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THE WATER MASSES AND CIRCULATION IN THE SOUTHEASTERN MEDITERRANEAN

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INTRODUCTION

The present study of the southern Levant basin (defined as the area within Lat. 36° 00 N and Long. 20° 00 E) is based on 205 oceanographic stations occupied by the R/V ICHTHYOLOG during 1966. The stations represent the main bulk of the data available for this area since 1959 (205 out of 351 stations) and can be considered as the first systematic study made over four consecutive seasons. Furthermore, this study represents the first detailed oceanographic investigation of the Egyptian coast soon after the damming of the Nile River. It is beyond the scope of the present paper to compare the oceanographic conditions of the area prior to the damming of the Nile.

METHODS AND MATERIALS

Four seasonal cruises were made by R/V ICHTHYOLOG to investigate the water masses and circulation in the southeastern part of the Levant basin of the Mediterranean. The area investigated extends 50 miles off the Egyptian coast between El-Arish, Sinai (Long. 33°40') and the Arab Bay, west of Alexandria (Long. 29° 05'). Six sections perpendicular to the coast were repeated

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in February, April, August and November 1966 (M o u s t a fa - H a s s a n, 1969; M o r c o s and M o u s t a f a H a s s a n, 1973). Figure 1 shows the sections and stations occupied during this study.

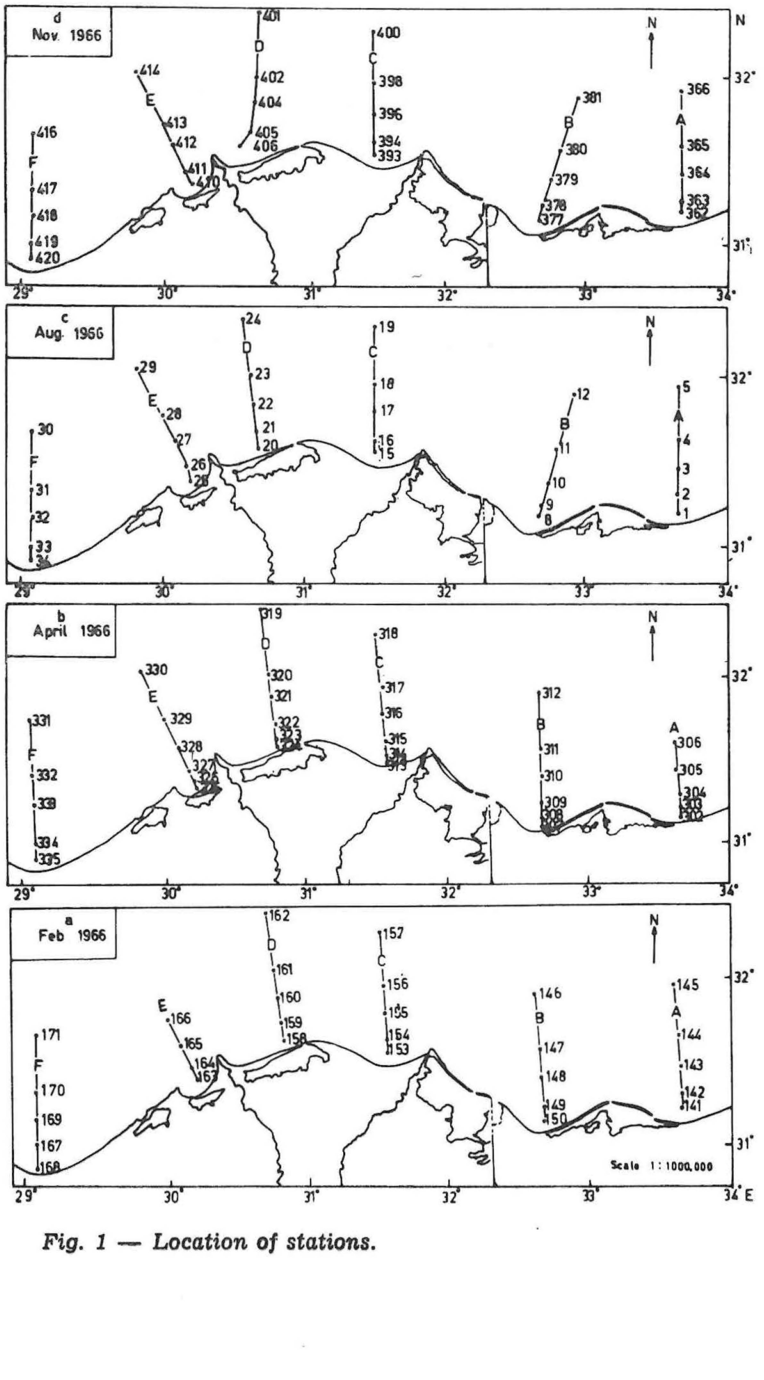


Fig. 1 — Location of stations.

RESULTS

Figures 2 and 3 represent the vertical distribution of temperature in the four season in the most eastern and western sections A and F, respectively. In winter, the temperature is higher in the eastern section A (17.5 to 17°C) than in the western section F (17 to 15°C). This trend becomes feeble or disappears in other seasons. The vertical gradient of temperature is very weak in winter due to winter convection. Thermal stratification increases in April and culminates in a strong thermocline in August (25 to 75 m) which becomes weaker and deeper (50 to 100 m) in November.

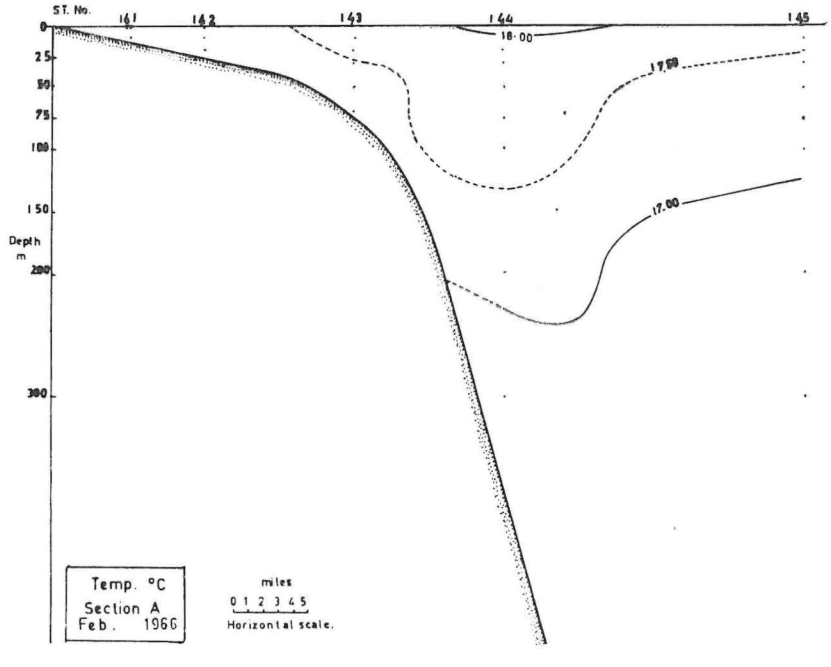


Fig. 2a — Vertical distribution of temperature in Section A, El-Arish, Sinai (Long 33° 40') in February 1966.

The salinity sections A and F (Figures 4 and 5) illustrate the great homogeneity of the water column due to vertical mixing by winter convection. The offshore station in the eastern section (A) shows a typical isohaline water of 39.31‰ compared with a similarly isohaline column of 39.27‰ in the western section (F). In spring, the upper layer becomes warmer and less saline than the lower layer. This may be attributed to the process of vertical convection becoming weaker, and the evaporation becoming less intensive. Evaporation reaches its maximum in winter (S v e r d r u p, J o h n s o n and F l e m i n g, 1942; W ü s t, 1959; M o r c o s, 1972). In spring, the influence of the less saline, surface and eastward coastal current is more restricted to the upper warmer layer.

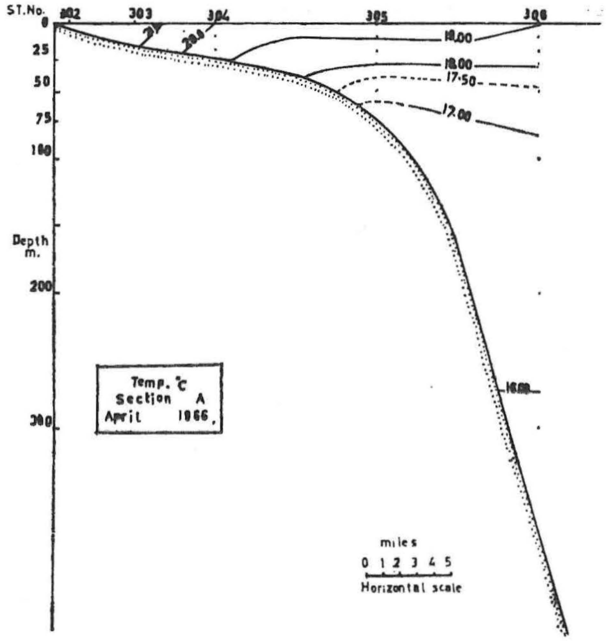


Fig. 2b — Vertical distribution of temperature in Section A in April 1966.

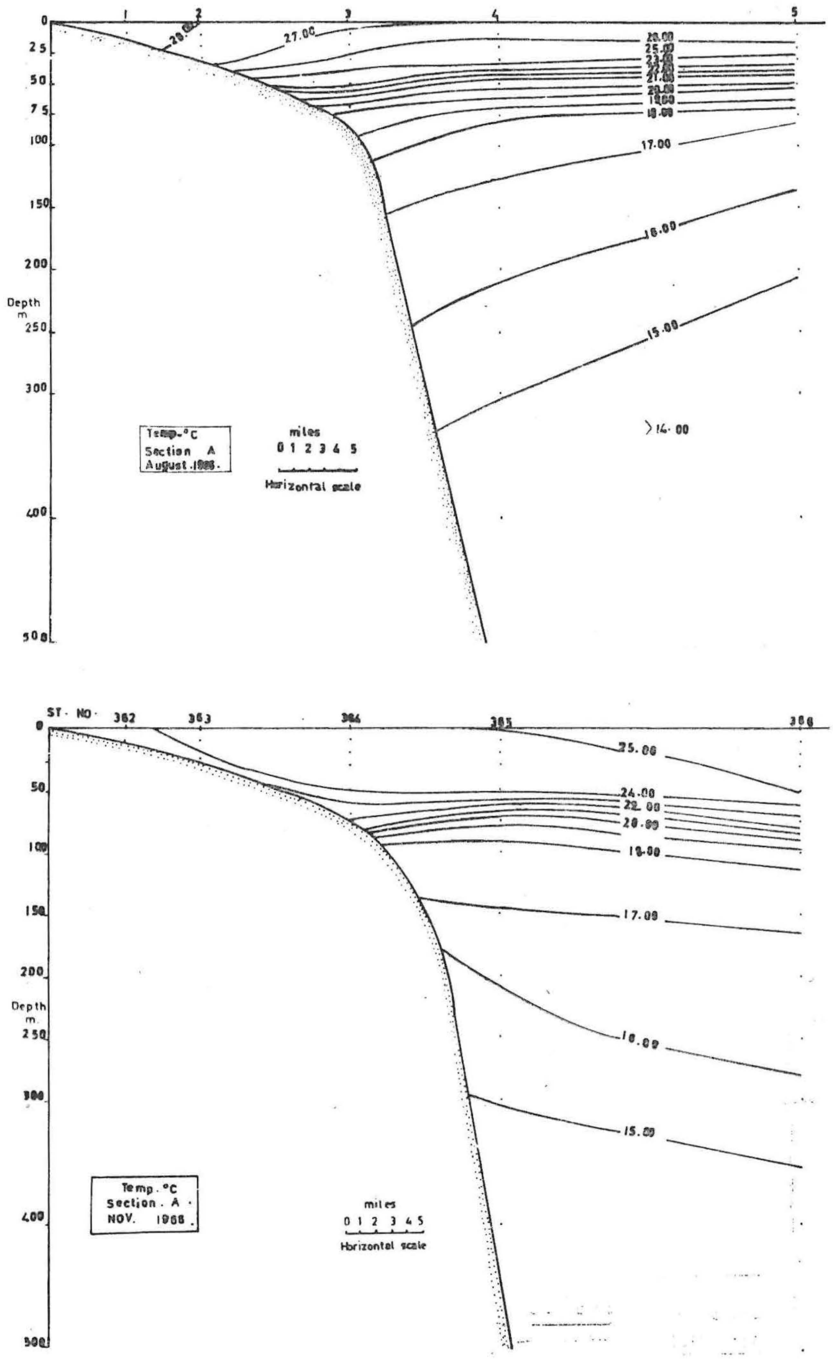


Fig. 2c — Vertical distribution of temperature in Section A in August and November 1966.

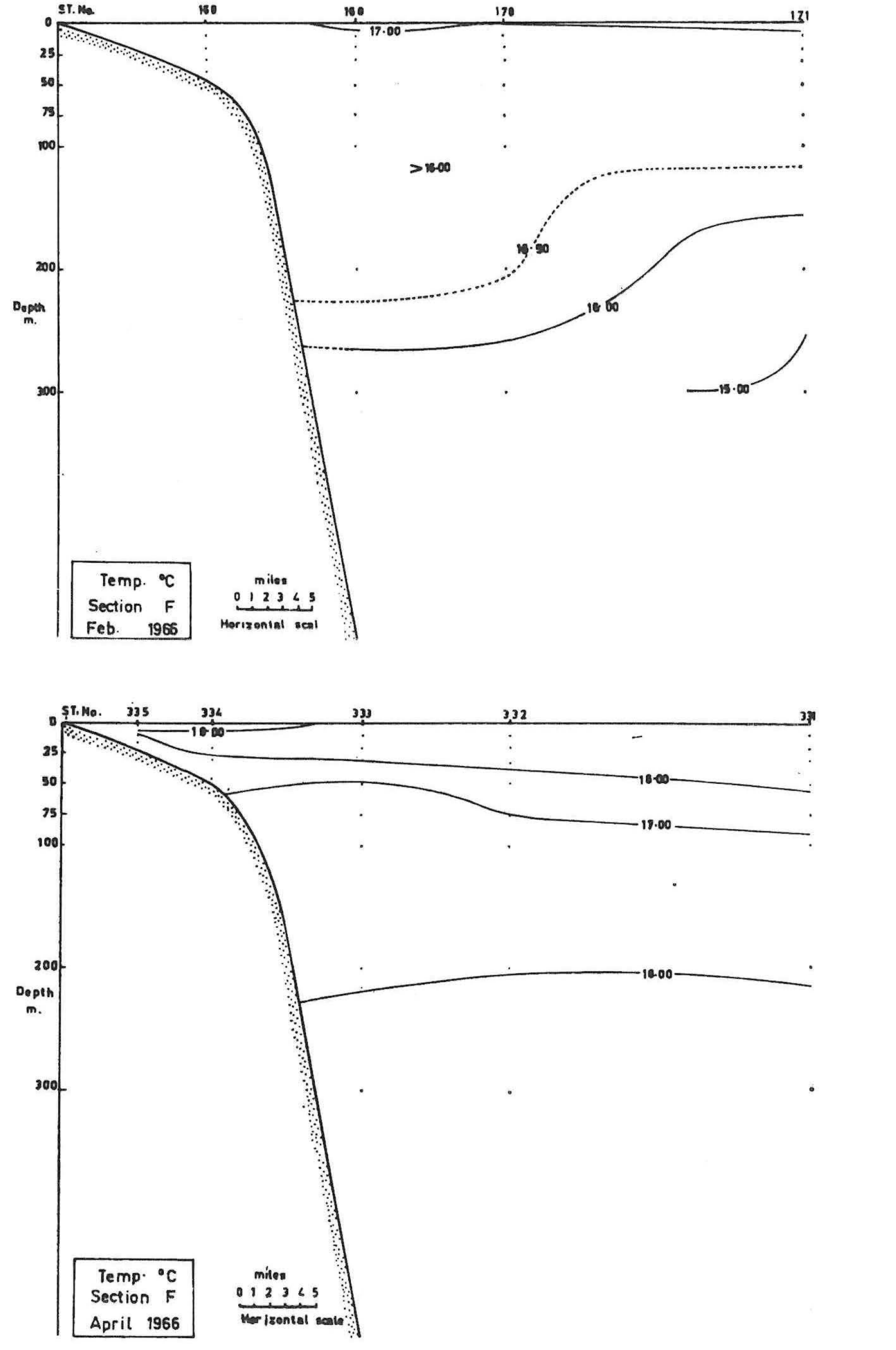


Fig. 3a — Vertical distribution of temperature in Section F, Arab Bay, west of Alexandria (Long 29°05') in February and April 1966.

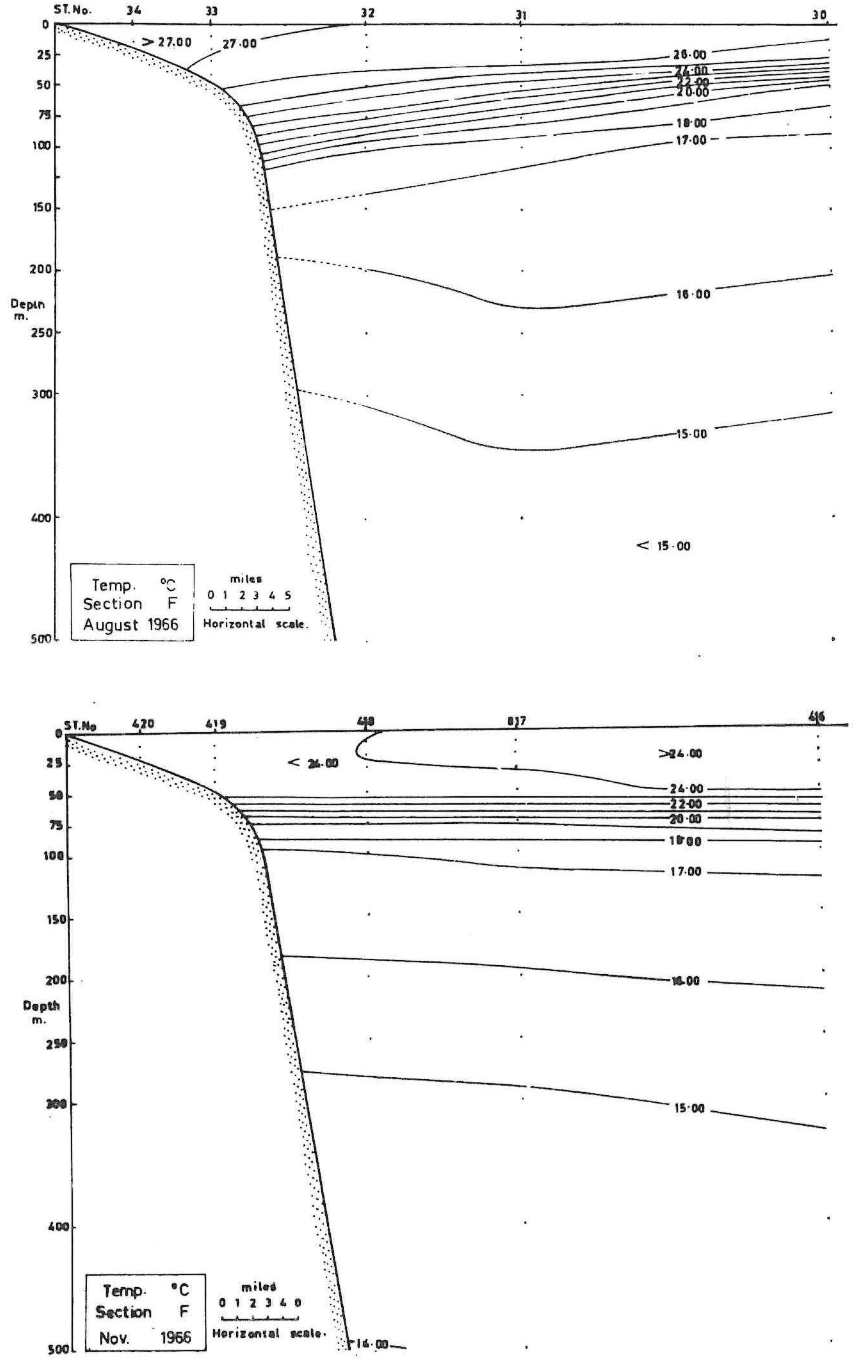


Fig. 3b — Vertical distribution of temperature in Section F, Arab Bay, in August and November 1966.

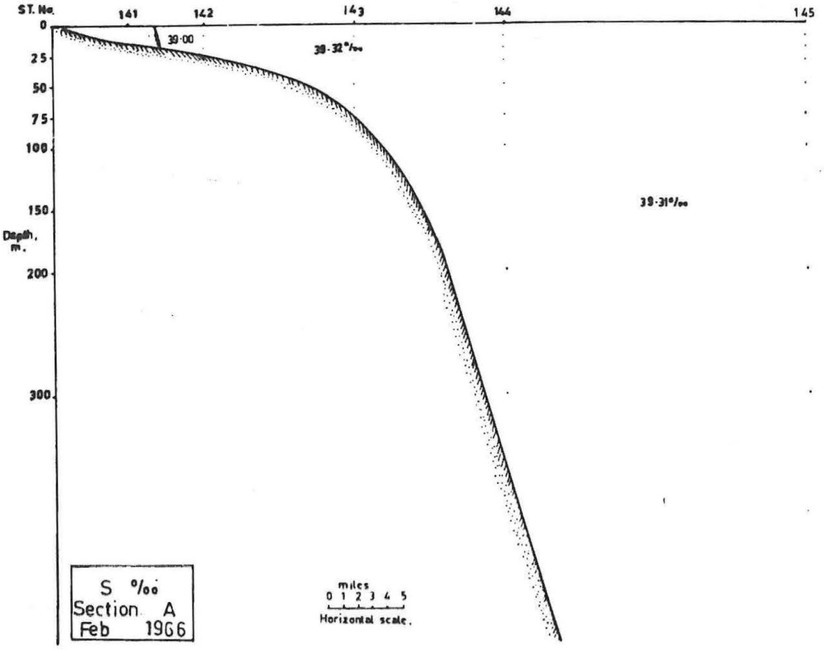


Fig. 4a — Vertical distribution of salinity in Section A, El-Arish, Sinai (Long. 33°40') in February 1966.

In summer and autumn, strong stratification manifests itself in the salinity sections as well. Figure 6 represents the vertical distribution of salinity in August and November in a section parallel to and 50 miles north of the Egyptian coast. Three layers are identified including a surface layer of maximum salinity, a subsurface layer of minimum salinity at about 50 to 100 m, and an intermediate maximum salinity between 150 and 300 m. The latter layer was identified by Nielsen (1912) and attracted the interest of many oceanographers including Wüst (1959, 1960, 1961), Lacombe and Tchernia (1960) and Morcos (1967, 1972). They have discussed characteristics of this layer, its seasonal and spatial distribution and possible mode of formation.

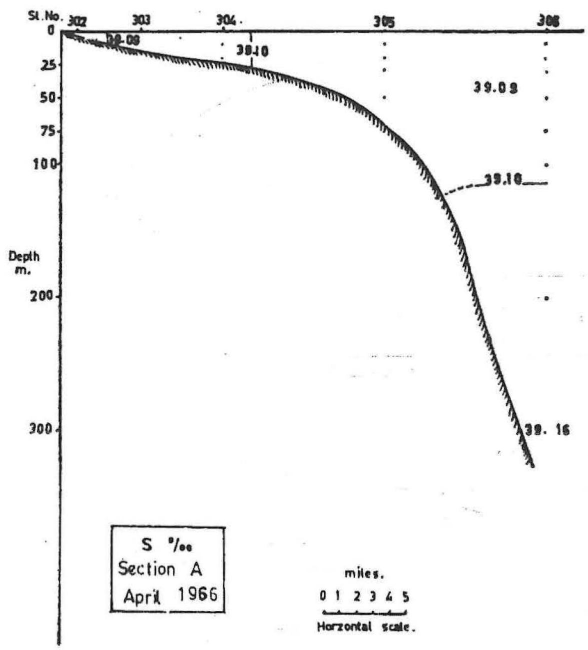


Fig. 4b — Vertical distribution of salinity in Section A in April 1966.

Figure 7 represents the T—S diagrams for the four seasons of the most offshore stations in the eastern, central and western sections. In winter, the T—S diagrams illustrate the typical isohaline water column and the slight decrease of temperature with depth. As a result, the T—S curves only occupy a very small range of density from 28.8 to 29.4σ_t. In spring, the T—S diagrams stretch to extend between 28 and 29.3σ_t due to the onset of heating, they range between 25.8 and 29.2σ_t in summer., and they decrease again in November.

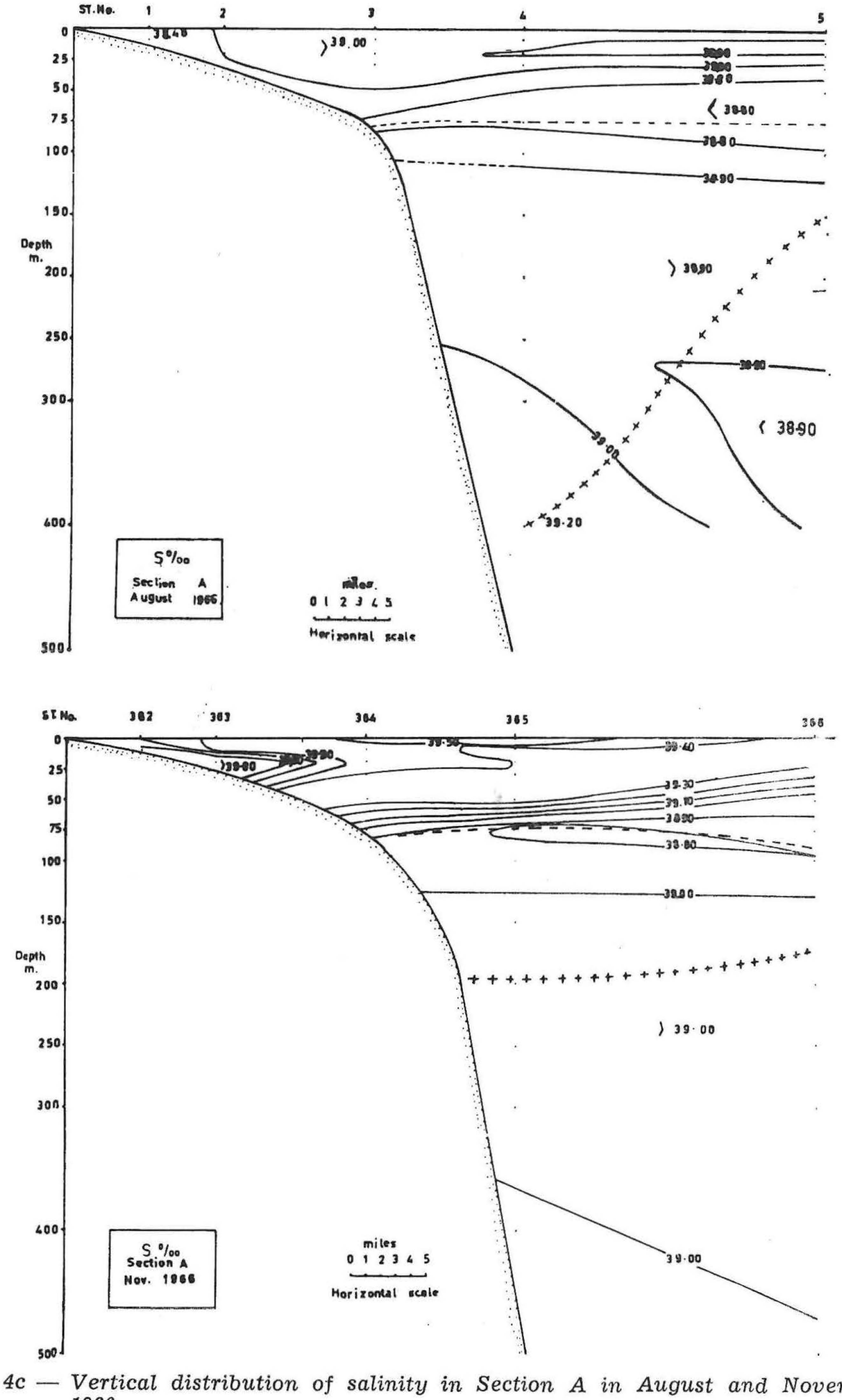


Fig. 4c — Vertical distribution of salinity in Section A in August and November, 1966.

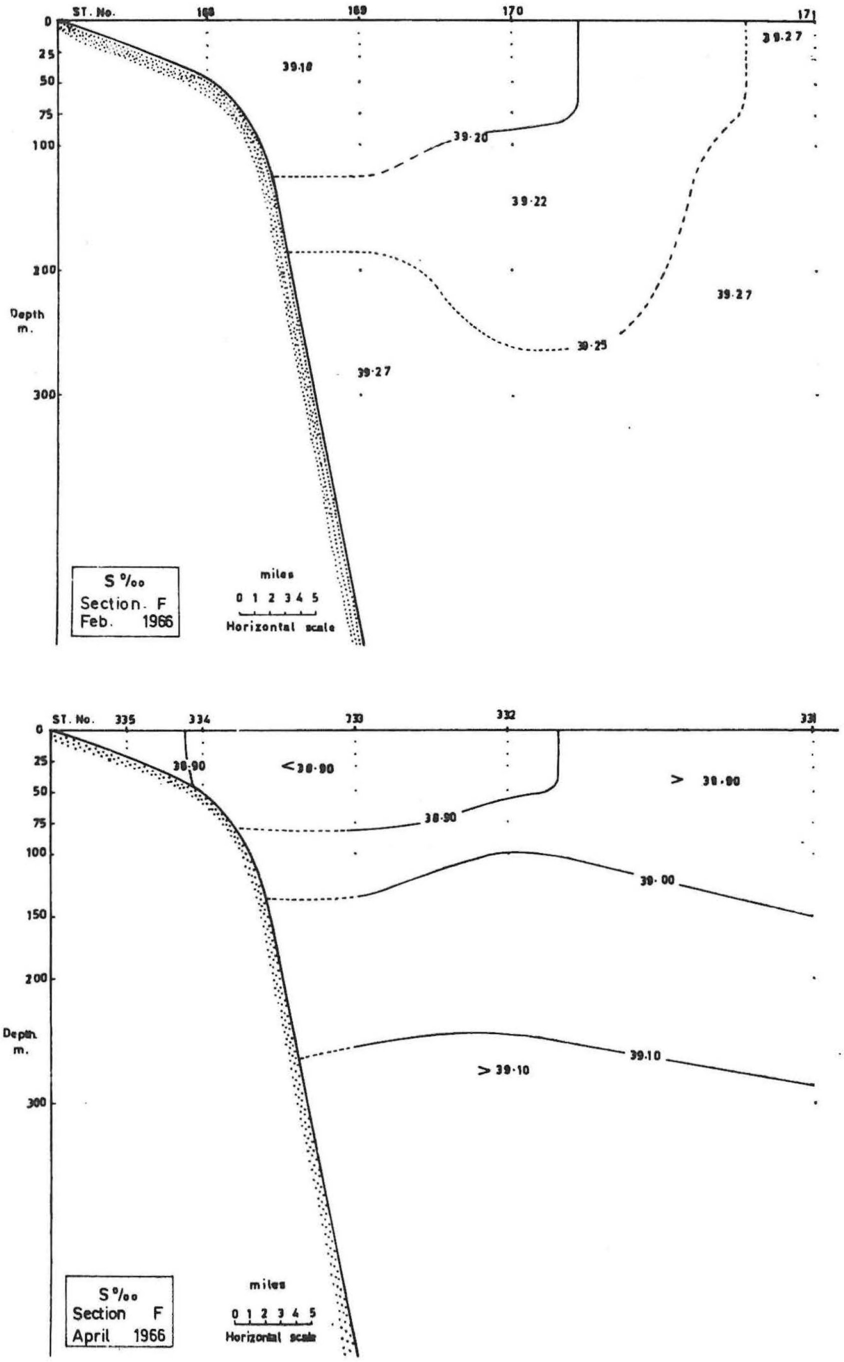
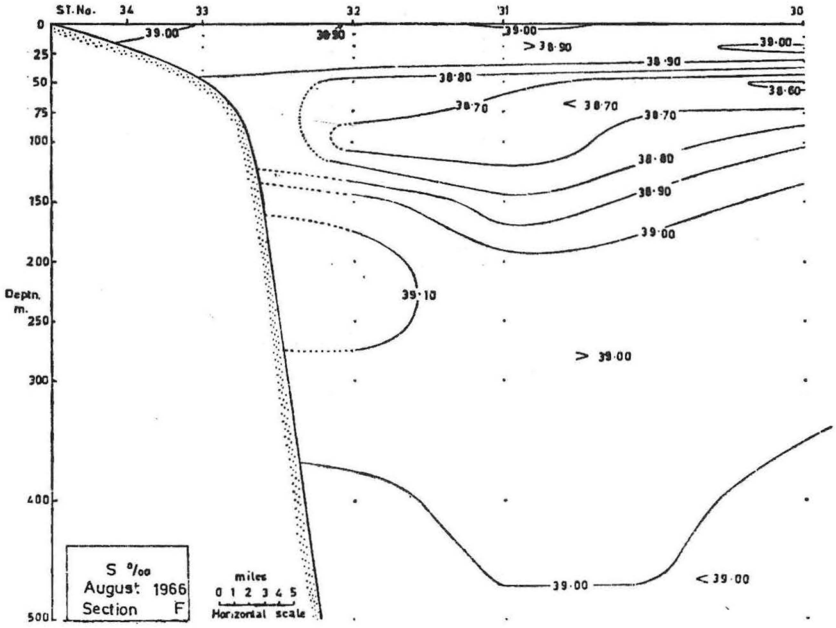


Fig. 5a — Vertical distribution of salinity in Section F, Arab Bay, West of Alexandria (Long. 29°05') in February and April 1966.



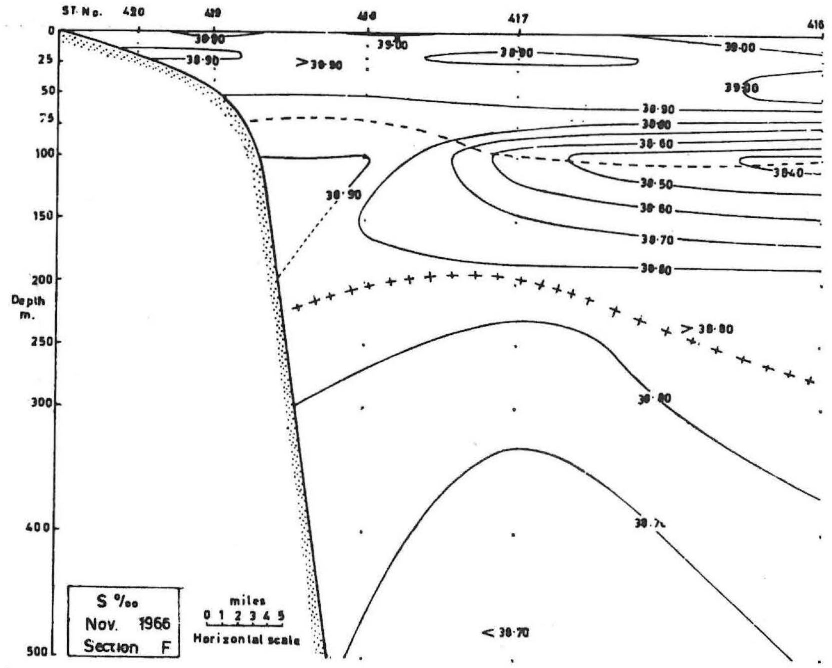


Fig. 5b — Vertical distribution of salinity in Section F in August and November, 1966.

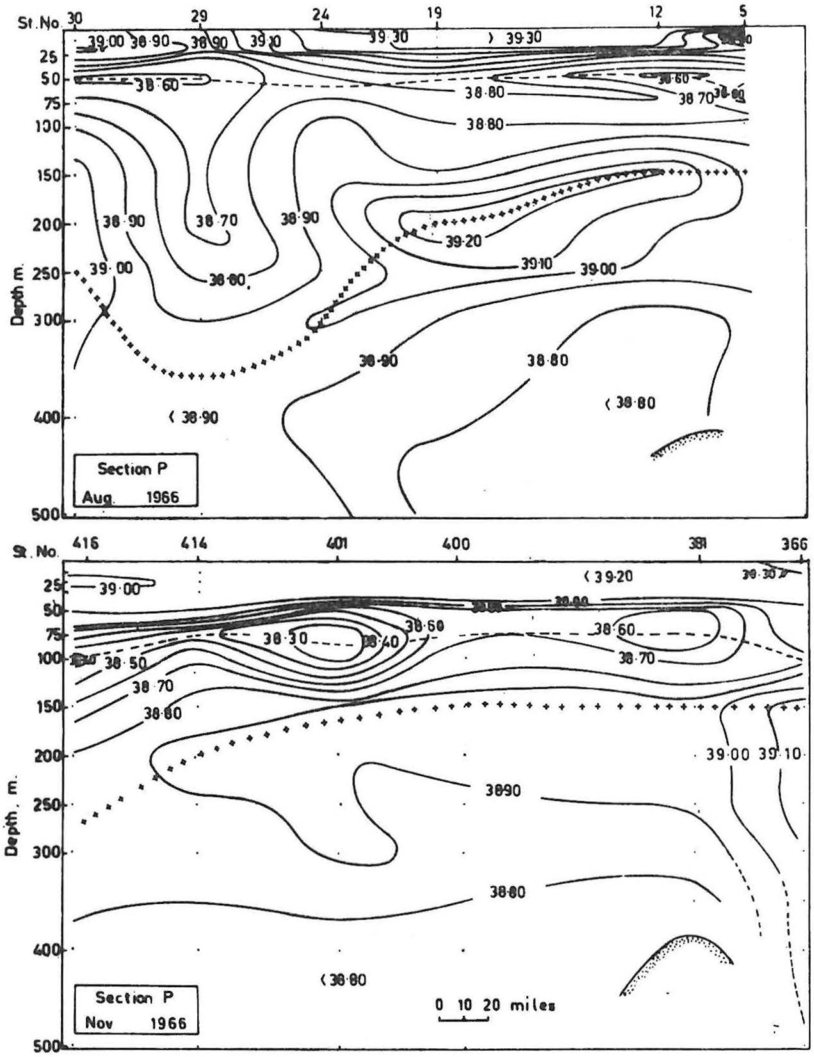


Fig. 6 — Vertical distribution of salinity in a section parallel to the Egyptian coast in August and November 1966.

In winter, one type of water is recognized at the corner of greatest density, i.e., high salinity and low temperature. In spring, two layers are distinguished in two of three stations while three layers are distinct in the T—S diagrams of August and November.

In Figure 8, the T—S diagrams at the four seasons are represented together for each station. A striking feature is that the water column in winter is not only isohaline from surface to about 300 m, but also the coolest and heaviest over the year. Heating from the surface after January will result

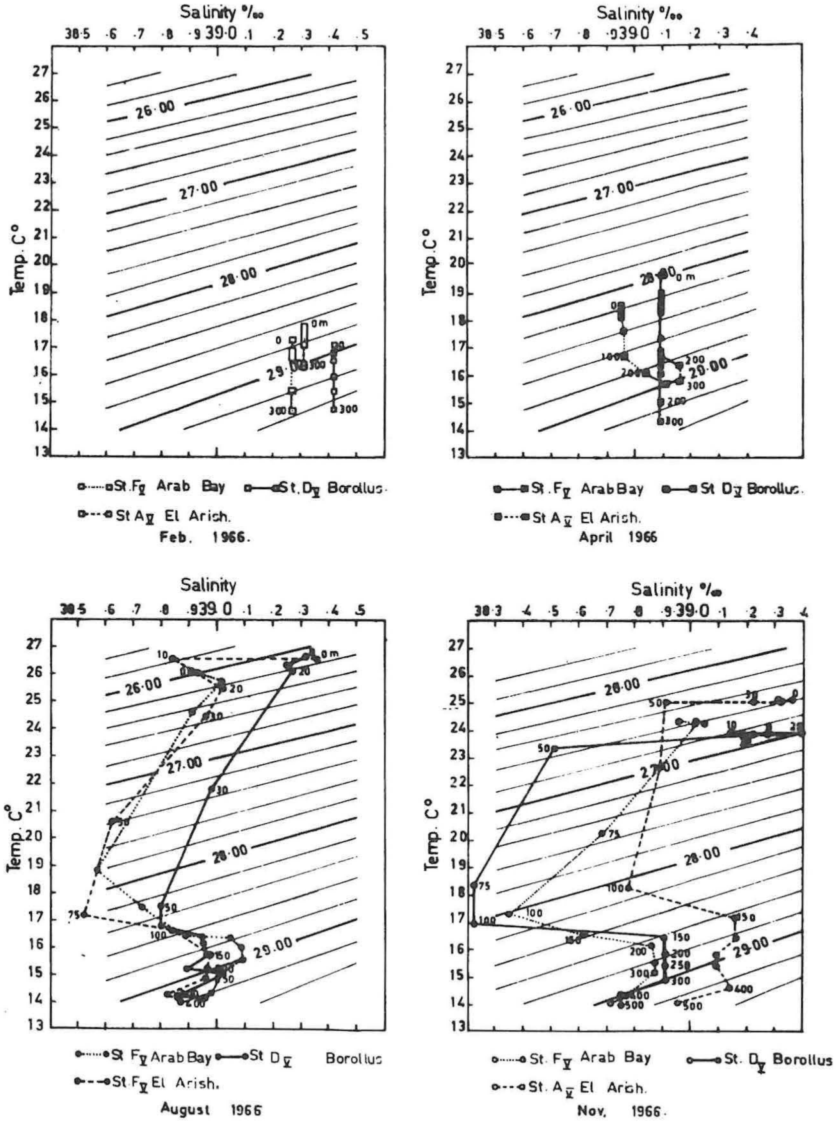


Fig. 7 — Regional characteristics of the T—S diagrams during February, April, August and November, 1966.

in a two layer columen; the upper layer is warmer and less dense, but retains the same salinity as the lower layer. This is the case in the central station (station Dv) which is presumably the transitional stage leading to the conditions in station A_v and F_v in April, where the upper layer is not only warmer but also less saline than the lower layer. However, it should be noted that even the lower layer (150 to 300 m) loses part of its salinity from January to April. This results in a limited decrease of density (0.2 to $0.4\sigma_t$) since the temperature of this layer remains almost unchanged. The new characteristics acquired by this layer in April are almost the same as the layer of intermediate maximum salinity in August. The T—S diagrams in Figure 8 are suggestive in indicating that the origin of the intermediate maximum salinity can be traced to the preceding spring and winter rather than looking for its origin in the northern part of the Levant Basin as discussed below.

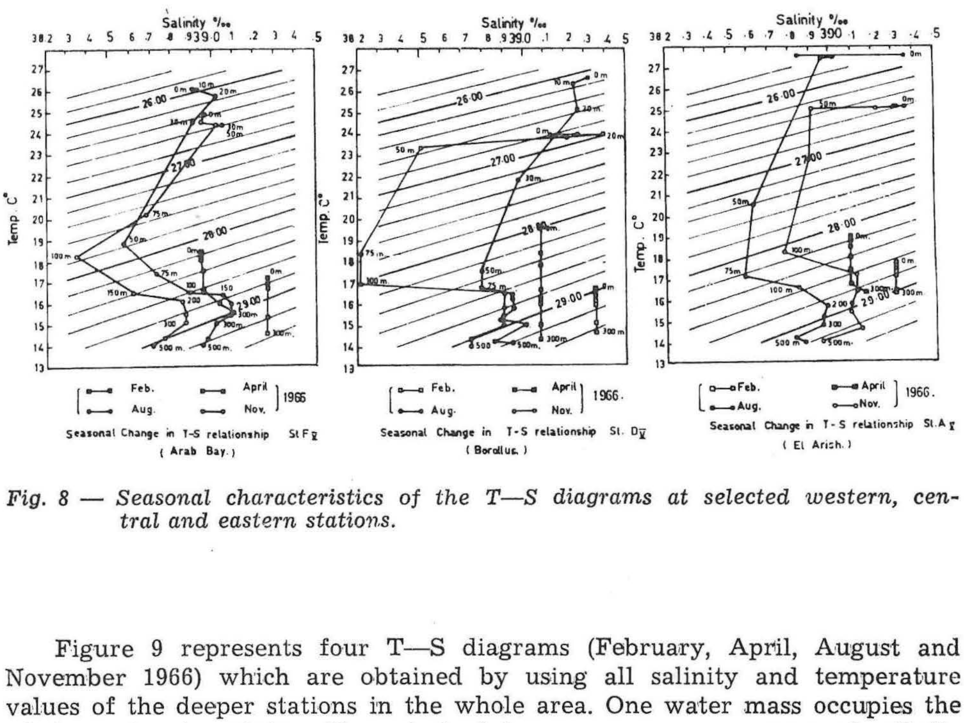


Fig. 8 — Seasonal characteristics of the T—S diagrams at selected western, central and eastern stations.

Figure 9 represents four T—S diagrams (February, April, August and November 1966) which are obtained by using all salinity and temperature values of the deeper stations in the whole area. One water mass occupies the whole region in winter. Characterized by a very narrow range of salinity (39. to 39.4‰) and temperature (14 to 18.2°C), it represents the heaviest water mass in the four seasons (28.6 to $29.4\sigma_t$). Again, two layers appear in spring and three layers appear in summer and autumn. In autumn two different types of water masses appear at the surface, one in the east with higher temperature and salinity and the other in the west with lower temperature and salinity. Each has almost the same density and mixing between them may take place along σ_t lines between 26.60 to 26.80.

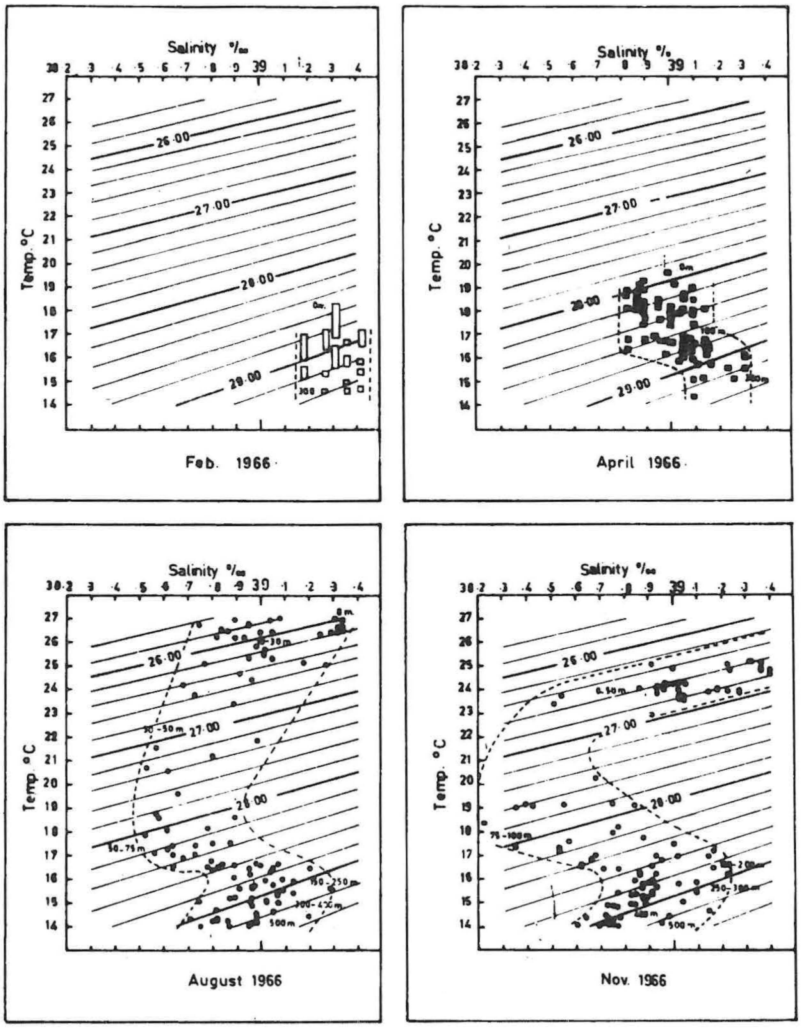


Fig. 9 — Average T—S diagrams in February, April, August and November, 1966.

DISCUSSION AND CONCLUSIONS

Characteristics and Circulation of the Main Water Masses.

In order to trace the circulation of the three water masses mentioned above, the core method of Wüst (1936) was applied. Figure 10 is a T—S diagram of the values representing the core of each of the three layers. The core of the layer is that part of the layer within which temperature or salinity or both reach extreme values. In this paper, salinity is the only criterion used. At each station three values were identified: the maximum salinity

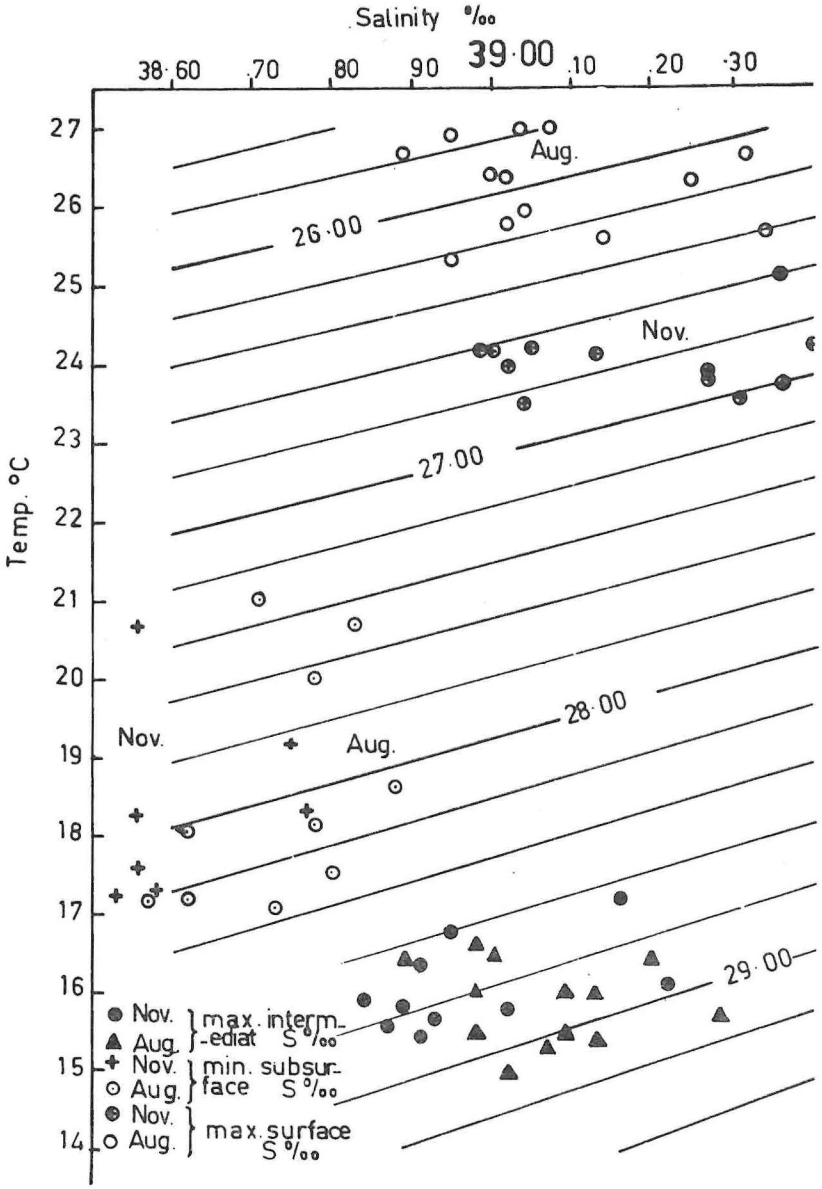


Fig. 10 — T—S relationship of the core of the three layers including maximum surface salinity, subsurface minimum salinity and intermediate maximum salinity.

within the upper 50 m, the subsurface minimum salinity, the intermediate maximum salinity within the whole water column. Figure 10 represents August and November since they are the only two seasons when the three water masses are clearly identified.

Layer of Maximum Surface Salinity.

This layer does not appear in winter and spring as a result of the vertical mixing by winter convection. With the increase of air and surface water temperature in summer, a strong thermocline develops below an upper warm and less dense layer. Increase of salinity by evaporation becomes mostly restricted to the surface layer (about 50 m) which remains isolated from the rest of the water column by a strong discontinuity layer. The increase in salinity is accompanied by increase in temperature and the resulting density remains below 26.5σ_t in August and 27.0σ_t in November. The increase of density from August to November is mainly due to decrease of temperature. Surface cooling results in an increase in the thickness of the layer to about 75 m (Figure 6) but the salinity remains high or even shows a slight increase of the THOR along the North African coast in July 1910.

Layer of Subsurface Minimum Salinity.

Little attention has been given to the subsurface minimum salinity layer in the literature dealing with the Eastern Mediteranean. Nielsen (1912) noted a decrease in salinity at station 156 which was the most eastern station of the THOR along the North African coast in July 1910.

A comparison of this station with ICHTHYOLOG station 30 in August 1966 (Figure 11) shows the presence of a subsurface minimum salinity at about 50 m in both cases. The presence of this layer is characteristic of the area in summer and autumn but disappears in winter and spring due to mixing by winter convection. Moreover, it is developed under the influence of the Atlantic Ocean surface water entering from the west. This current is recognized during the summer along the North African continental slope as clearly shown by the well-defined subsurface minimum salinity at 20 to 75 m depth in the core chart of Lacombe and Tchernia (1960) and Moskalenko and Ovchinnikov (1965). However, the magnitude of the current in winter cannot be inferred from the vertical distribution of salinity, since the subsurface minimum layer disappears under the influence of winter mixing.

The core of the minimum salinity layer represented in the T—S diagram in Figure 10 indicates that the salinity values are higher in August than in November. However, they spread over the same range of density, mainly, between 27.8 and 28.4σ_t. The same density is maintained because the decrease in salinity was compensated by a decrease in temperature. The vertical sections (Figure 6) show that the core is deeper in November than in August. It is assumed that the current of Atlantic origin finds its level of density at a deeper level in November than in August.

More details about the development of the minimum salinity layer from August to November are given in the charts of horizontal distribution of the core (Figure 12). In August, the layer appears in most stations at between 50 and 75 m. The main axis lies between the two 38.60‰ isolines enclosing water of less than 38.60‰ which flows eastward parallel to the coast. In November,

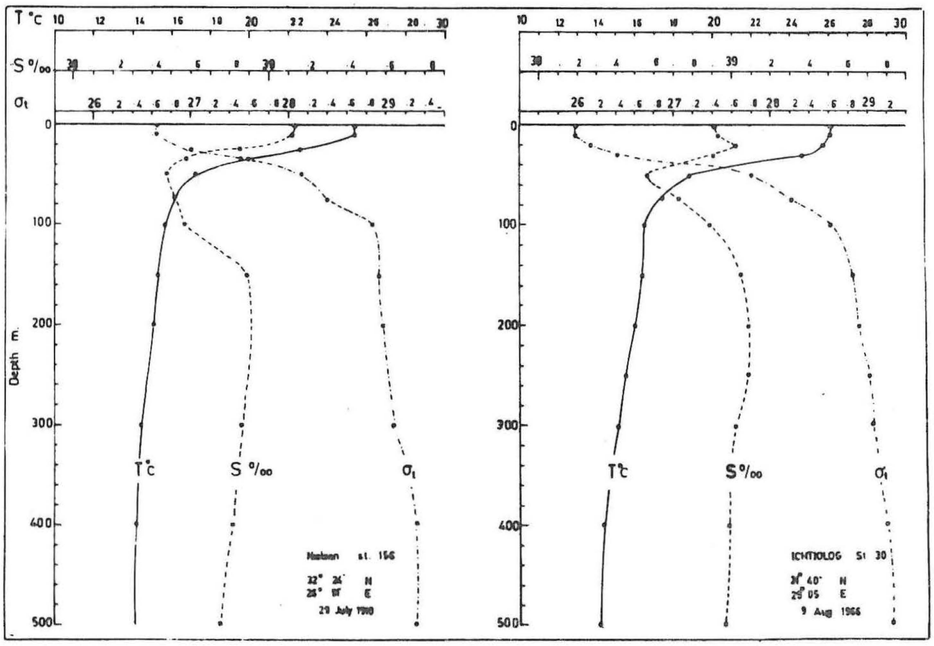


Fig. 11 — Vertical distribution of temperature, salinity and density (σ_t) *at THOR station 156, July (1910), ICHTHYOLOG station 30 (1966).*

the core layer is deeper (75 to 100 m). The shape and distribution of the isohalines are different. A tongue of lower salinity (38.30‰) in the west increases progressively to higher values in the east (38.90‰). This eastward increase of salinity is very peculiar. Compared with August the salinity is much lower in the west but exceeds that of August in the east.

The main axis of the minimum salinity layer runs closer to the shore in August than in November. The origin is generally attributed to an eastward flow of Atlantic waters. The present study of the core layer shows that this current is subject to seasonal variations in its position, depth and magnitude.

The November chart (Figure 12) shows signs of decay of this layer towards the east, presumably under the influence of mixing with the more saline and thick surface layer. As shown before, the layer of maximum surface salinity in November is thicker and slightly higher in salinity than in August.

The above discussion is based on the generally accepted theory that the layer of subsurface minimum salinity is developed under the influence of the Atlantic Ocean surface water. However, the T—S diagram in Figure 8 can be taken as an evidence that the layer of subsurface minimum salinity which appears in the T—S diagrams of August may be traced to the surface, less saline layer of the proceeding spring. The excessive evaporation and absence of rain during summer results in the increase of the salinity of the uppermost layer which remains in position due to the great salinity resulting from

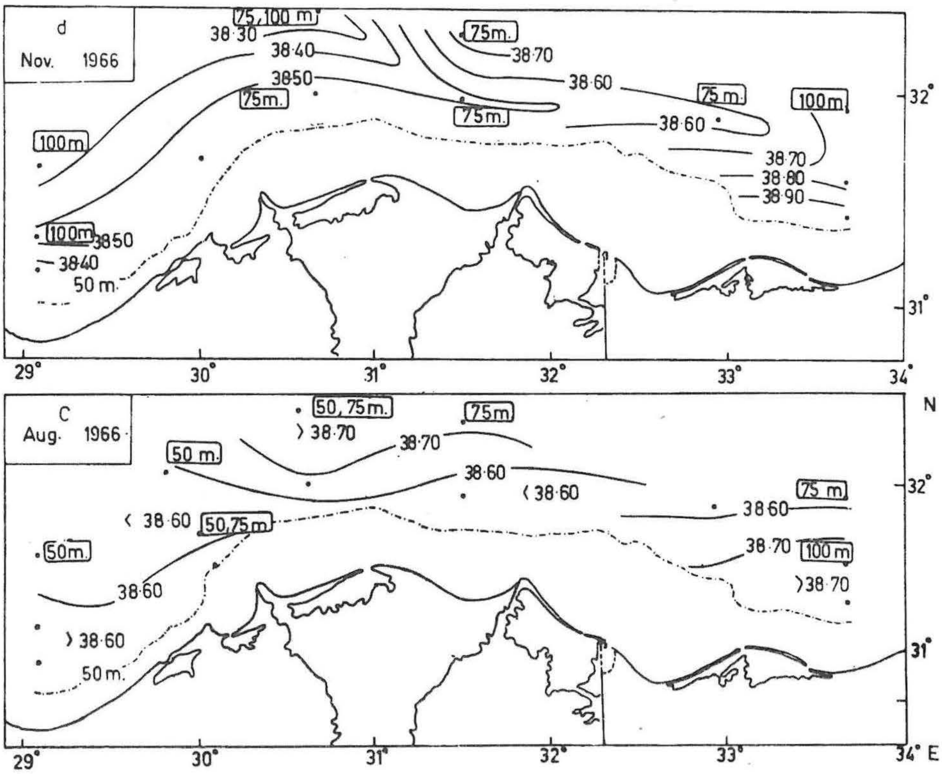


Fig. 12 — Core layer of subsurface minimum salinity in August and November.

heating of the surface layer. Such interpretation raises the question of the origin of the layer of subsurface minimum salinity, which may be formed by advection from the west or traced to the surface layer of the preceeding spring. Both sources can be considered as contributing by various degrees to the formation of this layer.

Layer of intermediate maximum salinity

The T—S diagrams in Figure 10 show that the core layer of the intermediate maximum salinity has a slightly higher density in summer (28.60 to 29.20σ_t) than in autumn (28.60 to 29.00σ_t). The salinity of the core layer in August is higher than in November. Morcos (1972) demonstrated that in both northern and southern Levant the core of the intermediate layer in summer is cooler than in winter, which suggests that this layer is deeper in summer.

Figure 13 a, b, c and d shows the distribution of the core in the four seasons. In February no intermediate maximum appears but the whole water column from 0 to 300 m has a homogenous water mass with identical salinity. In April the higher salinity appears at the lower levels mostly between 200 and 300 m.

In August, the intermediate maximum appears at 150 m in the eastern region, at 200 m in the central region and then tends to increase in depth in a westward direction. This tendency is also accompanied with a decrease in salinity towards the west. In November, the eastern area shows higher values in salinity than the central and western areas. Figure 13 shows a slight variation in depth compared with August.

The vertical sections of salinity parallel to the coast (Figure 6) show that the layer of intermediate maximum salinity has nearly the same depth in August and November in the eastern area (150 m), while it is deeper in August in the western area.

In November, the layer of intermediate maximum appears as a tongue of high salinity ranging between 150 and 300 m and showing a decrease of salinity within this tongue in a westward directions as indicated by the isohalines 39.10, 39.00, 38.90 and 38.80‰. The tongue shows a slight tendency to go deeper toward the west.

In August, the layer of intermediate maximum appears as a water mass of salinity higher than 38.90‰. Salinity higher than 39.20‰ is observed as a nucleus in the western and central region from where it decreases towards the east. A very clear tendency of increase in depth is observed in August with the core of the layer below 300 m at some stations.

The above observation agrees with the conclusion of Morcos (1967, 1972) that the formation of the layer of intermediate maximum salinity starts to take place in the southern Levant Sea during winter, becoming better defined in summer and autumn. The formation is more probable in the east from where it flows to the west.

This does not, however, contradict the conclusion of Nielsen (1912) that the main source of this layer takes place near the northern region of the Levant Basin from where it extends to the south and west. There still remains the possibility of finding in the Levant Basin two types of water of intermediate maximum salinity, one having its origin in the main source region in the northern Levant Basin, and the other being formed in the southern Levant Basin during the preceding winter.

A careful examination of the T—S diagrams of Wüst (1960, 1961) shows that the points representing the core layer of the intermediate maximum salinity at various stations in the Levant Basin reveal a more or less heterogeneous character compared with the homogeneous character in other basins of the Mediterranean. They spread accross the σ_t — lines of the T—S diagram in the Levant Basin, while they aggregate along the σ_t lines west of the Levant Basin. This comparison may be taken as an evidence that there is more than one source of formation of this layer in the Levant Basin. It indicates various source regions with respect to space and time. These waters acquire, by mixing, more homogeneity in spreading towards the Ionian Sea, and is recognized as a well identified water mass west of the Strait of Sicily. A thorough understanding of this problem requires more frequent, dense, close (in levels of sampling) and deeper observations inside and outside the present area of investigation.

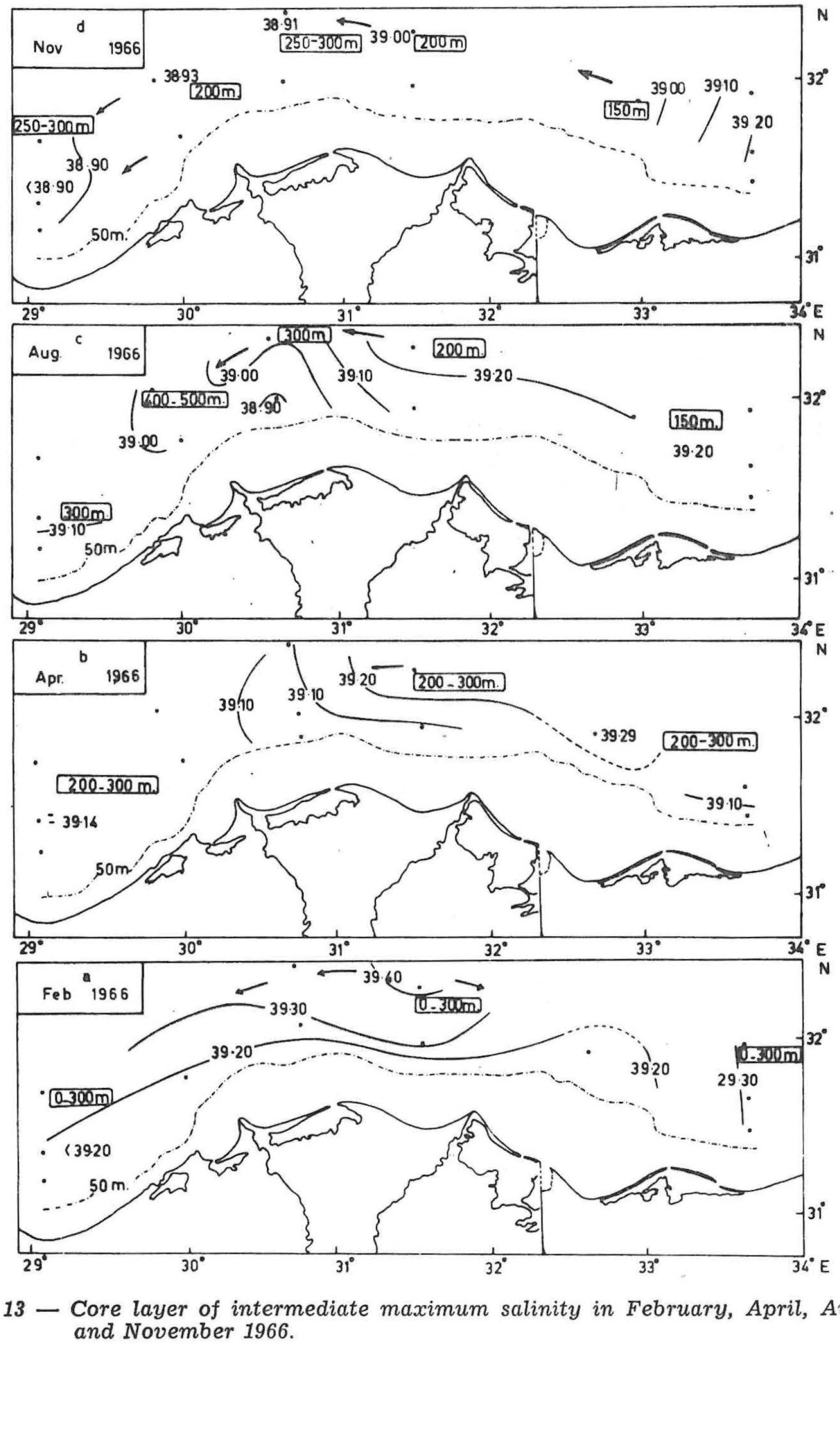


Fig. 13 — Core layer of intermediate maximum salinity in February, April, August and November 1966.

The present investigations indicate that at least two alternative or combined sources contribute to the formation of the subsurface minimum salinity layer as well as the intermediate maximum salinity layer. It is recommended that future investigations be directed towards the study of the sources, composition and processes of formation of these two layers.

SUMMARY

The present study depends on 205 oceanographic stations from four seasonal cruises which represent a major source of information from an area where data were hitherto scarce.

A layer of subsurface minimum salinity (50—75 m) appears along the Egyptian coast and is developed, under the influence of the Atlantic Ocean Surface current flowing eastward from Gibraltar. An alternative source is inferred from the present data, where the layer of subsurface minimum salinity in August can be traced to the surface, less saline layer of the preceeding spring.

Similarly an alternative source of the intermediate maximum salinity layer can be inferred from the present data. This layer appears as a tongue of high salinity between 150 and 300 m, with a tedency to become deeper and less saline towards the west. It is generally accepted that this layer finds its source in the surface water of the northern part of the Levent Sea from where it sinks in winter and spreads towards the south and west. The present study shows evidences that the layer of intermediate maximum salinity is formed locally during winter and becomes better defined in summer and autumn.

At least two alternative or combined sources contribute to the formation of the subsurface minimum salinity layer as well as the intermediate maximum salinity layer.

This is a matter which requires further investigations in the processes and sources of formation of both layers.

REFERENCES

L a c o m b e, H. ind P. T c h e r n i a. 1960. Quelques traits généraux de l'hydrologie Méditerranéenne d'après diverses campagnes hydrologiques recentes en Méditerranée, dans le proche Atlantique et dans le detroit de Gibraltar. Cah. Océanogr., *12* (8), pp. 527—547.

M o r c o s, S. A. 1967. On the origin of the Mediterranean intermediate water. IUGG Abstracts of Papers, Vol. V. No. 126, paper presented at International Association of Physical Oceanography, Berne, September 1967.

M o r c o s, S. A. 1972. Sources of Mediterranean intermediate water in the Levantine Sea. *In:* Studies in physical oceanography, a tribute to Georg Wüst on his 80th birthday, Ed. by A. L. Gordon, *2*, pp. 185—206, Gordon and Breach, New York.

M o r c o s, S. A. and H. M. M o s t a f a H a s s a n, 1973. Some hydrographic features of the Mediterranean waters along the Egyptian Coast. Thalassia Jugoslavica, *9*, pp. 227—234.

Moskalenko, L. V. and I. M. Ovtchinnikov, 1965. Water masses of the Mediterranean Sea. *In:* »Principal account of the geologic structure, of the regime, and of the biology of the Mediterranean.« (in Russian). Moskva Izdat. Nauka, p. 119.
Moustafa Hassan, H. 1969. The hydrography of the Mediterranean waters along the Egyptian coast. M. Sc. Thesis, University of Alexandria, 214 p.
Nielsen, J. N. 1912. Hydrography of the Mediterranean and adjacent waters. Rap. Dan. Oceanogr. Exped. 1908—1910, *I*, pp. 77—91.
Sverdrup, H. U., M. W. Johnson and R. H. Fleming. 1942. The oceans, their physics, chemistry and general biology. Prentice Hall, New York, 1087 p.
Wüst, G. 1936. Schichtung und Zirkulation des Atlantischen Ozeans. »Meteor« Werk, *6*, 1, Berlin.
Wüst, G. 1959. Remarks on the circulation of the intermediate and deep water masses in the Mediterranean Sea and the methods of their further exploration. Ann. Instituto Univ. Navale di Napoli, *28*, 12 p.
Wüst, G. 1960. Die Tiefenzirkulation des Mittelländischen Meeres in den Kernschichten des Zwischen-und des Tiefenwassers, Deut. Hydrograph. Z., *13* (3), pp. 105—131.
Wüst, G. 1961. On the vertical circulation of the Mediterranean Sea. J. Geophys. Res., *66*, pp. 3261—3271.

VODENE MASE I STRUJANJE U JUGOISTOČNOM MEDITERANU

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KRATAK SADRŽAJ

Istraživanja su vršena na krstarenjima u različitim sezonama. Vodene mase su određene na osnovu T—S dijagrama. Promatran je sloj površinskog maksimuma, podpovršinskog minimuma, te intermedijarnog maksimuma slanosti. Izneseno je mišljenje da podpovršinski sloj minimuma slanosti nije uslovljen jedino utjecajem atlantske vode, kako je ranije bilo iznošeno, nego da je u vezi i s površinskom slađom vodom iz ranijeg proljetnog razdoblja. Također je zaključeno, da postoji mogućnost formiranja intermedijarne vode visoke slanosti na više lokaliteta levantinskog bazena, a ne samo na jednom mjestu. Na to ukazuje nehomogenost te vode u samom levantinskom bazenu.