

THE HYDRODYNAMICS OF THE GULF OF CÁDIZ AND THE EXCHANGE OF WATER MASSES THROUGH THE GIBRALTAR STRAIT

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Abstract

Studies on the exchange of water masses through the Gibraltar Strait, between the Atlantic Ocean and the Mediterranean Sea, are numerous, mainly in recent years. However, there is a lack of works of synthesis about the mechanism, distribution and nature of the water masses etc., based on more recent data. On the other hand, the establishment of temperature and salinity data for the waters partially covering the continental shelf near Cádiz, has demonstrated the presence, in this area, of North Atlantic Surface Water (NASW), to about 140 metres depth, with clear seasonal variations. At a deeper level, some North Atlantic Central Water (NACW) has been detected, but the presence of Mediterranean Water (MW), which circulates below 500 metres, in the continental slope, has not been observed.

INTRODUCTION

The exchange of water masses between the Atlantic ocean and the Mediterranean sea is a very important factor in understanding the hydrodynamics of the Gulf of Cádiz and Alboran sea (Western Mediterranean). This paper presents a synthesis, based on data gathered from various studies, aiming to know the fundamental aspects of the hydrology of the Gulf of Cádiz and the influence of the Mediterranean ebb stream in the northern continental margin of the Gulf of Cádiz. This presents peculiar characteristics, due to its morphology and its location between the Atlantic and the Mediterranean, as the Gibraltar Strait, where the exchange of water between those two seas takes place, is situated on its eastern vertex.

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At present, the contribution of fluvial water and the rainfall in the Mediterranean are not enough to compensate the loss of water due to evaporation, and this sea presents a negative equilibrium, which, along with the differences in temperature and salinity (T-S) of water, favours the exchange of water masses, resulting in an inflow of Atlantic water through the Strait, and an outflow of Mediterranean water in depth, denser and more salty. LACOMBE (1971) estimates a net loss which lowers the level of the Mediterranean from 0.6 to 1 m per year. This loss is compensated, mainly at the level of the Strait, which provides a net volume of $5.4 \times 10^4 \text{ m}^3/\text{seg}$ (LACOMBE and TCHERNIA, 1972). At the same time, the salinity of the Mediterranean is kept more or less constant, thanks to the deep outflow, towards the Atlantic, of denser Mediterranean water (VILLANUEVA-GUIMERANS and RUIZ CAÑAVATE, 1989).

The existence of the Atlantic incoming surface stream has already been known for a long time, but with respect to the outgoing deep stream, though its existence was suspected (Sir Robert SOUTHWELL, 1675, Dr. T.H. SMITH, 1684), it was not verified until the demonstration by DUPONT D'URVILLE of the higher temperatures of deep waters, in comparison with the corresponding ones at the same depth in other zones of the Atlantic. The final proof arose in 1870-71, when CARPENTER demonstrated that not only the temperature was affected, but also the salinity and that both parameters were very close to the figures for the deep waters of the western Mediterranean (SECO SERRANO, 1962). Since then, several studies have been carried out.

WATER FLOWS

A. THE ATLANTIC FLOW

The Atlantic coasts of the Iberic Peninsula are influenced by the Gulf Stream. One of its branches turns with the trade wind of the Northeast and sweeps the coast of the Peninsula to the south, from Galicia to Cape San Vicente. It is the stream of Portugal, which runs afterwards from the Gulf of Cádiz towards the Canary Islands, to the SW (SANCHEZ and ZABALETA, 1972). In the zone of the Gibraltar Strait, whilst the most important part of the stream continues towards the Canary Islands, the part nearest the coast divides into various branches : one follows the coast of Africa, without completely entering the Gulf of Cadiz, while other enters it, along the coast and the peninsular continental margin (Fig. 1, 2a and 2b) as is demonstrated by the distribution of fine sediments (argillaceous mud), which, coming from the River Guadalquivir are found to the Southeast (SEGADO et al. 1984).

Water masses

In the Gulf of Cadiz, the North Atlantic Central Water (NACW), lies from 100 to 700 m, with values T-S from $12^\circ\text{C} - 35.70 \text{‰}$ to $16^\circ\text{C} - 36.25 \text{‰}$. A layer at 100 m is found on this latter, with isohalines about 36.4‰ , created as a result of atmospheric phenomena and showing a stationnal termohaline of $5^\circ\text{C}/100 \text{ m}$. This layer is named Atlantic Surface Water (NASW). In depth, the North Atlantic Deep

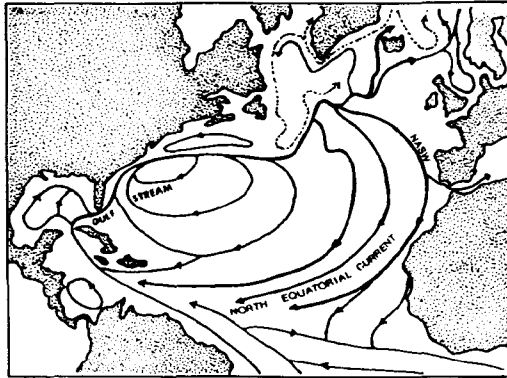
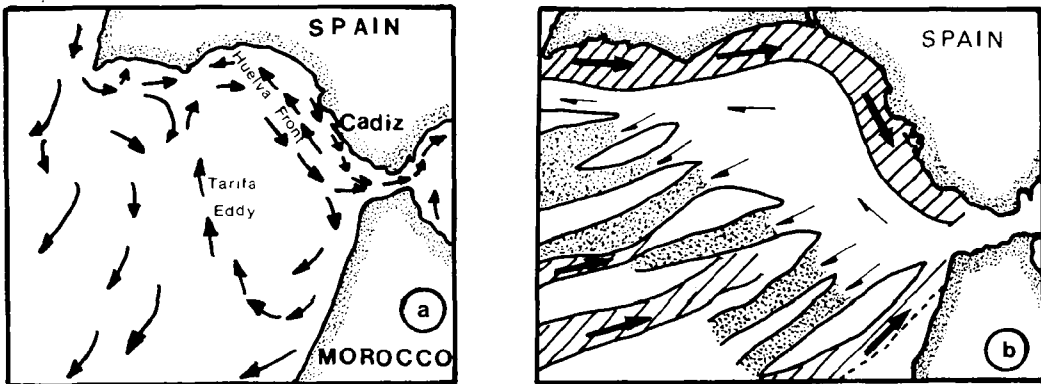


FIG. 1.- General circulation in the North Atlantic.

FIG. 2.- Currents in the Gulf of Cádiz. a) according to STEVENSON (1977);
b) according to FERNANDEZ Y ORTEGA (1982).

Water (NADW) expands (SVERDRUP, *op. cit.*). The establishment of the nature of the water masses in the continental shelf close to Cádiz has been carried out from temperature and salinity data, gathered along two oceanographic cruises related to the "Gibraltar Experiment" (BRYDEM and KINDER, 1985), carried out in April-May 1986 (BRAY, 1986) and September-October 1986 (SHULL and BRAY, 1989).

The isotherms (Fig. 3a & 3b) and isohalines (Fig. 4a & 4b) have been drawn at standard depths. From this analysis it can be deduced that the water masses circulating in this area pertain to the Atlantic Surface Water down to a depth of 140 m, while, from there onwards, the North Atlantic Deep Water can already be detected. Only in some offshore sites, and at depths greater than 200 m, a light influence of the Mediterranean ebb could be found. This influence is shown by means of an inversion of the isohaline and isotherm gradients, very clear from a depth of 500 m.

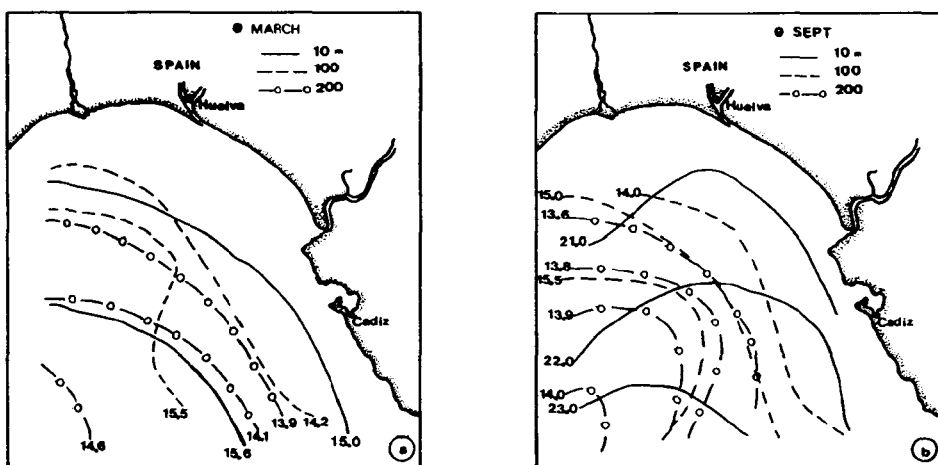


FIG. 3.- Potential temperature in the near continental margin. a) March; b) September.

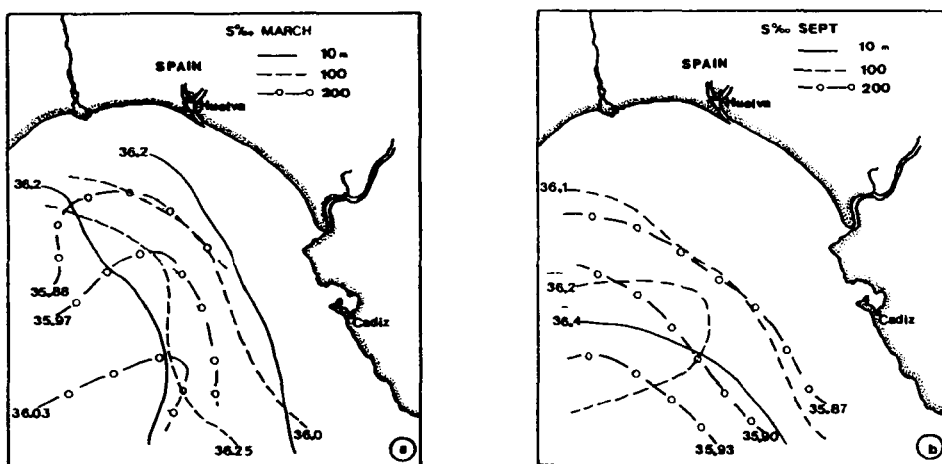


FIG. 4.- Salinity in the continental margin close to Cádiz. a) in March; b) in September.

The variation of the seasonal thermocline, which mainly affects surface water, and can be found down to 100 m depth, is due to the sun heating it during summer, resulting in rather high temperatures in September, while in March they are still low because of the winter influence (Fig. 3a & 3b).

Outcrops have been detected along the Atlantic coast of Morocco, carrying to the surface ACNA, mainly in the proximity of Cape Espartel and Cape Malabata, in the entrance of the Strait. Atlantic waters entering the Mediterranean along the coast of Morocco are richer in North Atlantic Central Water than those of the Spanish coast, in which the rate of Surface Water is greater.

Entrance to the Mediterranean

It is effected through Gibraltar Strait, the differences of density between the Atlantic flood and the Mediterranean ebb being about 2×10^{-3} . A high gradient of salinity (1.75×10^{-3} for 100 m) is a typical feature of the interface between these two waters. This interface is affected by internal tide waves which are of sinusoidal form in the west part of the Strait and more irregular in the east.

The mean longitudinal interface is rather continuous and more superficial in the east (50-80 m) than in the west (180-200 m), while the mean transversal interface is deeper in the south than in the north (Fig. 3b). Control is mainly made in the narrow sector close to Tarifa (ARMI & FARMER, 1988). Once in the Mediterranean, Atlantic Surface Water and North Atlantic Central Water are detected as flows of low salinity and rather low temperature in summer and high in winter.

Between the meridians 3° and 4° , NASW and NADW change to the south and divide into various branches: one performs an anticyclonic turn (Alborán Turn) and part of the water comes back to the Atlantic through the Strait. Another part runs along the North African coast to the east, and a third part goes to the Thyrrenian Sea and the Balear Sea, becoming more saline and dense (PARRILLA and KINDER 1987) (Fig. 5a & 5b).

B. THE MEDITERRANEAN FLOW

The water of Mediterranean origin which flows through the Strait towards the Atlantic is formed by two different kinds of water: one is the Levantine Intermediate Water (LIW), coming from the Eastern Mediterranean, which, after crossing the Strait of Sicily flows to the Gibraltar Strait and after bifurcating in the vicinity of the Island of Alborán runs along the base of the continental slope of the Mediterranean Spanish coast at a speed of 1 to 3 cm/s and enters under the NASW at a depth of 200-600 m (PARRILLA & KINDER, 1987)

Below that, the Mediterranean Deep Water (MDW) can be found. Its characteristics are a potential temperature below 12.9° and a homogeneous decrease in salinity and temperature (BRYDEN and STOMMEL, 1982). This water originates in the Gulf of Lions during winter months from a cooling of the superficial water, which becomes more dense and reaches deeper areas, going along the eastern coasts of Spain to the west, very close to the North-African margin, towards the Alborán Sea, at a speed of 5-10 cm/s (PARRILLA & KINDER, 1987).

The passage to the Atlantic

The passage of Mediterranean water over the sill takes place at a depth of about 200 m. Until recently, this flow was supposed to be homogeneous, but recent researches demonstrate that a difference (LIW and MDW) can occur, according to the type of tide (KINDER & PARRILLA, 1987).

Some authors mention variations in the direction of the flow (LACOMBE 1971); some are regular and are related to the type of tide and period of the year.

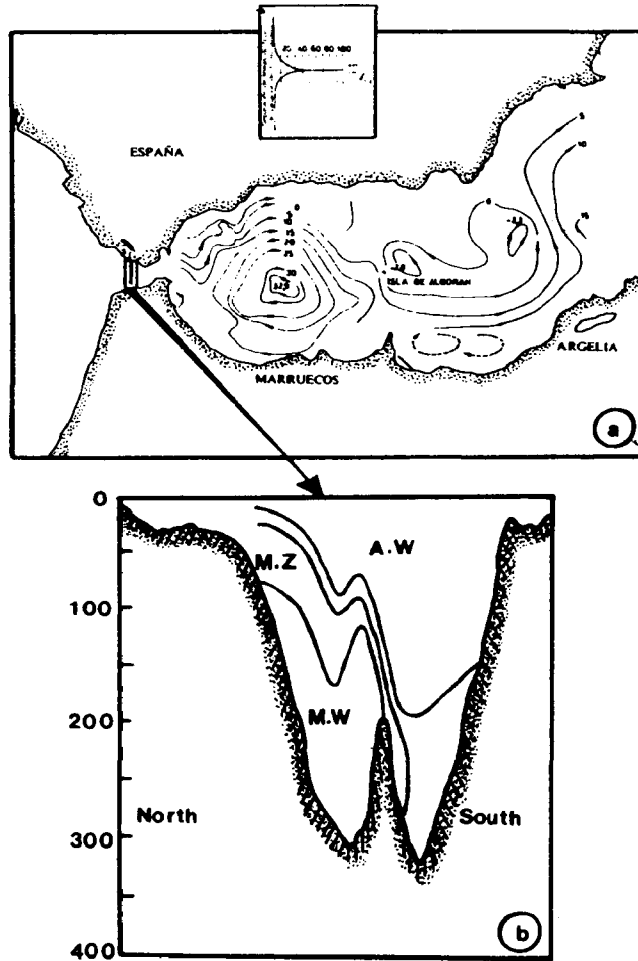


FIG. 5 a) Dynamic relief of the surface of the Alborán Sea, referred to 200 dbars (LANOIX, 1974);
 b) Water masses in the sill of Gibraltar (AW) Atlantic, (MZ) mixing zone, (MW) Mediterranean
 Water (VILLANUEVA GUIMERANS and RUIZ CAÑAVATE, 1988).

CARTER (1956) noted a seasonal variation in the direction of the net flow, during the winter period, related to the principal rainy season in the Mediterranean basin ; others are occasional, lasting a few days. In this respect, LACOMBE (1971) believes that, although the inversion is not reached, the net flow at the end of spring is just reduced to 20% of that existing at the end of summer. Recent researches carried out from recordings of echo sounders during the "Gibraltar Experiment" project (BRYDEM KINDER, 1985) show a total cessation of the flow in high water.

The circulation of Mediterranean Water in the Gulf of Cádiz

The first detailed scheme on the circulation of the Mediterranean ebb or Mediterranean underground stream in the Gulf of Cadiz was carried out by

MADÉLIAN (1970). The model has been later improved by other authors, in particular ZENK (1975).

The exit from Gibraltar Strait

The main area of exit is the sill of Gibraltar, at $5^{\circ} 45' W$, (Fig 5a and b), in which the hypothetical control models become critical (BRYDEN and STOMMEL, 1982). From this point, the stream runs to the NW, at a high speed, along the continental margin of the Iberian peninsula, under the influence of the bottom morphology, reaching a certain balance in depths of 600 and 1,500 m, already in the Gulf of Cadiz. The speed and direction of the stream are affected by the Coriolis force, intrusion mechanisms and a rough topography which favours the acceleration (Fig. 6). ARMI and FARMER (1988) propose the existence of two controls of the outgoing stream, one located in the sill of Caraminal, which gets lost periodically, as a consequence of tides, the other westward, in Espartel, where the flow is continuously hypercritical.

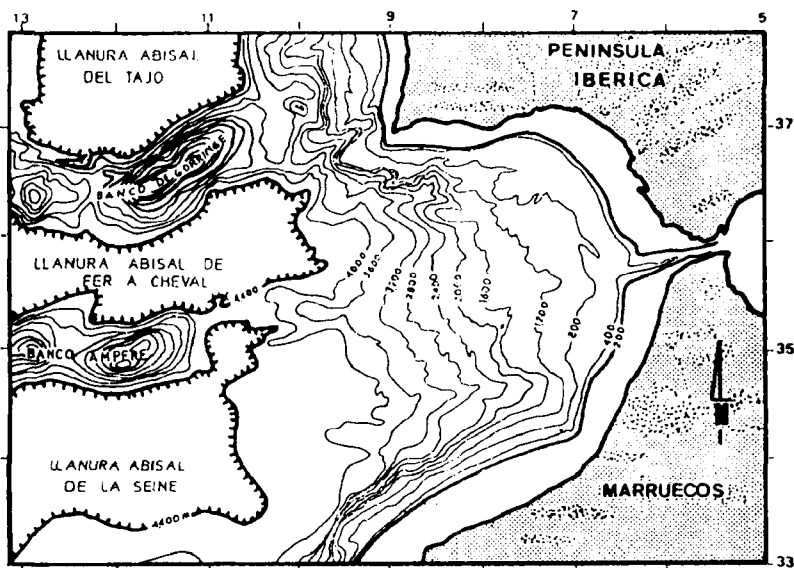


FIG. 6.- Bathymetry of the Gulf of Cádiz (MELIÈRES, 1974).

The circulation in the lower Northern Margin of the Gulf of Cadiz (Fig. 7 and 8)

a) Between the sill of Gibraltar and the meridian $6^{\circ} 30' W$, the stream current runs along a kind of straight channel, oriented W-SW. The salinity of the outgoing flow in the western part of the Strait, is higher than 38.20 ‰ and its temperature reaches $12.90^{\circ} C$ (KINDER and PARRILLA, 1987), maintaining its identity in regard to the supradjacent Atlantic water. This initial flow is approximately 15 km long and 150-200 m broad, its velocity ranging from 40 cm/s in the upper layers to more than 200 cm/s in the low parts (GRUNDLINGH, 1981).

b) Between $6^{\circ} 30'$ and $7^{\circ} W$, the Mediterranean flow spins clockwise towards the NW, following the morphology of the continental margin, nearly $6^{\circ} 30'$ and 6°

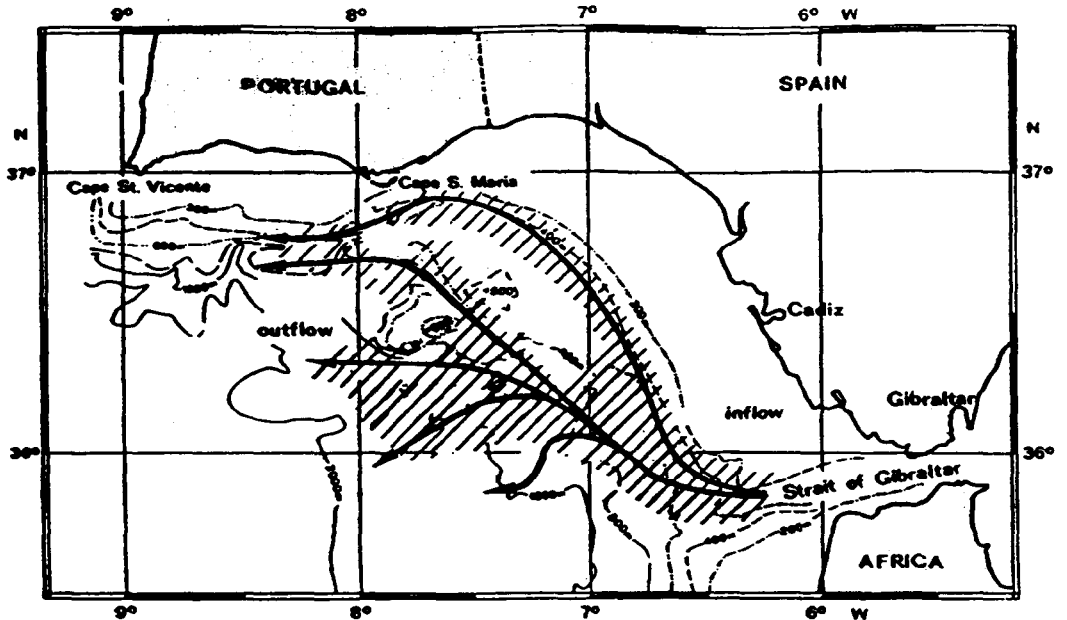


FIG. 7.- Circulation of the Mediterranean flow in the Gulf of Cádiz (Modified by ZENK, 1975).

40' W. To the north of the 6° 30' meridian, the main section is divided into various parts : one of them runs along the Iberian margin, while the others run perpendicular to the coast through various canyons located in the slope, in a NE-SW direction (MADELIAN, 1970, ZENK, 1975). Besides, the diagrams T/S show the Mediterranean water divided into two nuclei : the inferior, which is the principal one, with a maximum of salinity 37.42 ‰ and a temperature of 13.6°C, running at a depth of 756 m. It is the **Mediterranean Inferior water (MI)**; the other, not so deep, between 500 and 600 m, with a temperature of 13.72 °C and a salinity of 37.07 ‰, is the **Mediterranean Superior water (MS)** (AMBAR & HOWE, 1979).

c) **The Canyon Area.** Between 7°- 8° W and 36°-37° N, the flow enters an area of submarine canyons. MS water separates from MI water and both sink near the meridian 7° 30'W. The shallowest nucleus becomes stationary at 670 m (Max. temp. 13.58°, Sal. 36.74 ‰, Sigma-T 27.68), while the deeper, which is the principal one, becomes stationary at 1000 m (Sal. 37.08 ‰, Temp. 12.87°C, Sigma-T 28.08) (AMBAR & HOWE).

One of the branches, named by ZENK (1975) **Channel of the platform**, which is the most northerly, conveys a part of the flow to the NW along the Gulf of Cadiz, to Cape Santa María. From this point, following the bottom morphology, it changes its direction towards the west and goes to Cape San Vicente, with a maximum salinity of 36.50 ‰ [ZENK (1975) & THORPE (1976)].

The other branch, which has a width of 7.5 km and a depth of flow of 150 m runs in the south (ZENK, 1975), circulating between two morphological sills. MADELIAN (1970) has found in this channel salinities inferior to 36.4 ‰, and a rather high velocity (from 40 to 50 cm/sg at 860 m). It can be considered as a low-salinity

Mediterranean flow. ZENK (1975) found water of salinity higher than 36.5 ‰ in this branch, but at a shallower depth (645 m) and with inferior velocity (36 cm/sg).

The most important part of the outgoing Mediterranean flow runs in the **principal channel**, in which MADELIAN (1970), identifies two branches in regard to T and S data, but, during the researches carried out by the "Meteor", in 1971, a single mass of water, of 36.5 ‰, was determined. It would probably include the two branches. Subsequently ZENK (1975), following his studies on currents, determined small differences in velocity, less than the 25%, in the peak flow areas, and did not find any reason for the separation first suggested by MADELIAN.

The other part of the flow goes through the **south channel**, which is the most southerly and close to the Strait. It runs along a small canyon (1.5 to 2 km, KENYON & BELBERSON 1973), which takes a small portion of the water from the main stream current and directs it to the SW (HEEZEN, JONHSON 1969; MADELIAN 1970). The flow has a thickness of 100 m and a salinity of 36.8 ‰ (GRUNDLINGH, op cit.), although other values of only 35.7 ‰ have been found at 25 m from the seabed, it being the channel presenting the strongest interaction between the seafloor and the subsurface current, as it is demonstrated by the numerous sedimentary structures generated from the current in the seabed (KENYON & BELDERSON 1973).

Between the parallels of Tavira and Faro, MELIERES (1974) notes other possible branch, issuing from the **intermediate channel**, which would run along a valley SE-NW oriented (Fig. 8), to turn again to the west and join the main current stream. A flow velocity of 0.25 m/sg is supposed in this area, with a salinity of 36.5 ‰, according to the data from MADELIAN (1970). Although this author does not mention this possible branch, MELIERES considers that this branch has its own entity and is dynamically comparable to the other three.

d) The issue from the Gulf of Cádiz. Between the meridian 8° 40' and Cape San Vicente, the Mediterranean flow is divided into three separated branches of different depths (GRUNDLINGH op. cit.), one superficial, between 500 and 600 m, coming from the channel of the platform, which runs towards the North, after passing Cape San Vicente, along the continental margin of Portugal. MADELIAN (1970) states the existence of a S-N oriented canyon (8° 30' W) along which part of the water of this branch runs towards deeper areas, to finally join the central flow; another, central, between 700 and 900 m comes from the intermediate channel and runs to the Atlantic facing the NNW, moving away from the continental margin; a third flow, deeper, between 1200 and 1500 m., is the principal outgoing mass gathering water coming from the principal channel and south channel, and issues to the Atlantic towards the NW, between Cape San Vicente and Gettysburg Bank. ZENK and ARMI (1990) (Fig. 9) consider that this flow is divided into two; one, the principal one, at a depth of 1280 m, gathers water running along canyons, and other, at 750 m, coming from the platform and showing a strong trend to follow the bottom contour along the Portuguese continental margin.

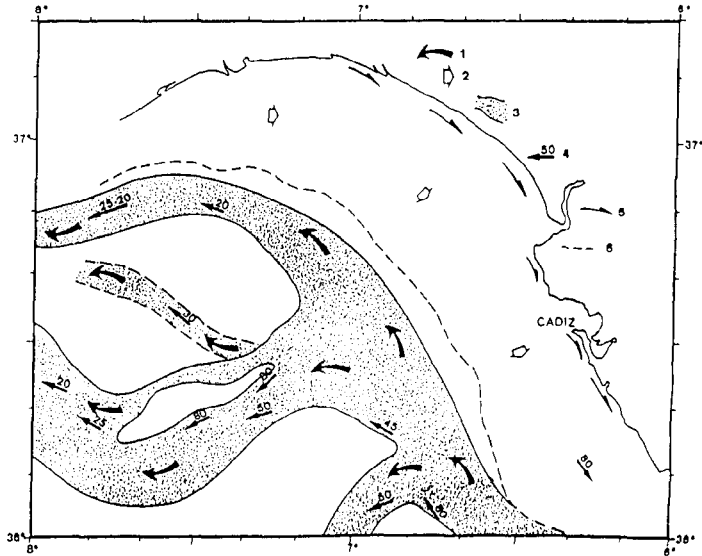


FIG. 8.- Hydrodynamic circulation model in the Gulf of Cádiz (modified by MELIÈRES, 1974: 1.- Flow-out Mediterranean (FMW); 2.- North Atlantic surface water (NASW); 3.- Areas where the Undercurrent (FMW) touches the sea floor; 4.- Currents speeds (cm/s); 5.- Litoral currents; 6.- Continental shelf limit (= 200 m).

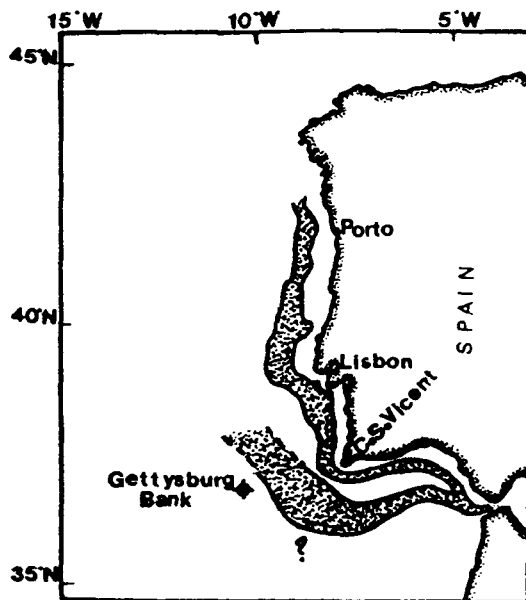


FIG. 9.- Mediterranean outflow in the Gulf of Cádiz (ZENK and ARMI, 1990).

TRANSPORTED FLOW

The attempts to calculate the outgoing Mediterranean flow have been numerous in recent years; ZENK (1975) considers an initial flow in the Gibraltar Strait of 0.95 Sv (1 Sv = $1 \times 10^6 \text{ m}^3/\text{sec.}$), with a salinity of 38.42 ‰ which is mixed with NACW, with a salinity of 35.6‰ along its course, increasing the latter, appraising a flow of 2.92 Sv in the canyons area.

GRUNDLINGH (1981) states a separation of the different types of water between the canyons and Cape San Vicente : the central branch would transport 2.0 Sv of the AMS type and the deepest branch, 2.3 Sv of AMI type, and represents the entrance in the canyons of 0.5 NACW units in the central current stream, and 0.9 NACW and NADW units, with a total flow of 4.3 Sv.

BUBNOV (1967) shows values of 3.9 to 4.1 Sv in the zone of Cape San Vicente, while AMBAR and HOWE (1979), from geostrophic calculations, give a value of 1.51 Sv for the outgoing water from the Strait. On the other hand, DENFANT (1961) obtains 0.66 to 1.38 Sv and LACOMBE (1971), 1.60 Sv.

More recent calculations of OCHOA and BRAY (1990) propose values of 0.7 Sv for the pure Mediterranean water in the Gulf of Cádiz and give values of 4.9 and 3.8 Sv to the influence of the seasonal changes in the flow, for the spring and autumn respectively, after being mixed at 8°W. The variability of the flow is evident, presenting two different types of oscillations : one regular, resulting from tides, which represent 10% of the total flow, and the other, sporadic, lasting only a few days, the origin of which is unknown.

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