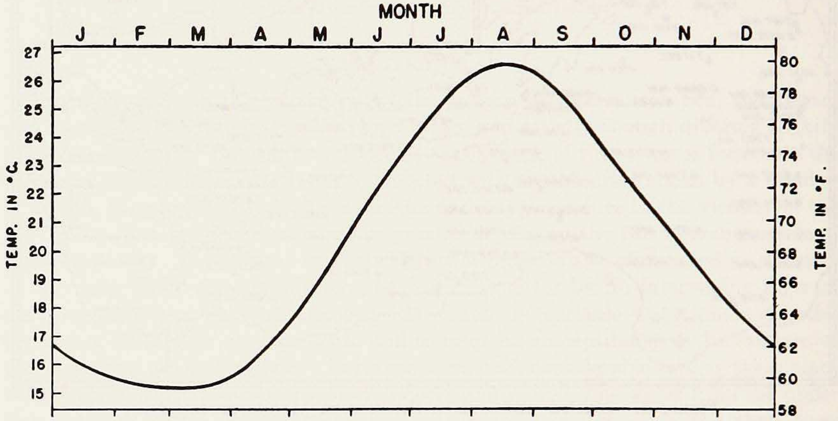

Figure. 2. Mean surface temperature cycle in the eastern Mediterranean Sea.

CHARACTERISTICS OF THE DEEP WATER

Before attempting to trace the sources of the deep water of the eastern Mediterranean, it is pertinent to examine its basic characteristics. For this purpose, temperature, salinity and oxygen curves from two centrally located Atlantis stations, 4711 in the Ionian Basin and 4699 in the Levantine Basin, are shown in Fig. 3. On the basis of Fig. 2, both of these stations were made close enough to the period of minimum surface temperatures to be fairly representative of winter conditions except in the upper 50 meters where some warming had already taken place.

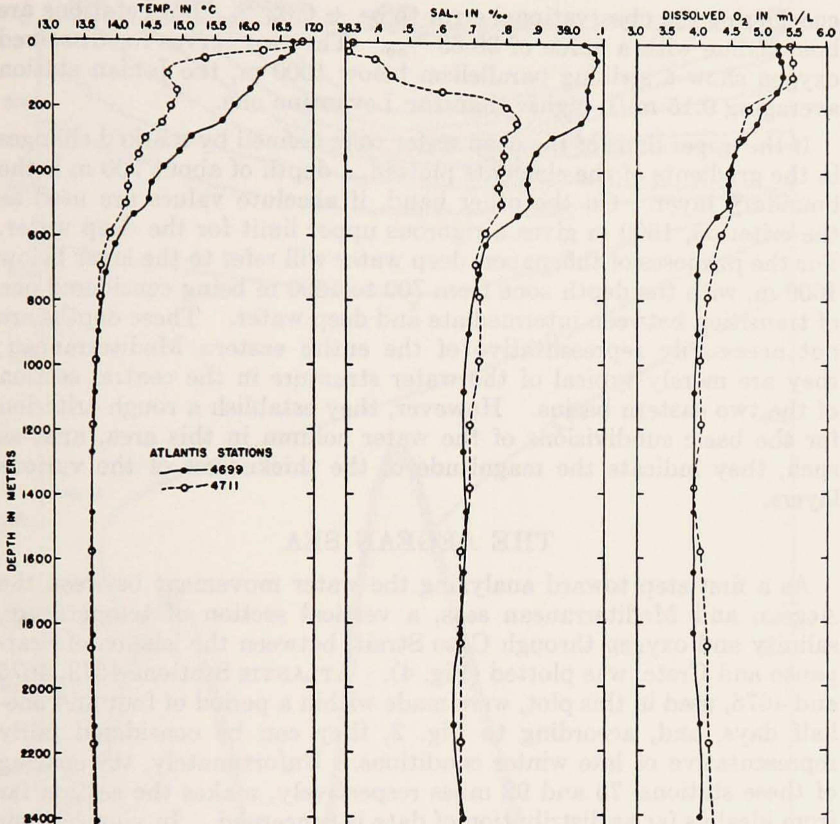

Figure. 3. Typical station curves from the central Levant (No. 4699) and the Ionian Sea (No. 4711).

The significant features of the two sets of curves are their difference in the upper 1000 m or so and their similarity below that depth. The temperature traces practically coincide below 850 m, both having a minimum value of 13.57° C. at 1600 m. The salinity curves show more irregular divergencies. Between 750 m, where the two curves cross, and 1600 m, the traces differ by as much as 0.04 ‰. Below 1600 m, considering the observational error to be ± 0.02 °/₀₀, both stations are homohaline with a value of 38.65 °/₀₀. The two curves for dissolved oxygen show a striking parallelism below 1000 m, the Ionian station averaging 0.15 ml/L higher than the Levantine one.

If the upper limit of the deep water were defined by marked changes in the gradients of the elements plotted, a depth of about 700 m is the boundary layer. On the other hand, if absolute values are used as the criterion, 1600 m gives a rigorous upper limit for the deep water. For the purposes of this paper, deep water will refer to the layer below 1600 m, with the depth zone from 700 to 1600 m being considered one of transition between intermediate and deep water. These depths are not necessarily representative of the entire eastern Mediterranean; they are merely typical of the water structure in the central section of the two eastern basins. However, they establish a rough criterion for the basic subdivisions of the water column in this area, and, as such, they indicate the magnitude of the thicknesses of the various layers.

THE AEGEAN SEA

As a first step toward analyzing the water movement between the Aegean and Mediterranean seas, a vertical section of temperature, salinity and oxygen through Caso Strait, between the islands of Scarpanto and Crete, was plotted (Fig. 4). Atlantis Stations 4673, 4675 and 4676, used in this plot, were made within a period of four and one-half days, and, according to Fig. 2, they can be considered fairly representative of late winter conditions. Unfortunately, the spacing of these stations, 75 and 92 miles respectively, makes the section far from ideal as far as distribution of data is concerned. In view of their geographical positions, a true bottom profile between them would be meaningless, and hence it was replaced by a schematic bottom curve showing the maximum and minimum depths between stations.

Even considering the subjectivity of the contouring of the station data, several features of the profiles stand out. For all three water properties plotted, the Aegean station (4673) shows weaker gradients and smaller over-all ranges than the Mediterranean station (4676). Station 4675, right over the sill between the two sea basins, shows some characteristics of each of the other two stations. In the upper 400 m, the temperature and salinity structure of this station closely resembles that of Mediterranean water. The oxygen distribution, on the other hand, differs somewhat from that of the other two stations, the gradients being smaller. Below 400 m, the water structure, in terms of all elements considered, is similar to that of Station 4673.

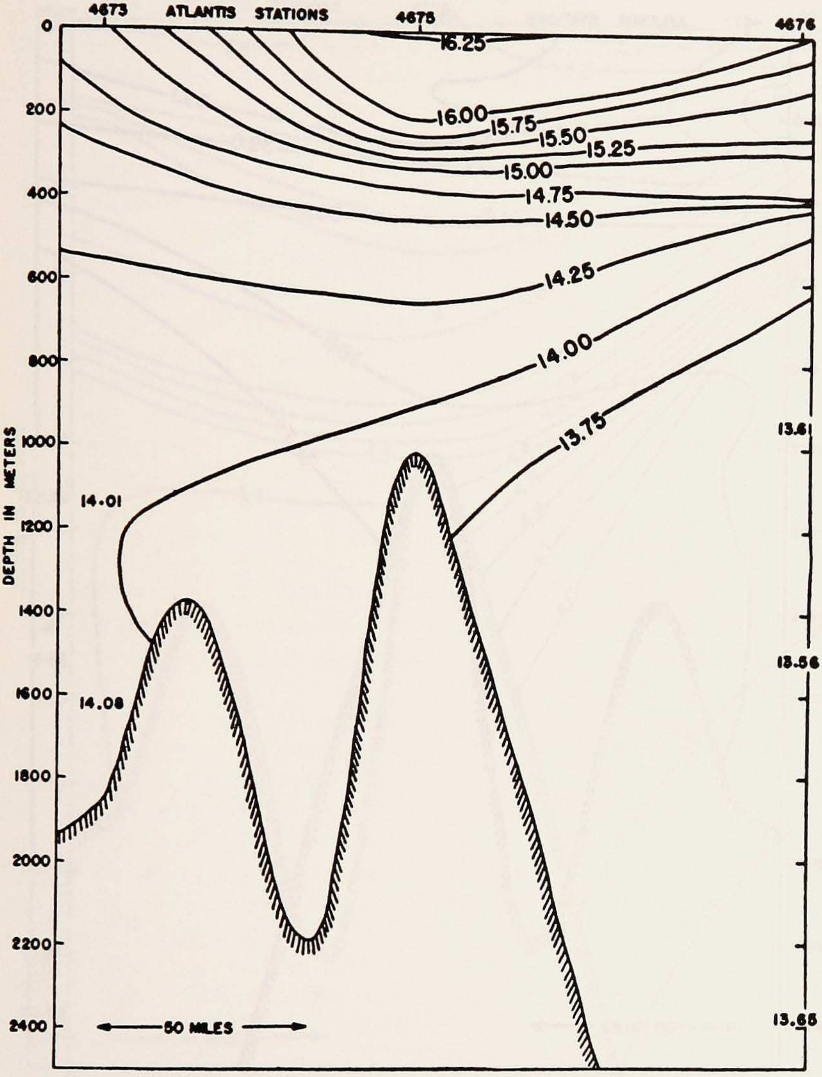

Figure 4a. Temperature section in °C. through Caso Strait.

The surface features indicate a marked flow of Mediterranean water into the southeastern Aegean. This assumption agrees with Nielsen's (1912) analysis of the water movements of the region. The discrepancy between the dissolved oxygen distribution and thermohaline structure at Station 4675, not explainable on the basis of dynamic considerations, is probably due to biological factors.

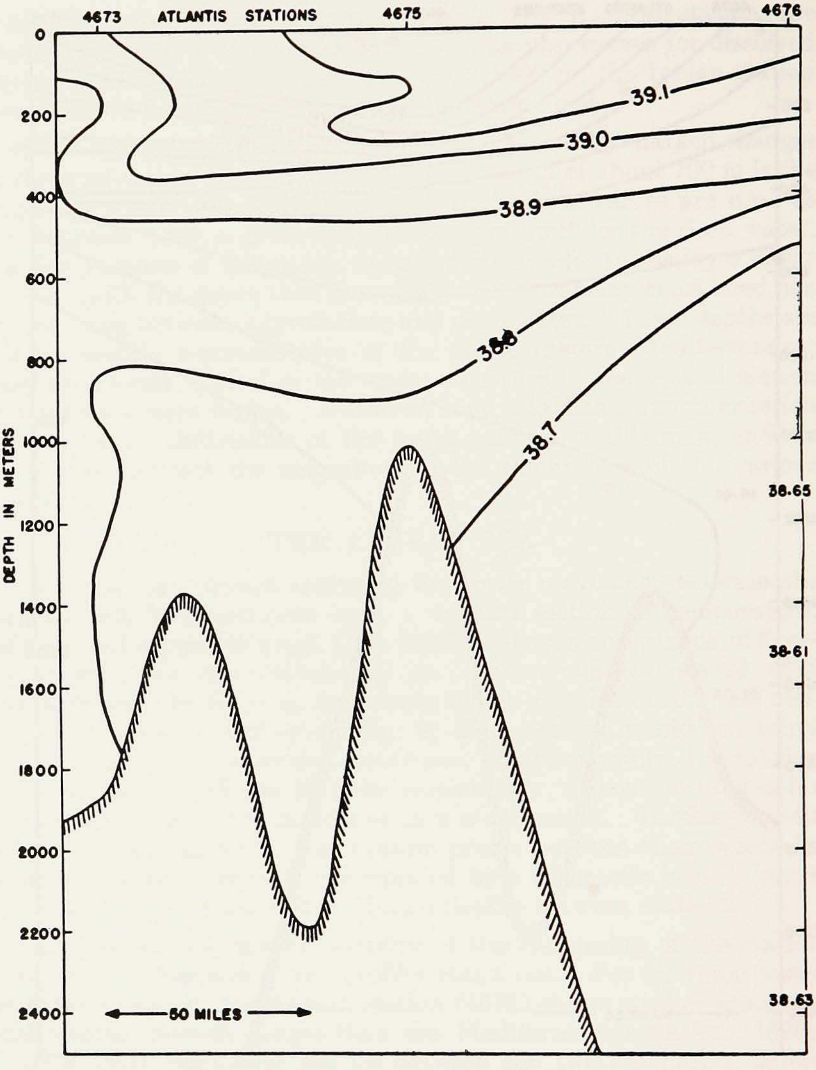

Figure 4b. Salinity section in °/oo through Caso Strait.

Relative to the main question at hand, the significant fact is *not* the inflow of Mediterranean water at the surface but the apparent failure of Aegean water to flow out at the bottom. This situation is indicated by all the isopleths shown in Fig. 4. However, it is brought out most clearly in the section for dissolved oxygen. On Station 4676 there is

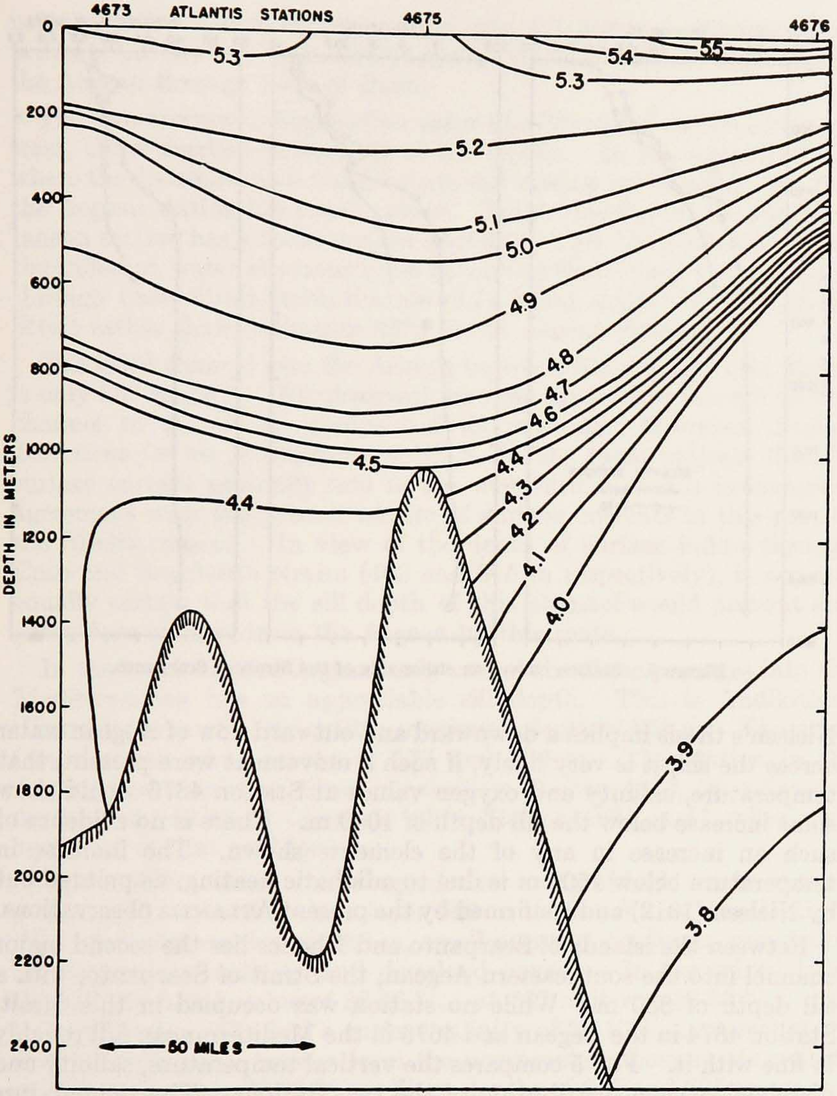

Figure 4c. Dissolved oxygen section in ml/L through Caso Strait.

a sharp gradient at 450 m. Here the oxygen values drop from 4.6 to 4.0 ml/L in 120 m, corresponding closely to the gradient at 550 m found on Station 4699 (Fig. 2). A similar gradient is completely absent on Station 4673, and probably on Station 4675 as well unless an extremely complex configuration of the isopleths is accepted. Since

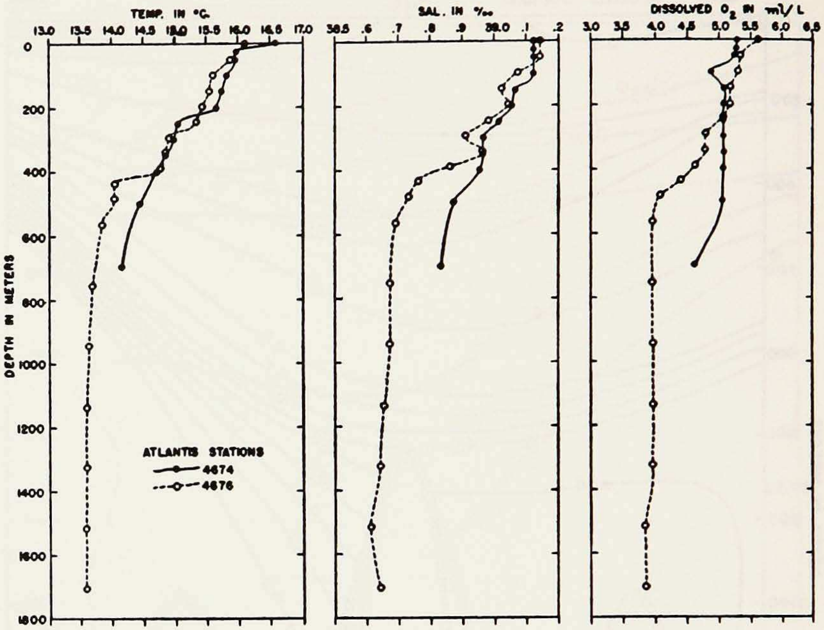

Figure 5. Station curves on either side of the Strait of Scarpanto.

Nielsen's thesis implies a downward and outward flow of Aegean water across the sill, it is very likely, if such a movement were present, that temperature, salinity and oxygen values at Station 4676 would show some increase below the sill depth of 1000 m. There is no evidence of such an increase in any of the elements shown. The increase in temperature below 1500 m is due to adiabatic heating, as pointed out by Nielsen (1912) and confirmed by the present ATLANTIS observations.

Between the islands of Scarpanto and Rhodes lies the second major channel into the southeastern Aegean, the Strait of Scarpanto, with a sill depth of 880 m. While no station was occupied in this Strait, Station 4674 in the Aegean and 4676 in the Mediterranean fall roughly in line with it. Fig. 5 compares the vertical temperature, salinity and dissolved oxygen distribution of the two stations. The temperature and salinity plots show a marked similarity from the surface to about 375 m, thus furnishing further evidence of the surface flow into the Aegean. In this connection it should be remembered that the surface water at Station 4674 may have entered the Aegean through Caso Strait rather than Scarpanto Strait. Unfortunately this problem cannot be resolved by means of the available data. However, the current pattern in the eastern Mediterranean, plus the width, depth and orientation of the two straits, makes it appear likely that surface water enters the Aegean through both of them.

The two corresponding station curves for dissolved oxygen, by contrast, show marked differences at all depths. In the upper 300 m, where the distribution of temperature and salinity is essentially similar, the Aegean station has lower values. Below this depth, the Mediterranean station has a lower oxygen content. This discrepancy between the different water characteristics resembles that found in the section through Caso Strait (with Station 4674 being similar to 4675 in the Strait rather than to Station 4673 in the Aegean proper).

The third channel into the Aegean between Rhodes and Asia Minor is only 350 m deep. No observations were made close enough to this channel to permit an analysis of its currents. However, *Sailing Directions for the Mediterranean* (U. S. H. O., 1942) indicate that its surface current generally sets to the westward. This is in complete agreement with the general nature of surface currents in this part of the Mediterranean. In view of the depth of surface inflow through Caso and Scarpanto straits (400 and 375 m respectively), it appears equally certain that the sill depth of this channel would prevent any subsurface outflow from the Aegean by this route.

In the southwestern Aegean only one of the three passages into the Mediterranean has an appreciable sill depth. This is Andikithira Channel, north of Crete, with a maximum depth of 805 m. The other two channels have depths of 137 and 290 m. The station in the Aegean Sea closest to these channels is Station 4670, 25 miles due north of Andikithira Channel, while Station 4671 is 41 miles east-northeast of that position.

Station 4670, which was occupied after a day of high winds, showed a thoroughly stirred surface layer 500 m thick. From this depth to the lowest observation at 865 m, small negative gradients were found in temperature, salinity and dissolved oxygen. In the mixed layer the salinity had a value of 38.96 °/₀₀, at 865 m it was 38.86 °/₀₀. Although Station 4671 had a surface salinity of 39.10 °/₀₀, typical of the water entering the Aegean from the northeastern Levant, its salinity at 895 m was only 38.83 °/₀₀. Since depths of 865 and 895 m are well below the sill of the channel, and since their corresponding salinities are about 0.20 °/₀₀ higher than those of the deep water of the eastern Mediterranean, it should be evident that the southern Aegean cannot be a main source of this water. It could be a major source only if its subsurface outflow were mixed with water of considerably lower salinity to give an average of 38.65 °/₀₀.

THE STRAIT OF SICILY

As the evidence presented appears to eliminate the Aegean Sea as a source of the eastern Mediterranean deep water, the only other two possible sources must be examined minutely. These are the western Mediterranean, via the Strait of Sicily, and the Adriatic Sea.

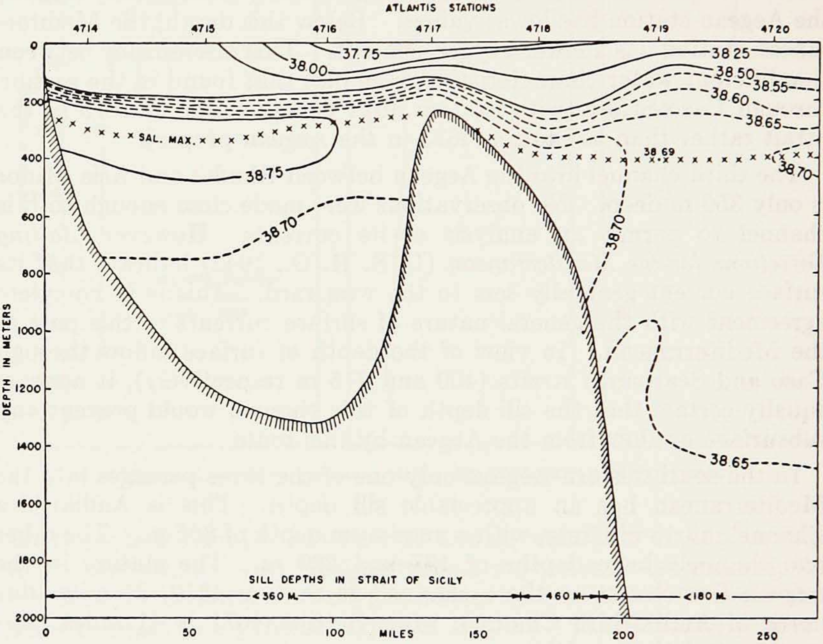

Figure 6. Salinity section in °/oo east of the Strait of Sicily.

The Strait of Messina was ruled out as a major channel for water transport between the western and eastern Mediterranean by Nielsen (1912) on the basis of the tidal nature of the currents. The small net transport through the Strait is confirmed by Vercelli (1925). Since the minimum width of the Strait is only 1.7 miles and the sill depth 110 m, the mass transport through it, even under conditions of unidirectional flow, would be very small compared to that through the Strait of Sicily or the Strait of Otranto.

Fig. 6 shows the salinity profile for a north to south section running from the Gulf of Sidra to the east coast of Sicily. This section was made during the last days of April, and, while not representative of winter conditions, it is sufficiently close to that season to be used in the following analysis.

The station depths vary greatly, since the section was run close to the edge of the shelf which drops off sharply from the eastward extension of the Strait of Sicily to the Ionian Basin. The significant depths in this section, however, are the sill depths of the Strait. These are indicated in Fig. 6.

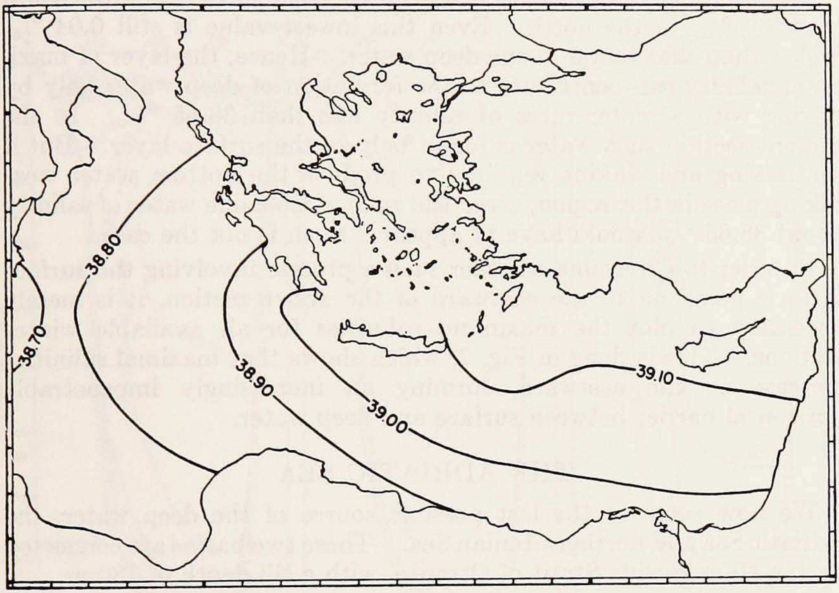

Figure 7. Maximum salinities in °/oo in the eastern Mediterranean Sea.

The most striking feature of the section is the layer of fresher surface water at Stations 4716, 4717 and 4718. This is the core of the current which enters the Mediterranean through the Strait of Gibraltar as Atlantic water and then follows the African Coast through the Strait of Sicily as far east as the Levantine Coast, where it gradually changes its characteristics. Considering the lower boundary of this current to be represented by the midpoint of the sharpest positive gradient at each station, we find its depths to be 125, 75 and 25 m respectively. To the south and north of this main current, even though the surface salinities are considerably higher, a positive salinity gradient is still present in the upper layer. At Stations 4714 and 4715, to the south, the midpoint of the maximum gradient is found at 175, while at Stations 4719 and 4720, to the north, it is found at 25 m.

Throughout the section a maximum salinity, marked by x, occurs below the positive gradients at depths between 250 and 400 m. These depths are generally close to the sill depths in the eastern extensions of the Strait. The absolute sill depth of the Strait of Sicily, northwest of Pantelleria, is only about 320 m. This situation leads to the conclusion that the water entering the eastern Mediterranean from the west is limited to the upper few hundred meters and that the most saline water found in this section is formed in the eastern basins.

The maximal values mentioned decrease from 38.79 °/₀₀ in the south to 38.69 °/₀₀ in the north. Even this lowest value is still 0.04 °/₀₀ higher than that found in the deep water. Hence, the layer of maximum salinity can contribute to the formation of deep water only by mixing with a water mass of salinity less than 38.65 °/₀₀. In the present section such water is found only in the surface layer. But if the mixing and sinking required to produce the bottom water were taking place in this region, a vertical zone of isohaline water of salinity about 38.65 °/₀₀ would have to appear. Such is not the case.

In order to determine whether such a process involving the surface layer is going on to the eastward of the above section, it is merely necessary to plot the maximum salinities for all available winter stations. This is done in Fig. 7, which shows that maximal salinities increase to the eastward, forming an increasingly impenetrable horizontal barrier between surface and deep water.

THE ADRIATIC SEA

We now come to the last possible source of the deep water, the Adriatic Sea and northern Ionian Sea. These two basins are connected by the 40-mile-wide Strait of Otranto, with a sill depth of 780 m.

Station data from the Adriatic are relatively plentiful. Between the years 1911 and 1914 the ships NAJADE and CICLOPE made a series of comprehensive cruises, reoccupying the same stations a number of times at different seasons. Since the sections run by the two ships overlap to a considerable extent, and since the CICLOPE stations are incomplete in their subsurface sampling, the following remarks concerning the Adriatic are based on NAJADE data alone. It is felt that these furnish adequate geographical and seasonal coverage for the purpose at hand.

An examination of these data shows a considerable variation from year to year for the same season. For example, in February 1912 the maximum surface salinity was found to be 38.53 °/₀₀ at a position in the Strait of Otranto, while in March 1913 the maximum value was 38.81 °/₀₀ at a position about 150 miles northwest of the Strait. These marked changes are not surprising when it is considered that only one-quarter of the Adriatic Sea extends to depths greater than 200 m, with an average depth for the entire Sea in the neighborhood of 300 m.

This, of course, implies that a major portion of Adriatic water is directly affected by the prevailing weather regime. It is of interest to note that during the 1912 cruise, when surface salinities were low, the wind was blowing from directions between NE and NW 22% of the time and from directions between S and SE 21% of the time. Corresponding figures during the 1913 cruise of high surface salinities were 11% from the north and 41% from the south. This suggests that the amount of Mediterranean surface water entering the Adriatic will fluctuate with the frequency of southerly and southeasterly winds over the area.

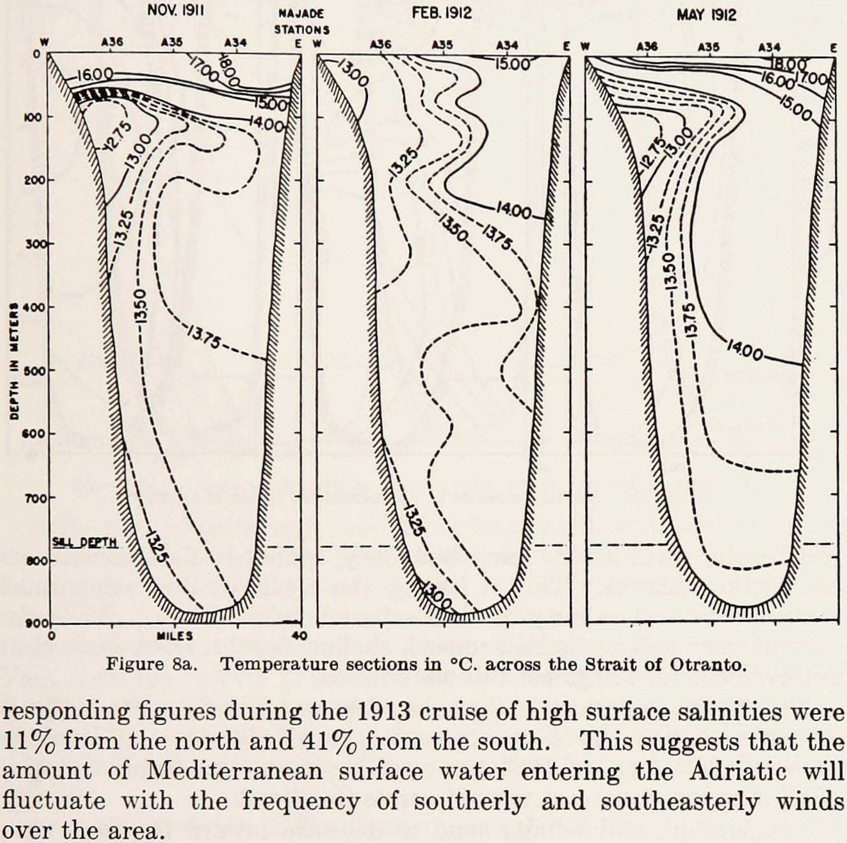

Figure 8a. Temperature sections in °C. across the Strait of Otranto.

Fig. 8 shows three sections made in successive seasons across the Strait of Otranto. No summer section was made in this vicinity. In examining these profiles it should be kept in mind that the vertical scale is exaggerated by a factor of 185. According to both Nielsen (1912) and Feruglio (1912) who made independent studies, using different data, there is a counterclockwise circulation of the surface water in the Adriatic. This is comparable to the circulation in the Mediterranean proper as well as to that in the Aegean. The existence of this current, which enters and leaves the Adriatic through the Strait

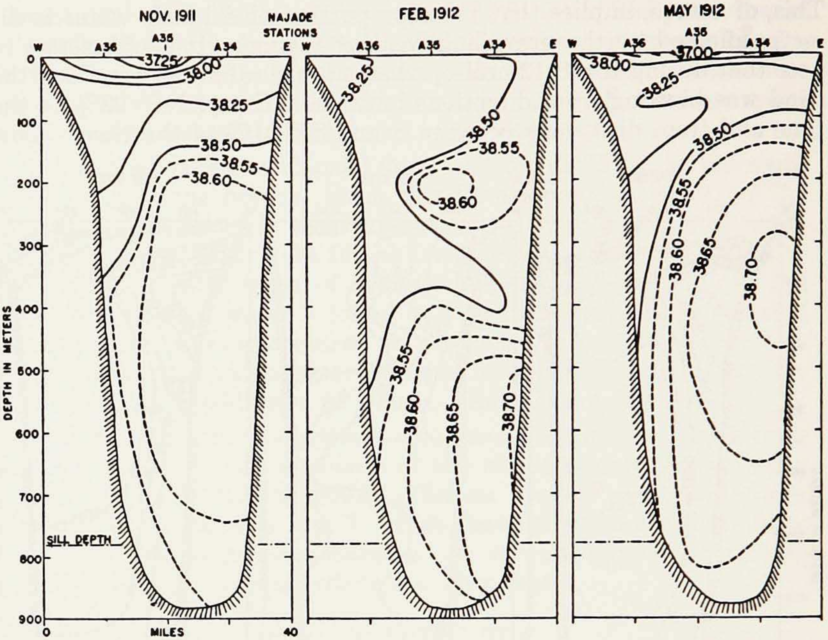

Figure 8b. Salinity sections in °/₀₀ across the Strait of Otranto.

of Otranto, much less its lower boundary, cannot be determined from the sections shown. This is largely the result of the rather small temperature and salinity gradients found below 25 m. While the current may well be limited to such shallow depths, there is no clear cut evidence for or against this assumption.

Despite the variations in the subsurface water structure found from section to section, one feature is common to all of them. All isopleths have a definite vertical tendency resulting in an appreciable variation of all elements from east to west across the Strait.

Temperature and salinity tend to decrease toward the west while dissolved oxygen content shows a slight and poorly defined increase in the same direction. The temperature and salinity values found below 200 m in these sections straddle the values representing typical Ionian Sea deep water (Fig. 3). Only the oxygen values are consistently higher. Although dissolved oxygen, even below the photic zone, is a much cruder indicator of water movement than salinity or temperature, being subject to consumption by varying quantities of plankton, its distribution can shed light on dynamic processes if used with caution and in conjunction with other indicators.

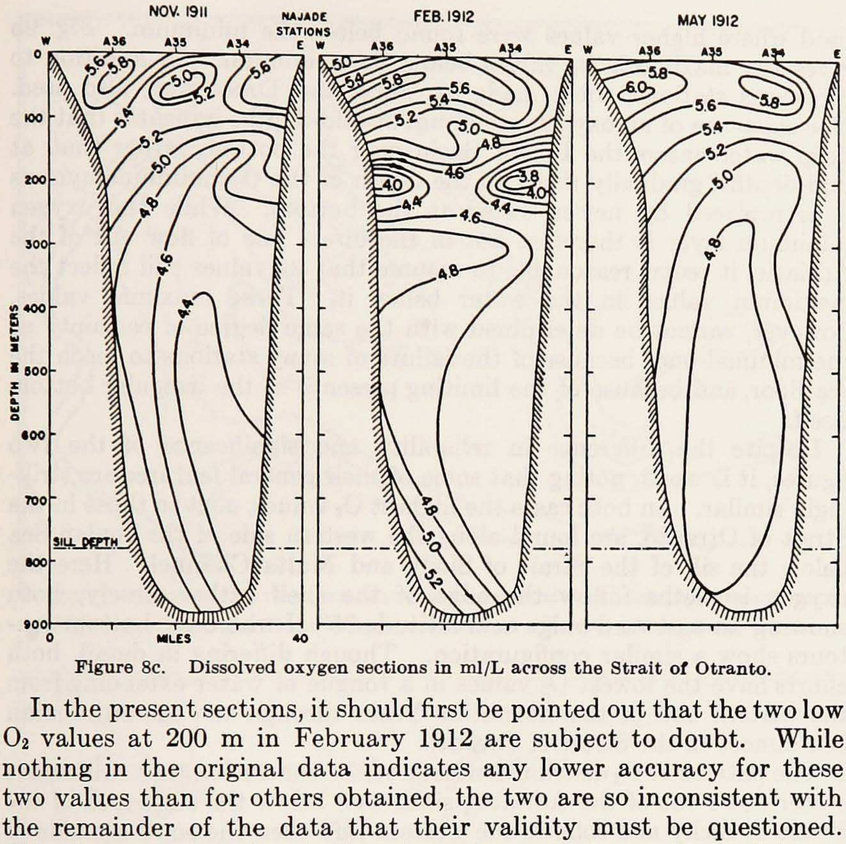

Figure 8c. Dissolved oxygen sections in ml/L across the Strait of Otranto.

In the present sections, it should first be pointed out that the two low O_2 values at 200 m in February 1912 are subject to doubt. While nothing in the original data indicates any lower accuracy for these two values than for others obtained, the two are so inconsistent with the remainder of the data that their validity must be questioned. This, however, is only of minor importance to the problem at hand. If the O_2 values in the deeper water were similar, or even lower, than those of the central and eastern Ionian Sea, then there would be considerable doubt about the direction of flow through the Strait of Otranto.

Since the amount of dissolved oxygen below the zone of photic activity and aeration by mixing can never increase—in fact, will generally diminish due to utilization by plankton or decomposing organic material—there exists a rough inverse correlation between the dissolved oxygen content and the time elapsed since the formation of the particular water mass. If subsurface water flows out of the Adriatic Sea, we should expect its dissolved oxygen content to decrease with increasing distance from the Strait of Otranto.

Fig. 9a shows isopleths of dissolved oxygen for the minimum value throughout the eastern Mediterranean. Only those station data were used where higher values were found below the minimum. Fig. 9b gives the maximum O_2 values below the minimum. In addition to ATLANTIS stations, those made by THOR and DANA were also used. The existence of an oxygen minimum at mid-depths indicates that the deep water enters the Ionian Basin near the bottom rather than at mid-depths, gradually rising to the depth of the O_2 minimum layer as it is replaced by newer water at the bottom. While the oxygen minimum layer is therefore not in the direct line of flow out of the Adriatic, it seems reasonable to assume that its values will reflect the maximum values in the water below it. These maximal values, however, cannot be determined with the same degree of certainty as the minimal ones because of the failure of many stations to reach the sea floor, and because of the limiting presence of the irregular bottom itself.

Despite the difference in reliability and significance of the two figures, it is worth noting that some of their general features are strikingly similar. In both cases the highest O_2 values, next to those in the Strait of Otranto, are found along the western side of the Ionian Sea below the sill of the Strait of Sicily and Malta Channel. Here the oxygen isopleths follow the edge of the shelf rather closely, both showing an eastward bulge near latitude 35° N where the bottom contours show a similar configuration. Though differing in detail, both charts have the lowest O_2 values in a tongue of water extending from the eastern end of the Levantine Basin through the eastern Ionian Sea almost to the Strait of Otranto.

The pattern of O_2 distribution leads to the conclusion that subsurface water flows out of the Adriatic, sinks well below the sill depth of the Strait of Sicily and follows the western and then the southern side of the Ionian Sea in a slow drift along the bottom. Since the Coriolis' force tends to deflect the water to the right, it continues along the African Coast into the Levantine Basin rather than forming a closed circuit in the Ionian Sea. This confirms Nielsen's (1912) thesis on the circulation in the deep water of the Ionian Sea. The eastern and northern sectors of this circulation are not clearly defined. This is not surprising when it is considered that the water flowing out of the Adriatic mixes continuously with the water in the eastern Mediterranean, thus gradually losing its characteristic oxygen distribution. Furthermore, on the basis of the changeable water structure in the Adriatic, it is probable that the outflow from that Sea has varying characteristics which are reflected in the irregularities of a composite diagram, such as Fig. 9, where station data from different years and seasons are used synoptically. Another probable source of irregularities in the oxygen data is the indeterminable effect of biological activity on oxygen consumption.

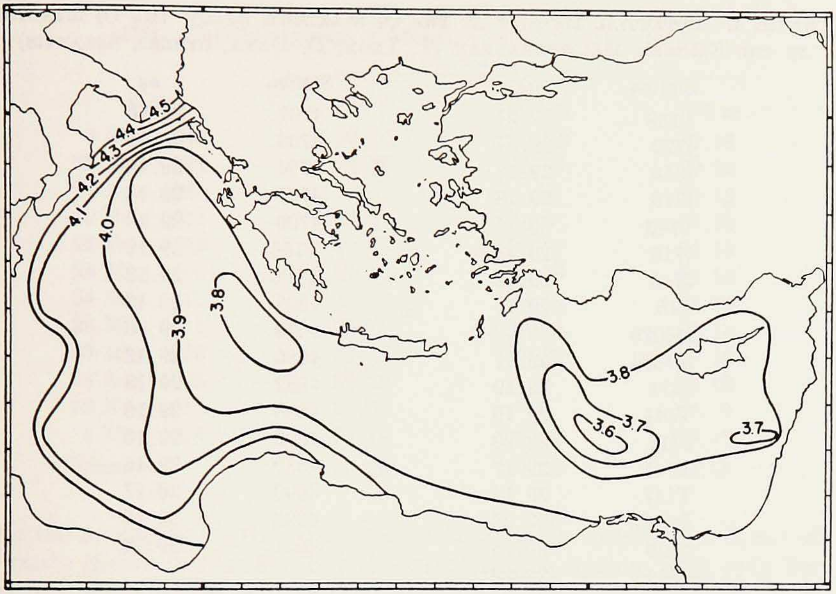

Figure 9a. Minimum dissolved oxygen in ml/L in the eastern Mediterranean Sea.

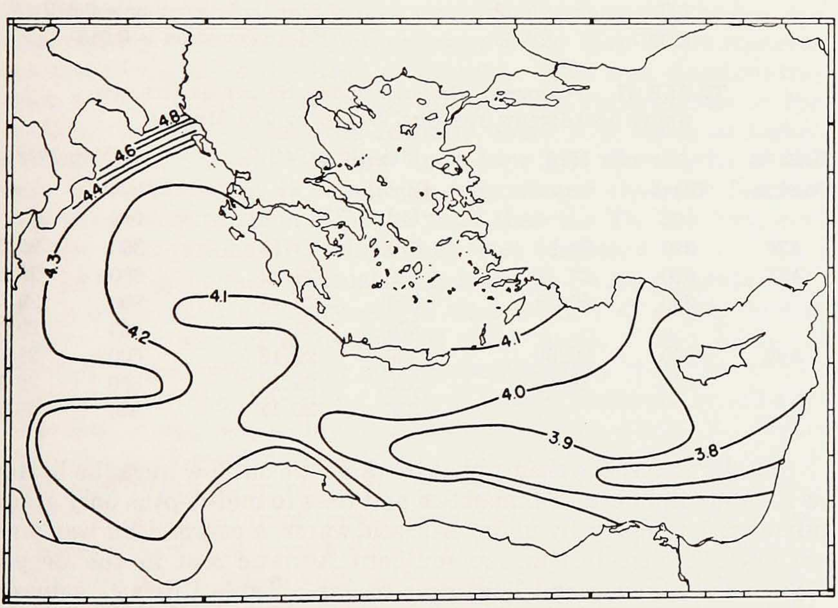

Figure 9b. Deep maximum dissolved oxygen in ml/L in the eastern Mediterranean Sea.

TABLE I. POTENTIAL DENSITY AT THE O_2 MAXIMUM BELOW THE O_2 MINIMUM IN THE EASTERN MEDITERRANEAN (T, THOR; D, DANA; OTHERS, ATLANTIS)

Station	σ_θ	*Station*	σ_θ
T189	29.21	4707	29.16
4720	29.17	4706	29.18
4644	29.17	4704	29.19
4719	29.18	4701	29.18
T143	29.15	4700	29.16
4716	29.18	T156	29.19
4715	29.19	T160	29.18
T15	29.15	4699	29.16
D4076	29.22	4679	29.16
D4064	29.17	4680	29.13
4711	29.19	4682	29.15
T144	29.19	4683	29.16
4712	29.20	4696	29.16
T145	29.17	4689	29.16
T147	29.17	4690	29.17
D4075	29.20	4693	29.15
4709	29.18	4691	29.18
4646	29.13		
4708	29.17	Mean 29.173	
D4070	29.17	Range 29.13–29.22	
T152	29.18	Standard deviation = 0.019	
D4067	29.18	Mean deviation = 0.015	

TABLE II. POTENTIAL DENSITY IN THE STRAIT OF OTRANTO ABOVE AND BELOW THE SILL DEPTH OF 780 METERS

NAJADE	*November 1911*		*February 1912*		*May 1912*	
Stations	*Depth (m)*	σ_θ	*Depth (m)*	σ_θ	*Depth (m)*	σ_θ
A36	370	29.11	570	29.13	390	29.06
A35	600	29.11	700	29.12	600	29.07
	860	29.15	800	29.13	800	29.14
			878	29.16	850	29.13
A34	600	29.09	600	29.13	600	29.08
	850	29.10	800	29.16	800	29.10
			855	29.17	860	29.11

In order to test the theory that the Adriatic outflow hugs the bottom as it enters the western Ionian Sea and rises to mid-depths only gradually as it is replaced by newer Adriatic water, a comparison was made of potential densities in the southern Adriatic and in the deepest layers of the Ionian and Levantine basins. Table I lists σ_θ values at the deep 0_2 maximum for the entire eastern Mediterranean. Table II

TABLE III. Potential Density between 500 and 800 m at Najade Station A28. Position within 4 Miles of 41° 16′ N, 18° 15′ E

Date	*Depth* *800 m*	 *600 m*	 *500 m*
3 Mar. 1911	29.20	29.20	29.18
26 May 1911	29.22	29.15	29.16
24 Aug. 1911	—	—	29.13
29 Nov. 1911	29.27	—	29.20
26 Feb. 1912	29.18	29.17	29.15
28 May 1912	29.28	29.18	29.18
24 Aug. 1912	29.16	29.16	29.14
26 Mar. 1913	29.19	29.16	29.13
23 May 1913	29.16	29.13	29.13
24 Aug. 1913	29.20	—	29.13
23 Nov. 1913	29.21	—	29.12
1 Mar. 1914	29.14	29.14	29.12
Mean	29.20	29.16	29.15

lists the σ_θ values for the three sets of Najade stations in the Strait of Otranto shown in Fig. 8. For the westernmost station, A36, only the deepest observation is given, while for the other two stations σ_θ is given for observations above and below the sill depth of 780 m.

An inspection of the two tables reveals a substantially higher potential density in the deep Mediterranean water than in the observations around the sill of the Strait of Otranto. This is in direct contradiction to the conditions necessary to fulfill the requirements of the postulated theory. Unless the Adriatic water is of equal or higher potential density it will not flow downslope into the depths of the Ionian Sea. However, it should be remembered that the Najade observations were made in different years than the Thor, Dana, and Atlantis observations with which they were compared.

The key to this puzzling situation is found in Najade Station A28, which was occupied on every one of that vessel's 12 cruises in the Adriatic. This station is located 60 miles north of the Strait of Otranto and somewhat closer to the southwestern than the northeastern shore of the Adriatic. With a counterclockwise circulation in that Sea, it can reasonably be assumed that the station is located outside the northward flowing water. Table III gives the potential density at a depth 20 m below the sill and at two depths well above the sill. It is evident from these figures that during a majority of the time there will exist at least a shallow layer of water at the bottom of the Adriatic which has a sufficiently high density to sink to those depths of the eastern Mediterranean at which the deep oxygen maximum was found. Since the rapidity with which the fluctuations of temperature and salinity in the Adriatic take place is not known, there is no way of evaluating the significance of the sampling portrayed by the values in Table III. However, there is little reason to doubt that the deep outflow through the Strait of Otranto is far from continuous.

A more detailed examination of Station A28 made on 3 March 1911 discloses that the entire water column appears to have been recently mixed. Potential temperatures vary between 12.78° and 13.12° C. and salinities between 38.57 and 38.64 °/₀₀. Salinities at 500, 600 and 800 m were 38.62 and 38.64 °/₀₀, while all values above these depths as well as the value at 1000 m, near the bottom, were either 38.57 or 38.58 °/₀₀. All potential densities fell in the range from 29.18 to 29.22 g/L. The dissolved oxygen values furnish the clearest indication of recent and complete mixing. They vary between 5.7 and 5.9 ml/L, giving a minimum concentration of 97% of saturation value.

Among all the NAJADE and CICLOPE data from the Adriatic, the above station is the only one displaying this degree of homogeneity. Among some of the other deep stations part of the water column was well mixed but never the entire column from surface to bottom. The fact that this situation occurs only once in the data at hand merely proves that the condition is possible; it sheds no light on the frequency of occurrence. Nevertheless, it tends to substantiate the irregularity of the water structure in the Adriatic, and, concomitantly, that of the outflow near the bottom.

Since the Adriatic water which flows out of the Strait of Otranto near the bottom is a mixture of water masses having higher and lower salinities than that of the end product, it seems appropriate to identify the sources of these component masses. Low salinity water enters the Adriatic in the form of surface inflow from the Ionian Sea (as seen in Fig. 8) and as fresh water, the latter largely from the rivers of northern Italy. Since there is no evidence of excess evaporation from the Adriatic, such as is clearly indicated in the Levant by the high surface salinities, the only way in which the total salt content of this Sea can be maintained is through an influx of water of higher salinity than that of the outflowing deep water. The only possible sources of such water are the surface and intermediate layers in the northeastern Ionian Sea. Fig. 8 exemplifies the situation where the surface inflow is relatively fresh while the saltier water is found from 150 m all the way to the bottom on the eastern side of the Strait of Otranto.

However, as was pointed out previously, the surface salinity in the Adriatic varies greatly from year to year. For instance, during the seven NAJADE cruises between February 1911 and September 1912, the maximum surface salinity fluctuated between 38.34 and 38.58 °/₀₀, whereas during her five subsequent cruises between March 1913 and February 1914 it lay in the range from 38.69 to 38.81 °/₀₀. Where high surface salinities appear in the Adriatic, vertical salinity gradients become small and the boundary between surface and intermediate water becomes less distinct.

The water structure at Station A28 of 3 March 1911 strongly suggests the mechanism whereby the deep water of the eastern Mediterranean is formed. Surface and intermediate water of Mediterranean origin, down to a depth of several hundred meters, flows into the Adriatic, is thoroughly mixed there with fresher water by the vertical convection set up by surface cooling in winter, and then flows back into the Ionian Sea along the western side and bottom of the Strait of Otranto.

As the high salinity surface water flows in from the south, its temperature is somewhat higher than that of water formed in the Adriatic. Consequently, its density will be lower than that of intermediate water with approximately the same salinity. The resulting stability of the water column probably accounts for the infrequent occurrence of such thoroughly mixed water as was found on the above station. In other words, stability of the upper water column is generally maintained either through the low salinity of Adriatic water or through the high temperature of Ionian Sea surface water.

The Adriatic bottom water which flows south into the eastern Mediterranean is probably formed by the gradual sinking of water from mid-depths of the Adriatic. This water, in turn, may be replaced by water drawn in horizontally from contiguous areas or by water sinking from the surface layer above it when the stability of the column is slight, as on the above mentioned Station A28, or by a combination of horizontal and vertical advection. It is significant, for instance, that in the three sections across the Strait of Otranto, shown in Fig. 8, the dissolved oxygen percentage of saturation below 300 m in the western half of the channel averages roughly 82%. If the outflowing water were drawn largely from the surface layer in the Adriatic, this percentage would be much closer to the saturation value, considering the short distance from its source.

As the average oxygen saturation percentage in the eastern half of the Strait below 300 m is only a few percentage points lower than that in the western half, the possibility should be kept in mind that turbulence in the Strait due to opposite running currents will cause some of this inflowing water to mix with the outflowing current and thus be deflected back into the Ionian Basin without fully penetrating into the Adriatic. This process would tend to reduce the horizontal gradients across the Strait.

It had been suggested previously that, because of the shallowness of the Adriatic, its water structure closely follows the fluctuations of the existing weather regime. By the same line of reasoning it appears highly probable that the circulation through the Strait of Otranto is also directly affected by changes in wind direction and intensity. Southerly and southeasterly winds tend to drive more surface water into the Adriatic. An excess inflow of this nature must be compensated for by an increased outflow which can then take place only in subsurface layers.

SUMMARY

1. Below 1600 m the water in the center of the Ionian and Levantine basins is identical in temperature and salinity structure. The amount of dissolved oxygen at these depths is consistently higher in the Ionian Sea by about 0.15 ml/L.
2. No evidence was found of a subsurface flow of Aegean water into the eastern Mediterranean via the three channels between the island of Crete and Asia Minor. Due to the high salinity and oxygen values in the southern Aegean, below the sill depths of these channels, such an effluent, if it existed, would be readily detectable in the Mediterranean stations. A similar situation was found in the channels into the Aegean, located between Crete and the Greek mainland.
3. The water entering the Ionian Sea through the Strait of Sicily was eliminated as a major component of the deep water of the eastern Mediterranean. The somewhat fresher water flowing out of this Strait is separated from the deep water by a permanent intermediate layer having a higher salinity than the layer below it. The Strait of Messina was ruled out as a factor in this problem because of its shallow sill depth, narrowness, and the tidal nature of its currents.
4. The Adriatic Sea, the only other possible source of deep eastern Mediterranean water, has a complicated water structure. Due to its restricted size and shallow mean depth it is particularly susceptible to short term weather fluctuations. Thus, single sections or stations cannot be considered representative of average conditions for any particular season. Nevertheless, three sections across the Strait of Otranto indicate an outflow of Adriatic water on the bottom and western side of this Strait. This is consistent with the dissolved oxygen distribution in the entire eastern Mediterranean. There is generally a minimum value at mid-depths, with a secondary maximum below it wherever the bottom is deep enough. In both the minimum and maximum oxygen layers the highest values are found near the Strait of Otranto and along the western edge of the Ionian Sea. This oxygen pattern suggests a counterclockwise circulation in the deep water of

the eastern Mediterranean, with Adriatic water hugging the bottom as it enters the northwestern Ionian Sea and gradually rising to middepths as it is replaced by newer water from the same source. An analysis of one station in the Adriatic, occupied on 12 occasions, shows that, during a majority of the time, water at depths of the sill in the Strait of Otranto has a higher potential density than the deep water of the eastern Mediterranean and can therefore flow downslope into the Ionian Sea. This water is composed of relatively fresh water, largely river effluent from the northern Adriatic, and of Ionian Sea water of relatively high salinity from intermediate depths and of variable salinity from the inflowing surface layer. These component water masses are mixed in the southern Adriatic, particularly by surface cooling and vertical convection in winter. The resultant mixture gradually sinks to the bottom and flows slowly out of the Strait of Otranto back into the Ionian Sea. There seems little doubt that this outflow is quite irregular, depending to a large extent on the prevailing weather regime.

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