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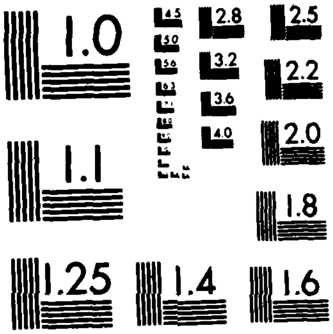
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upper 200 m and has a typical width of [illegible] km. [illegible] horizontal temperature gradients ([illegible] °C per km) are found in summer and fall when the net change across the front is [illegible] °C, salinity undergoes a corresponding [illegible] change. Strongest gradients of surface layer depth and sound channel depth occur in winter when both parameters change [illegible] across the front. The anticyclonic gyre of warm water in the western Alboran Sea has a diameter of 75 to 100 km and appears to be permanent. When cool water upwelled along the southern coast of Spain is entrained into the gyre, the main features of the Alboran Sea circulation are enhanced and can be clearly seen in satellite infrared images.

RECENT OBSERVATIONS OF THE ALBORAN SEA FRONT

by

Robert E. Cheney

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NAVOCEANO Technical Note 3700-73-77

September 1977

ABSTRACT

Four sets of observations were obtained in the western Mediterranean Sea during the period November 1976 to April 1977 in order to study the structure and seasonal variability of the Alboran Sea Front. The data were gathered from USNS KANE and consist of 217 XBT's (expendable bathythermographs) and 28 SV/STD (sound velocity-salinity-temperature-depth) stations. These data, together with previous observations in spring and summer, indicate that the Alboran Sea Front is a persistent feature throughout the year. It meanders from Gibraltar eastward through the basin, establishing a series of alternating anticyclonic and cyclonic gyres. The front is confined to the upper 200 m and has a typical width of 50 km. Strongest horizontal temperature gradients (0.1°C per km) are found in summer and fall when the net change across the front is 5-7°C; salinity undergoes a corresponding 2°/oo change. Strongest gradients of sonic layer depth and sound channel depth occur in winter when both parameters change 200 m across the front. The anticyclonic gyre of warm water in the western Alboran Sea has a diameter of 75 to 100 km and appears to be permanent. When cool water upwelled along the southern coast of Spain is entrained into the gyre, the main features of the Alboran Sea circulation are enhanced and can be clearly seen in satellite infrared images.

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I. INTRODUCTION

One of the most intense oceanic fronts in the Mediterranean occurs just inside the Strait of Gibraltar in the Alboran Sea. It is created by the swift "jet" of Atlantic water which flows through the Strait and meanders eastward through the Alboran basin. Figure 1 illustrates the direction and magnitude of surface currents in the Alboran Sea as revealed by a detailed hydrographic survey in summer 1962 (Lanoix, 1974). The western basin of the Alboran Sea, between Gibraltar and Alboran Island at 3°W, is dominated by a vast anticyclonic gyre with a diameter of 100 km. Surface current speed reaches 90 cm s^{-1} on the north side of the gyre and 60 cm s^{-1} on the south. The jet of Atlantic water flows around the northern half of the gyre and then continues eastward along the Algerian coast. Between 1°W and 2°W the current gains cyclonic curvature and veers northward. Speed of the inflowing Atlantic water diminishes downstream as the current becomes broader; surface current speed is 50 cm s^{-1} at 3°W, 35 cm s^{-1} at 1.5°W, and 25 cm s^{-1} at 1°W.

The Alboran Sea is thus divided into two regions with different surface circulation patterns: the western basin with its intense anticyclonic gyre, and the broader cyclonic flow in the eastern basin. This pattern is representative only of the upper 200 m; below this depth Mediterranean intermediate and deep water drifts westward toward the Strait of Gibraltar where it empties into the Atlantic.

Although Ovchinnikov *et al*. (1976) believe that the circulation in figure 1 is anomalous and not representative of the normal pattern of flow in the Alboran, there is ample evidence indicating that similar conditions persist throughout the year. Studies by Donguy (1962), Grousson and Faroux (1963), Lacombe *et al*. (1964), Mommsen (1976), Eubanks *et al*. (1977), and Cheney (1977) all lend support to the permanence of the anticyclonic gyre in the western basin.

The Alboran Sea Front coincides with the axis of maximum current speed and separates waters of different physical and acoustical characteristics. To the left of the current, looking downstream, water is cooler and more saline than on the opposite side. Depending on season, the horizontal temperature difference across the front may be as large as 7°C and salinity on opposite sides may differ by 2°/oo. In addition, sonic layer depth (SLD) and sound channel depth (SCD) are generally 100-200 m shallower on the left side of the current than on the right. These changes take place across a typical frontal width of about 50 km.

Physical reasons for the existence of the Alboran Sea Front can be explained simply. The Mediterranean, or more specifically the Alboran Sea, may be thought of as a two-layer body of water. The upper 150 m is composed of North Atlantic water which is relatively warm and fresh; actual values of temperature and salinity of this layer vary with season, but typical summer values are 20°C and 36.4°/oo. Below 200 m is a mixture of Mediterranean intermediate and deep water; this water mass is nearly homogeneous and has temperature and salinity values of 13.1°C and 38.4°/oo. Waters of the deep Mediterranean are thus significantly cooler and saltier than the overlying Atlantic water.

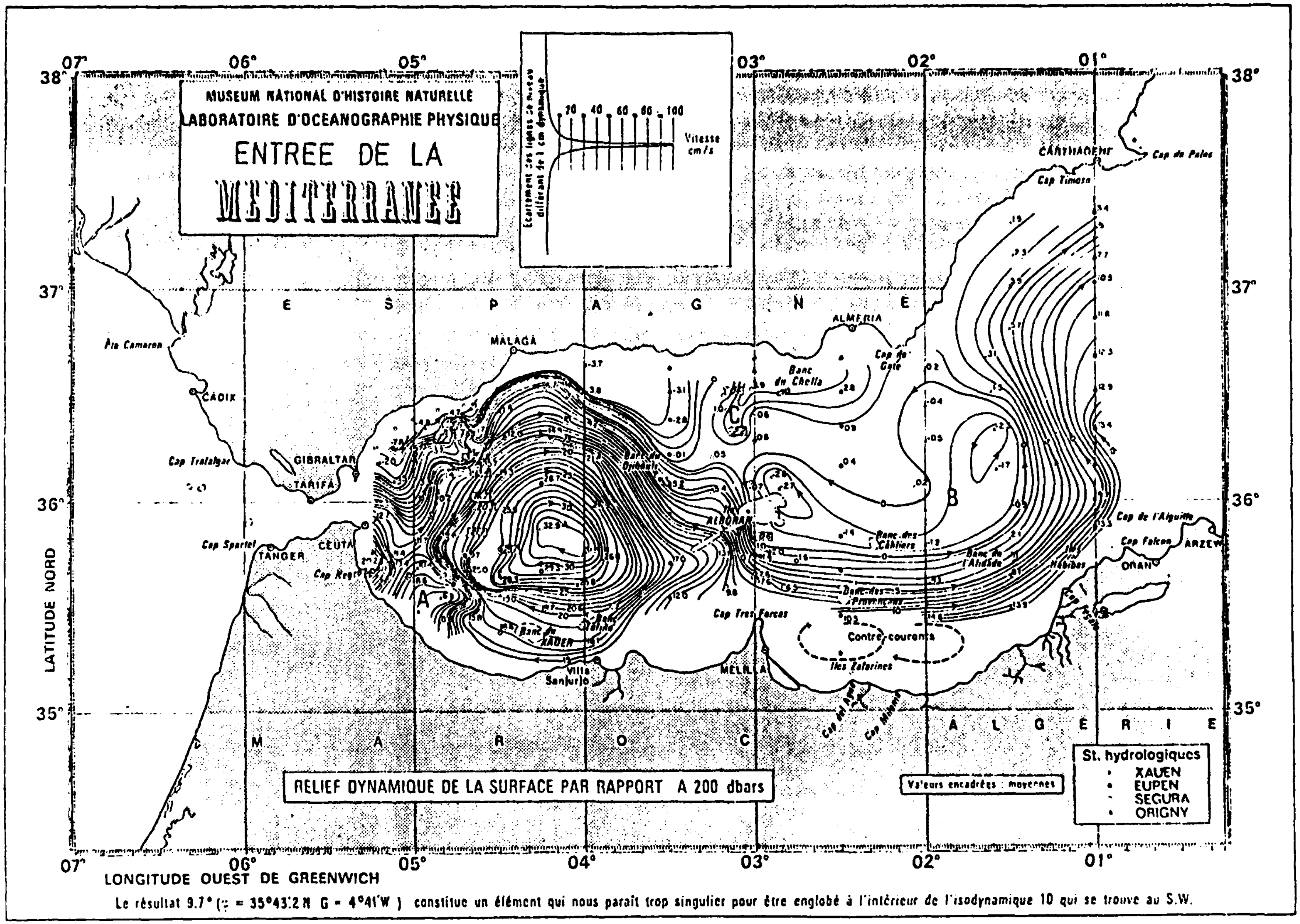

FIG. 25

Fig. 1 - Surface circulation in the Alboran Sea during 1962 survey.
More closely spaced streamlines indicate swifter currents; arrows indicate direction of flow.

The boundary between these layers, known as the thermocline, has a thickness of about 50 m and is a region of large vertical gradient. SLD coincides with the top of the thermocline while the sound channel axis occurs along the lower edge. Across a swift current such as the incoming Atlantic water, the thermocline is not horizontal, but tilted. Facing downstream, the thermocline slopes downward to the right. The result is a narrow region of relatively large horizontal gradient of temperature, salinity, sound velocity, SLD, and SCD.

II. DATA COLLECTION

A ship-of-opportunity program was initiated in 1976 to gather data from oceanic frontal regions around the world. Scientists aboard NAVOCEANO ships either transiting through or doing work in frontal zones were requested to take XBT's or SV/STD's, as time allowed, to define the structure of known fronts and explore regions of suspected frontal activity.

Four data sets obtained in the Alboran Sea during 1976-77 are the subject of this report. Observations are listed in Table 1. The first three sets of observations, which occur in fall and winter, have data well distributed throughout the basin and allow three-dimensional analysis of the frontal region; one of these also includes SV/STD stations. The fourth data set is in spring and consists of a single line of XBT's from 0°W to Gibraltar. These observations are discussed separately in the following sections.

Table 1
Observations in the Alboran Sea

Date	Vessel/Cruise	Data
1-4 Nov 1976	KANE 343706	76 XBT's
19-26 Jan 1977	KANE 343714	52 XBT's; 28 SV/STD
3-9 Mar 1977	KANE 343715	62 XBT's
24-27 Apr 1977	KANE 343726	27 XBT's

III. RESULTS

(a) 1-4 November 1976

Of the surveys presented here, the November data are the most evenly distributed, providing a complete description of the Alboran Sea Front between Gibraltar and 0°W. As noted previously, the front is confined approximately to the upper 200 m; below this depth both horizontal and vertical gradients of temperature and salinity are small. Although T-7 XBT's (760 m depth) were used for all of these surveys, information on the front was essentially contained in the upper third of each trace. Isotherms at the surface and at 100 m during 1-4 November are shown in figure 2. Both temperature maps show a region of large horizontal gradient meandering through the basin; the axis of the front corresponds approximately to the 17°C isotherm at the surface and the 15°C isotherm at 100 m. Average horizontal gradient at both levels is 0.1°C per km and the total difference in temperature across the front is 4-5°C. Colder temperatures are found north of the front, indicating that the current flows toward the east, as expected. Just inside the Strait between 4°W and 5°W is the anticyclonic gyre which was so prominent in the 1962 data (figure 1). Continuing eastward, alternating cyclonic (cold) and anticyclonic (warm) gyres are found on opposite sides of the front as the current meanders downstream. The front appears to be quite coherent from Gibraltar to 1°W but then begins to break down. A large (75 km) eddy-like feature appears between 1°W and 0°.

Sonic layer depth (SLD) and sound channel depth (SCD) are shown in figure 3; values were determined by assuming a positive salinity gradient of 1.5 °/°° per 100 m across the main thermocline (constant salinity otherwise) and converting temperature traces to sound velocity profiles. Because of the well-developed mixed layer and strong thermocline that existed at the time of the November survey, errors introduced in the calculation of SLD and SCD by inexact knowledge of the salinity field are considered to be small (less than 5 m for SLD, 10 m for SCD). Both SLD and SCD display patterns consistent with the thermal field; smaller values are found on the north side of the front than on the south. Axis of the front coincides with the 40 m SLD contour and the 175 m SCD contour. SLD reaches a minimum of 0 m north of the front and is a maximum of 80 m inside the two anticyclonic gyres. SCD varies from 100 m to 250 m on opposite sides of the front with the alternating system of the gyres again clearly evident.

The temperature section in figure 4 is across the front at 4°W. On the south side near the center of the anticyclonic gyre, the thermocline, approximated by 15°C, is nearly 200 m deep while on the opposite side of the front it approaches the surface. SLD and SCD exhibit corresponding changes in depth. At the 100 m level strong horizontal gradients therefore exist. Below 200 m the water is virtually isothermal.

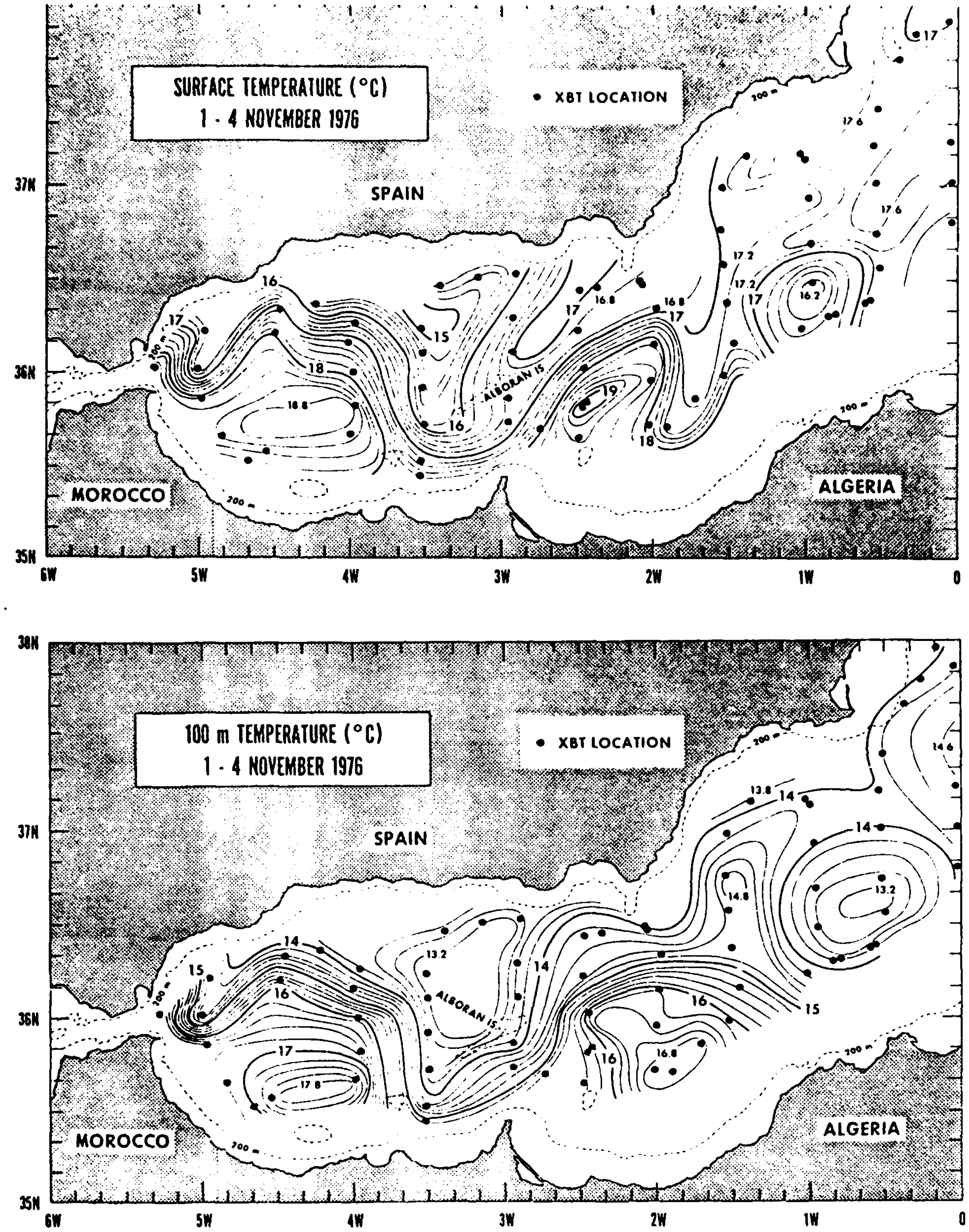

Fig. 2 - Maps of temperature at (a) the surface and (b) 100 m during Novembe The Alboran Sea Front corresponds to the 17°C and 15°C isotherms, respectively. Warmer temperatures are found south of the front. The meandering front creates a series of alternating anticyclonic (warm) and cyclonic (cold) cells.

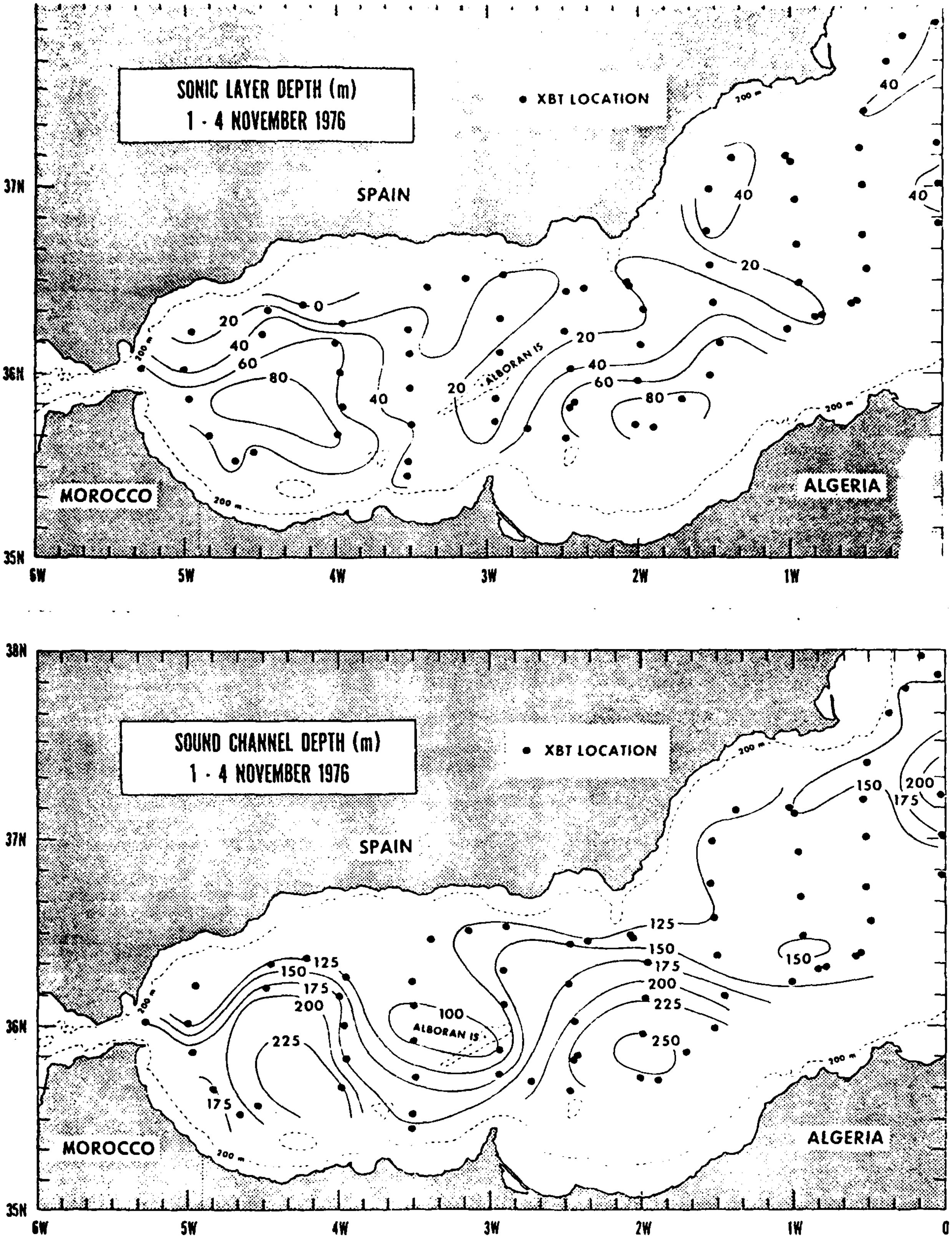

Fig. 3 - Depth contours of (a) SLD and (b) SCD during November. The Alboran Sea Front corresponds to the 40 m and 175 m contours, respectively. In both cases larger (deeper) values are found south of the front.

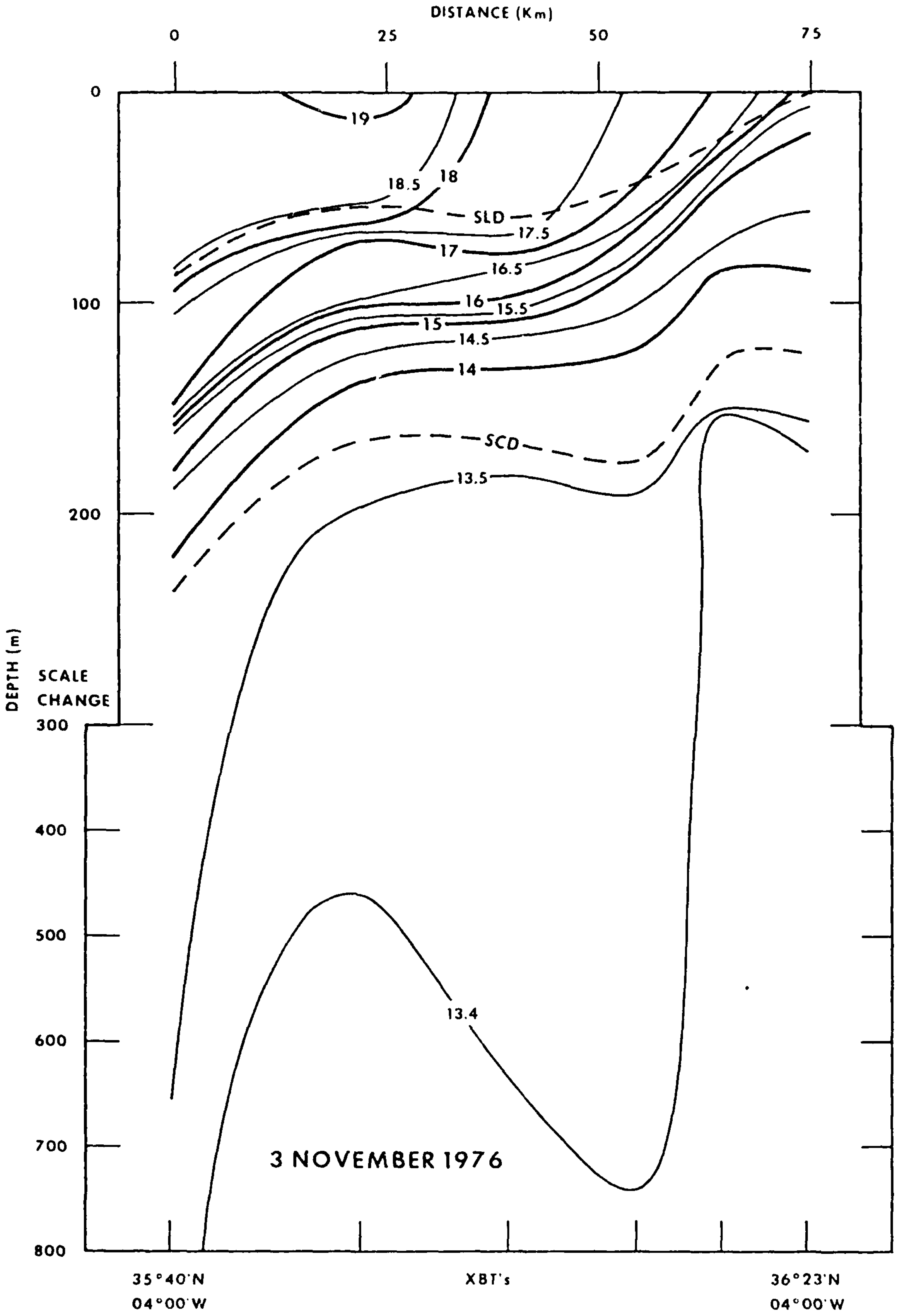

Fig. 4 – Temperature section along 4°W during November. The front is indicated by the sloping thermocline. SLD and SCD undergo corresponding changes in depth. Below 200 m the water is nearly isothermal.

(b) 19-26 January 1977

The series of January observations is especially valuable because of the inclusion of 28 SV/STD stations among the XBT's. As will be shown, this permits a more accurate determination of the sound velocity field, provides better information on the varying thickness of the Atlantic layer, and allows calculation of direction and magnitude of the prevailing current. Temperatures at the surface and 100 m (figure 5) show that thermal gradients are of approximately the same magnitude as in November (0.1°C per km), but the difference in temperature across the front is now only 1-2°C, less than half that of November. The axis of the front follows the 15°C isotherm at the surface and 14°C at 100 m. Although there are few observations west of 4°W, the data suggest that the main anticyclonic gyre is still present. The principle feature revealed by this survey, however, is a broad cyclonic gyre around Alboran Island at 3°W, corresponding to that found in the November survey.

Winter conditions in the Mediterranean are characterized by a weak thermocline with temperatures in the upper layer of Atlantic water only 1-2°C warmer than the underlying Mediterranean intermediate water. In a situation such as this, accurate determination of SLD and SCD from XBT's alone is difficult. SLD and SCD distributions in figure 6 were therefore constructed using only measured sound velocity profiles obtained from SV/STD stations. Values can be seen to correlate well with the temperature fields. Axis of the front coincides approximately with the 120 m SLD contour and the 175 m SCD contour. SLD and SCD reach minimum values of 40 m and 125 m, respectively, inside the cyclonic gyre at 3°W while values of 160 m and 250 m are attained outside on the opposite side of the Alboran Sea Front. The anticyclonic gyre inside the Strait is again suggested but not defined.

Warmer temperatures and large SLD and SCD values in the northeast corner of the survey area indicate that the front bends around to the north at this point. These and other features of the Alboran Sea Front are confirmed by calculated surface currents shown in figure 7(a). Contours in this illustration are of dynamic height anomaly (cm) relative to 200 m. Direction of flow is as shown and current speed is proportional to the horizontal gradient of dynamic height; as indicated by the scale at right, tighter contours represent a swifter current. Figure 7(a) shows the jet of Atlantic water flowing eastward through the Strait at a speed of 50 cm s^{-1} (approximately 1 knot). As the current turns abruptly to the south it broadens and slows to 25 cm s^{-1}. It then flows eastward between Alboran Island and the coast of Africa and finally turns northward to establish a cyclonic cell around the Island. The main body of the current ultimately continues eastward through the Alboran basin.

Throughout the year a strong halocline separates the relatively fresh (36.4%) Atlantic water from the salty (38.4%) Mediterranean water underneath. Figure 7(b) shows contours (m) of the 37.5% surface, indicative of the depth of the boundary between the two water types. As expected, the halocline is deep (120 m) south of the front and rises to 60 m or less on the north side. At the center of the cyclonic gyre it reaches a minimum value of 20 m.

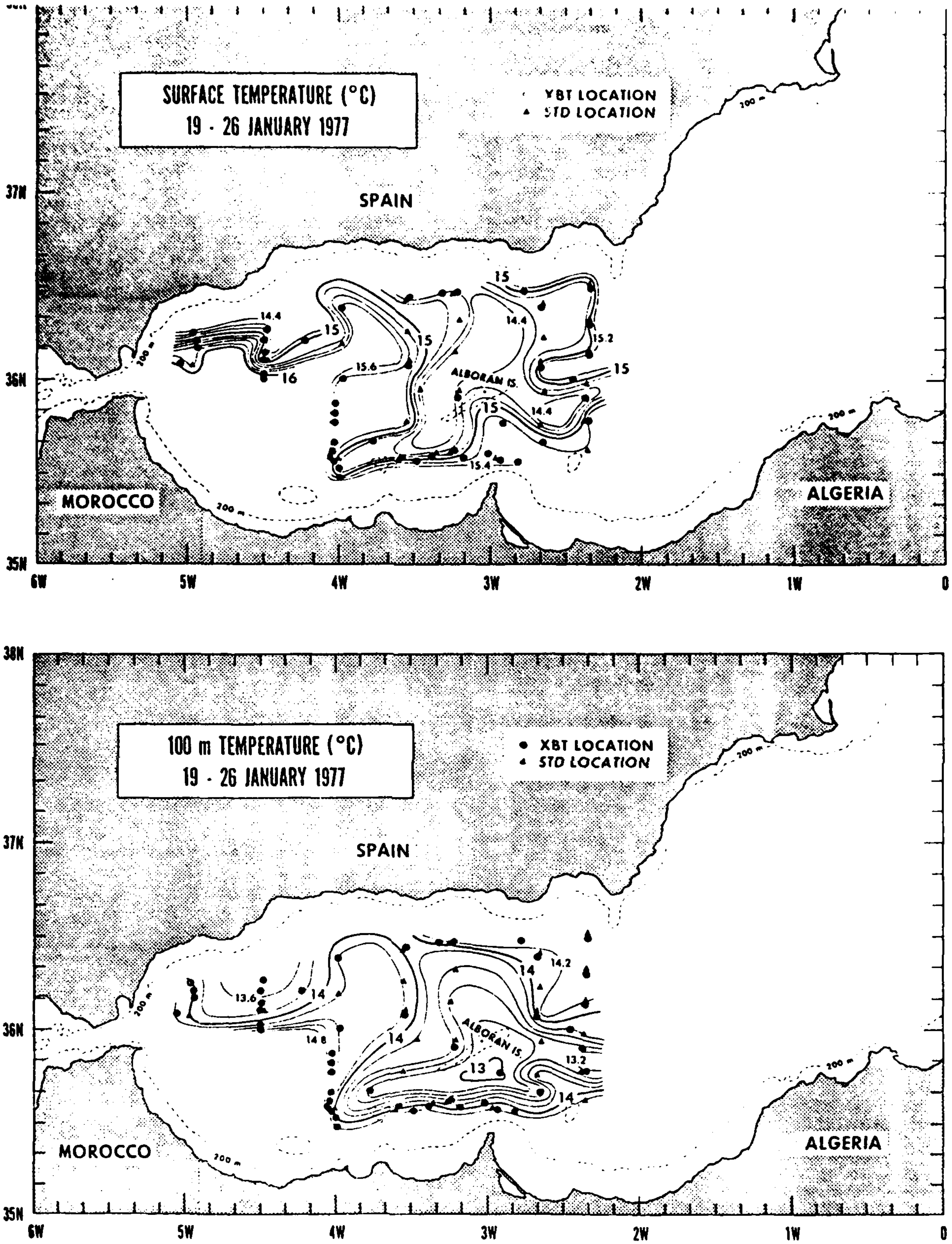

Fig. 5 - Maps of temperature at (a) the surface and (b) 100 m during January. The Alboran Sea Front corresponds to the 15°C and 14°C isotherms, respectively. The primary feature revealed by the survey is the cyclonic (cold) gyre around Alboran Island.

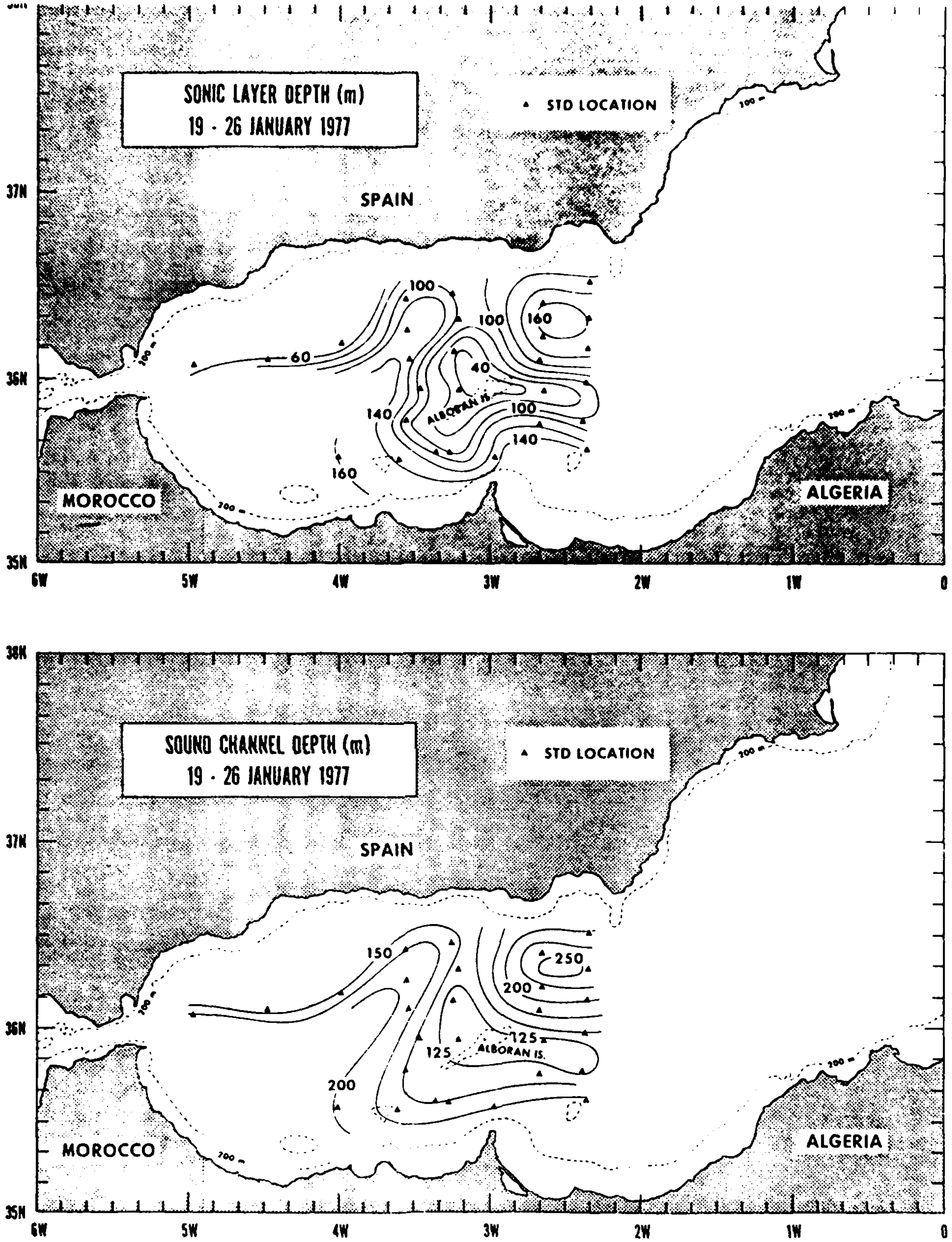

Fig. 6 - Depth contours of (a) SLD and (b) SCD during January. The Alboran Sea Front corresponds to the 120 m and 175 m contours, respectively. Smaller (shallower) values are found at the center of the cyclonic cell around Alboran Island.

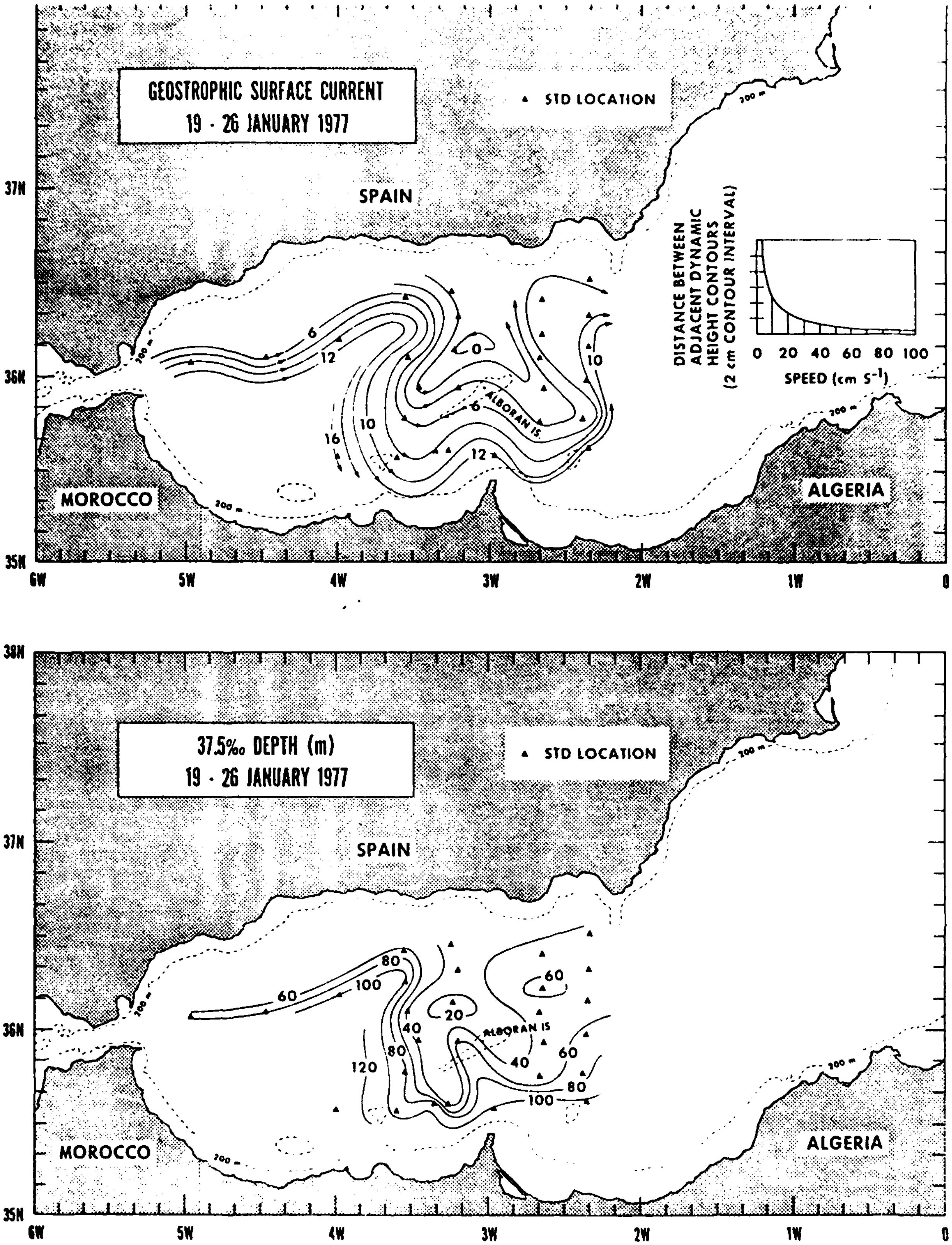

Fig. 7 (a) Streamlines of surface current during January. Current speed is proportional to streamline separation as shown by scale at right.

(b) Depth of the Atlantic/Mediterranean interface as indicated by the 37.5°/°° isohaline surface.

(c) 3-9 March 1977

In late winter 1977, XBT's were obtained in two separate regions of the Alboran Sea, as shown by surface and 100 m temperature maps in figure 8. In the western area the anticyclonic gyre of warm water is clearly evident at 100 m. Temperature difference across the front at this depth is 2°C and the horizontal gradient is about 0.05°C per km. Axis of the Atlantic current in this figure coincides approximately with the 14°C isotherm. At the surface, however, a different pattern emerges. Instead of a continuous temperature gradient across the front, the frontal zone corresponds to a surface temperature maximum. The Atlantic jet apparently advects warmer near-surface water into the cooler surface layers of the Mediterranean, producing a thin stream warmer than water on either side. This feature is found only in the upper 10-20 m of the western basin and probably exists only in later winter. A somewhat analagous feature is the Gulf Stream's "warm core" which is created by the transport of subtropical water into more northerly latitudes. In the eastern area the front is weaker but is still evident at both the surface and 100 m levels.

Strong horizontal gradients of SLD and SCD are found across the edge of the western anticyclonic gyre (figure 9). SLD varies from zero outside the gyre to 180 m at the center and at the boundary changes 100 m in a distance of only 15 km. SCD varies correspondingly from 50 m to 250 m. In the eastern area the front is not well defined by SLD but does exhibit a 100 m change in SCD.

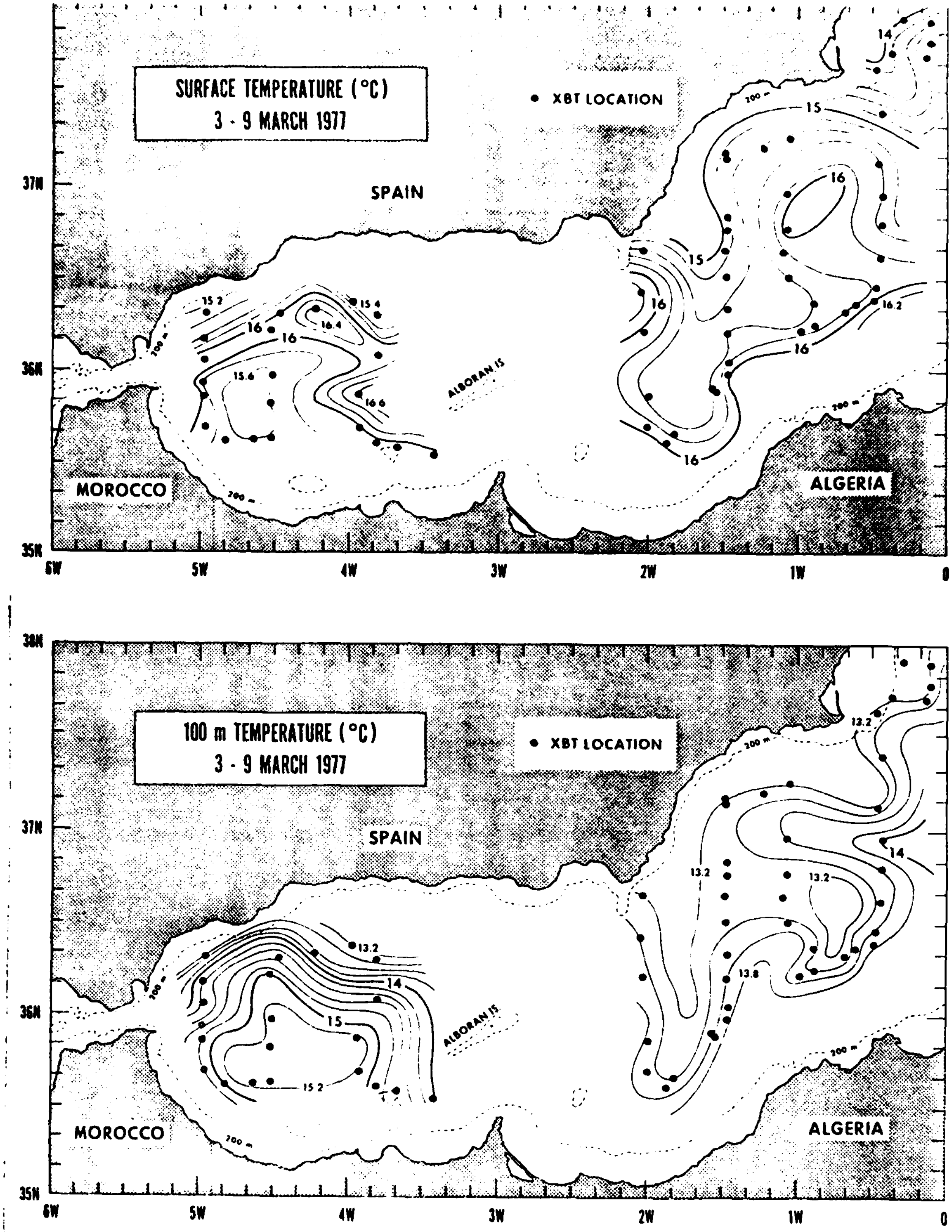

Fig. 8 - Maps of temperature at (a) the surface and (b) 100 m during March. In the western Alboran Sea incoming Atlantic water appears as a surface temperature maximum while at 100 m the front takes on its more common appearance.

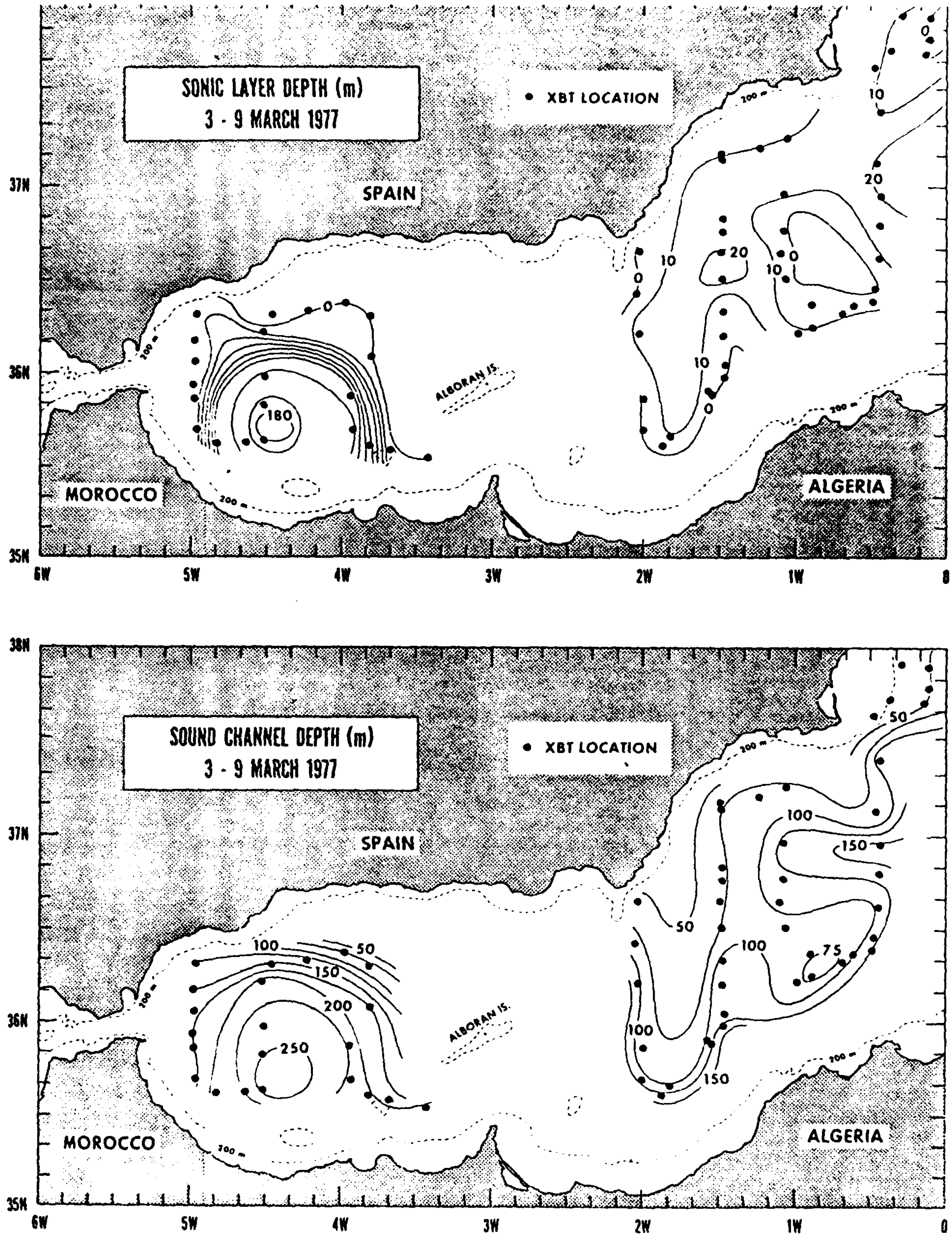

Fig. 9 - Depth contours of (a) SLD and (b) SCD during March. The anticyclonic gyre in the western Alboran Sea is clearly defined while the eastern area is characterized by much weaker horizontal gradients.

(d) 24-27 April 1977

The April temperature section is displayed in figure 10. It runs the length of the Alboran Sea approximately along the axis of the basin except for a northward excursion between 3°W and 4°W. Dashed lines indicate SLD and SCD. Surface heating in spring produces a thermocline which extends to the surface and creates a uniformly shallow SLD throughout the basin. SCD, however, exhibits alternating deep and shallow values along the sections with variations of about 100 m. There is a corresponding variation of about 2°C in 100 m temperature. Regions of deep SCD and warm 100 m temperature appear to coincide with typical locations of anticyclonic cells while areas of shallow SCD and cool 100 m temperature correspond with locations of cyclonic circulation (see figures 2, 5, and 8). While it is sometimes difficult to draw meaningful conclusions from single-line surveys of this type, the data are consistent with the existence of a series of alternating gyres such as those created by the meandering front observed in November, January, and March. Evidence provided by this section thus points to the existence of the Alboran Sea Front in April as well.

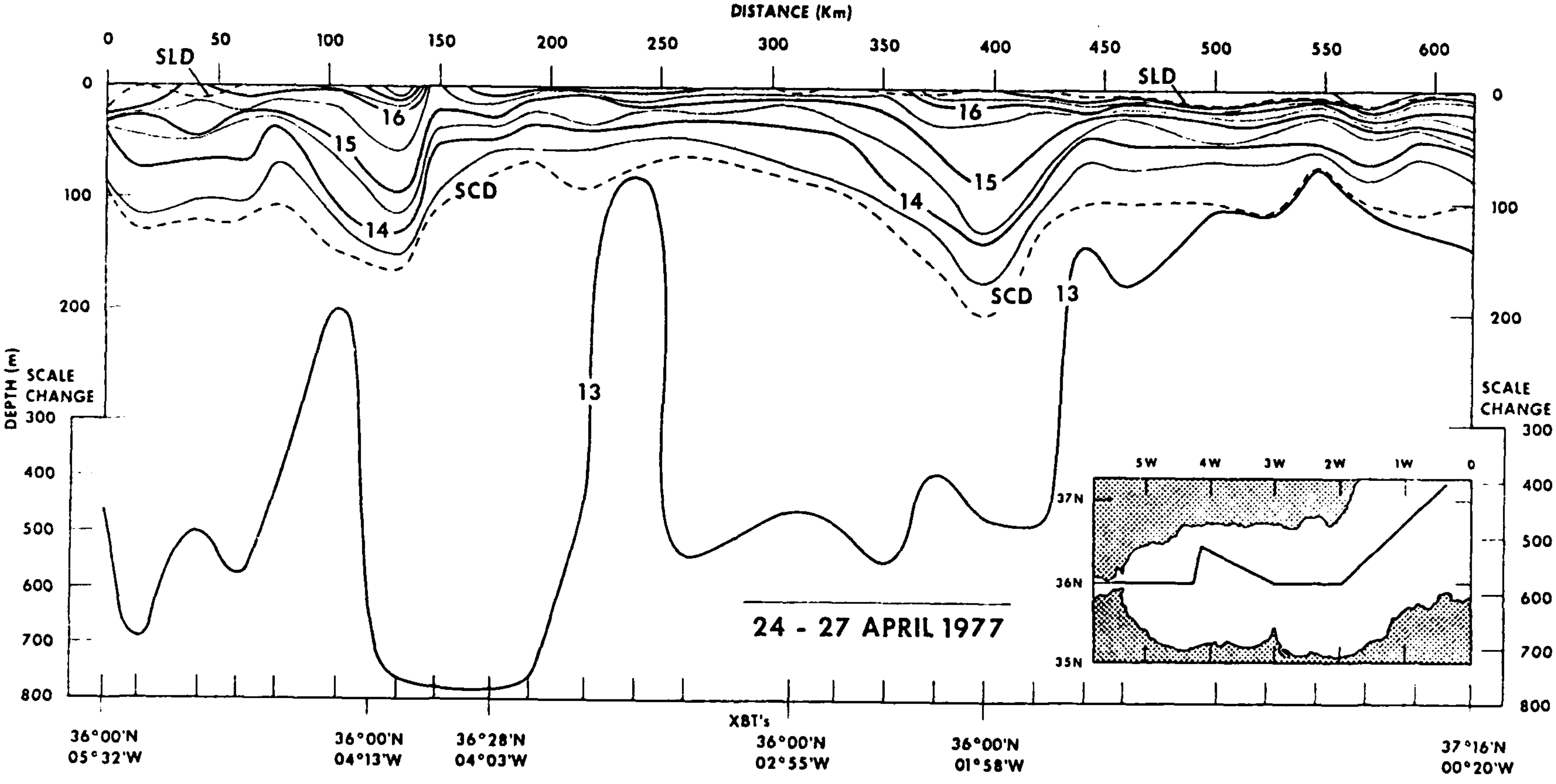

Fig. 10 - Temperature section through the Alboran Sea in April. SLD and SCD are indicated by dashed lines. Because of surface heating, SLD is shallow throughout. The section indicates alternating regions of deep and shallow SCD, with differences on the order of 100 m.

IV. SATELLITE INFRARED DATA

During certain periods, the Alboran Sea Front can be clearly seen in satellite infrared imagery. The example shown in figure 11 is from the NOAA-5 satellite and was received and enhanced by the Centre de Météorologie Spatiale in Lannion, France. It shows a stream of relatively cool surface water (indicated by lighter grey shades) being entrained around the northern and eastern edges of the main anticyclonic gyre. Warmer water is found inside the gyre. Circulation in the eastern Alboran Sea is not as well defined.

The cool water which creates this striking surface temperature effect and permits the front to be seen is due to upwelling along the southern coast of Spain. Lanoix (1974) attributes this upwelling to physical processes within the anticyclonic gyre. As Atlantic water circulates around the gyre it converges toward the center, creating downwelling. To conserve mass, upwelling must occur outside the gyre, and the principle upwelling region is near the Spanish coast. Once sufficient oceanographic data are obtained to adequately describe seasonal fluctuations of the Alboran Sea Front, real-time frontal locations obtained by satellite can be related to physical and acoustical properties to develop simple prediction models.

Fig. 11 - NOAA-5 infrared image of the Alboran Sea Front. Cold water (lighter shades) upwelled along southern Spain is entrained into the anticyclonic gyre, allowing the circulation pattern to be seen. This image was received and enhanced by the Centre de Meteorologie Spatiale in Lannion, France, 17 August 1977.

V. SUMMARY

Observations in January, March, April and November indicate that the Alboran Sea Front is a persistent feature throughout the year. It meanders from Gibraltar eastward through the basin, establishing a series of alternating anticyclonic and cyclonic gyres. The front is confined to the upper 200 m and has a typical width of 50 km. On the south side of the front are found warmer temperatures, lower salinities, and deeper values of SLD and SCD compared to the north side.

Physical characteristics of the Alboran Sea Front vary with season, as shown in Table 2. Included in the table are observations in May 1976 (Cheney, 1977) and July/August 1962 (Lanoix, 1974). Values in this table represent the net difference existing across the frontal zone. Although the largest horizontal temperature differences occur in summer and fall, maximum SLD and SCD gradients are found in late winter. Limited salinity data suggest that a strong salinity gradient exists year-round. In all seasons, the largest differences are found in the western half of the Alboran Sea where horizontal temperature gradients across the front are approximately 0.1°C per km; further downstream the front weakens perceptibly.

The anticyclonic gyre of warm water in the western Alboran Sea appears to be permanent. It is created by the Atlantic water "jet" which flows to the northeast through the Strait of Gibraltar and then bends southward, establishing a clockwise circulation pattern. The gyre has a diameter of 75 to 100 km. Lanoix (1974) has shown that Atlantic water converges toward the center of the gyre, causing downwelling, and ultimately produces upwelling of cold water near the southern coast of Spain. This upwelled water can be seen clearly on satellite infrared imagery and, when it is entrained into the gyre, enhances the main features of the Alboran Sea circulation. Real-time frontal locations obtained by satellite, together with information on the front's seasonal variability, can be used to predict physical and acoustical conditions in the Alboran Sea.

Table 2
Seasonal variability of the Alboran Sea Front
Indicated values represent net change across the frontal zone

		ΔT_0 (°C)	ΔT_{100} (°C)	Δ SLD (m)	Δ SCD (m)	Δ S °/₀₀
WINTER	January	1.6	1.8	120	125	1.3
	March	1.2	2.0	180**	200**	-
SPRING	April*	2.0	1.8	20	140	-
	May	0.6	1.5	120	120	-
SUMMER	Jul/Aug	7.5**	3.6	-	-	2.0**
FALL	November	4.0	4.6**	80	150	-

* Values were obtained from a single-line survey from 0° longitude to Gibraltar and represent the variability along this section.

** Maximum value for this sample.

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