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Tritium in the western Mediterranean Sea during 1981 *Phycemed* cruise

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Abstract—We report on simultaneous hydrological and tritium data taken in the western Mediterranean Sea during April 1981 and which implement our knowledge of the spatial and temporal variability of the convection process occurring in the Northern Basin (Gulf of Lion, Ligurian Sea). The renewal time of the deep waters in the Medoc area is calculated to be 11 ± 2 years using a box-model assumption. An important local phenomenon of "cascading" off the Ebro River near the Spanish coast is noticeable by the use of tritium data. In the Sardinia Straits area tritium data indicate very active mixing between 100 and 500 m depth. The tritium subsurface maxima in Sardinia Straits suggest the influence of not only the Levantine Intermediate Water (LIW) but also an important shallower component. In waters deeper than 500 m, an active mixing occurs between the deep water and the LIW via an intermediate water mass from the Tyrrhenian Sea by "salt-fingering". Assuming a two end-member mixing, we determine the deep tritium content in the Sardinia Channel to be 1.8 TU. For comparison, the deep tritium content of the Northern Basin is equal to 1.3 TU.

Tritium data relative to the Alboran Sea show that a layer of high tritium content persists all along its path from Sardinia to Gibraltar on a density surface shallower than the intermediate water. The homogeneity of the deep tritium concentrations between 1200 m depth and the bottom corroborate the upward "pumping" and westward circulation of deep waters along the continental slope of the North African Shelf. From the data measured in the Sardinia Straits and in the Alboran Sea, an upper limit of the deep advection rate of the order of 0.5 cm s^{-1} is estimated.

1. INTRODUCTION

TRITIUM is an ideal tracer for water masses circulation studies. Large amounts of tritium entered the oceans after nuclear bomb testing in 1954, and larger inputs occurred between 1963 and 1965. The time distribution of tritium incorporation into surface water is relatively well documented (DREISIGACKER and ROETHER, 1978; ROETHER *et al.*, 1987).

The tritium source function and its half-life (12.43 years) already have provided information relative to the rates of water exchange through the Strait of Gibraltar (ROETHER and WEISS, 1975) and to the circulation of the Mediterranean Eastern Basin (ROETHER *et al.*, 1987). The present study is essentially based on measurements carried out on samples taken during the *Phycemed* cruise in the Western Basin in April 1981.

In Section 2, we briefly describe the experimental procedure and the field work. Section 3 describes the general hydrological features of the western Mediterranean Sea. In Section 4 we discuss how tritium data, combined with hydrological data, can define local processes and determine some time constants, relative to deep-water formation and circulation.

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2. METHODS AND FIELD WORK

At sea, water was sampled from Niskin bottles into 125 ml flasks, previously baked at 170°C in vacuum and then filled with argon. Particular caution was taken on shipboard as well as in the laboratory to avoid tritium contamination through water vapor exchange (WEISS *et al.*, 1976).

Tritium concentrations were determined using the helium-3 regrowth technique (JENKINS, 1981). Helium-3 formed by β-decay of tritium for a given storage time is measured by mass spectrometry. Forty ml of each sample were transferred using pre-baked syringes in a bulb made of Corning-1720 glass. The initial step was done in a glove-box under a nitrogen flow.

The seawater sample was degassed and sealed prior to storage in the Corning-1720 bulb at –20°C to limit helium diffusion through the glass. The degassing step as well as the measurements of helium by mass spectrometry have been described previously (JENKINS, 1981). The location of the different stations is shown in Fig. 1. Table 1 gives longitude, latitude and sampling date.

Tritium data are expressed in TU units, i.e. the number of tritium atoms relative to 10^{18} hydrogen atoms. A half-life time value of 12.43 years is used for tritium decay (MANN *et al.*, 1982; TAYLOR and ROETHER, 1982). TU values, calculated for the date of sample collection, are reported (Table 2) as TU81N units (i.e. the tritium ratio that the sample would have had on 1 January 1981). All TU81N data, regardless of time of collection, are thus directly comparable (ÖSTLUND, 1984).

The detection limit of our method at the time of these measurements was 0.1 TU. The reproducibility for 1 TU samples is around 0.1 TU. For higher tritium concentrations, the relative uncertainty is around 4%. More details about the analytical procedure and the analytical accuracy are given in JEAN-BAPTISTE *et al.* (1987). In this study we have used the hydrological data available after calibration of the continuous CTD casts (BNDO, Ifremer, Brest). The results are given with 0.005°C and 0.005‰ absolute accuracies, respectively, for temperature and salinity.

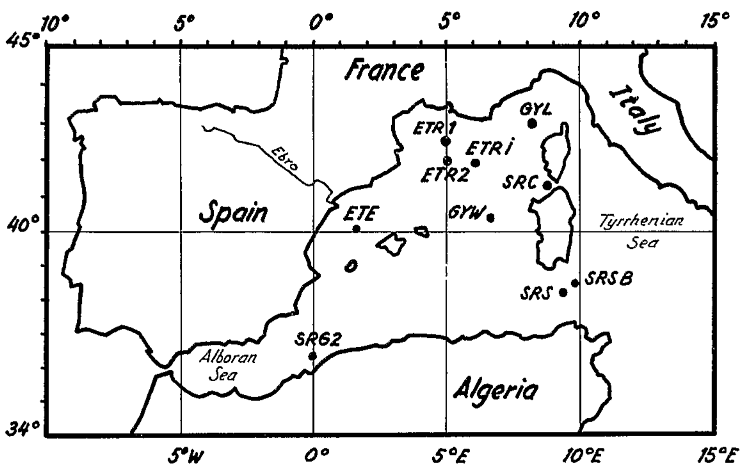


Fig. 1. Map of the *Phycemed* 1981 cruise (see the exact coordinates of the stations in Table 1).

Table 1. Postions and dates of stations sampling during the Phycemed 1981 *cruise*

Station	Position	Date (1981)
GYL	43°05′N–8°01′E	7 April
ETRI	42°00′N–5°59′E	9 April
ETR1	42°31′N–4°52′E	9 April
ETR2	42°02′N–5°05′E	10 April
ETE	40°06′N–1°42′E	12 April
SRG2	36°17′N–0°06′W	17 April
SRS	38°23′N–9°25′E	20 April
SRSB	38°36′N–9°51′E	21 April
GYW	40°37′N–7°11′E	22 April
SRC	41°23′N–8°37′E	24 April

Table 2. Tritium and hydrological data. TU units refer to the date of sampling. TU81N units refer to 1 January 1981

Station	Depth (m)	TU	TU81N	Salinity (‰)	Potential temperature (°C)	Sigma-θ
ETRI	21	8.85	9.0	38.032	13.514	28.651
	31	8.15	8.3	38.235	13.088	28.898
	74	5.8	5.9	38.413	12.897	29.075
	100	6.2	6.3	38.482	13.098	29.087
	148	5.1	5.2	38.498	13.105	29.098
	199	3.75	3.8	38.493	13.006	29.115
	226	4.0	4.1	38.495	13.010	29.117
	302	3.85	3.9	38.476	12.914	29.121
	345	3.15	3.2	38.472	12.889	29.123
	648	3.25	3.3	38.461	12.819	29.129
	752	2.55	2.6	38.468	12.849	29.128
	1189	2.45	2.5	38.462	12.812	29.131
	1997	1.3	1.3	38.452	12.775	29.131
ETR1	53	4.6	4.7	38.385	13.064	29.019
	100	4.6	4.7	38.436	12.825	29.108
	146	4.3	4.4	38.442	12.806	29.117
	196	4.6	4.7	38.432	12.766	29.117
	401	3.05	3.1	38.455	12.804	29.127
	500	3.2	3.3	38.457	12.796	29.130
	797	2.55	2.5	38.456	12.789	29.131
	999	2.85	2.9	38.456	12.782	29.133
	1194	2.65	2.7	38.456	12.780	29.133
	1589	2.6	2.65	38.453	12.769	29.133
	1684	2.75	2.8	38.454	12.764	29.135
ETR2	31	5.3	5.4	38.246	13.065	28.911
	40	6.1	6.2	38.289	12.956	28.967
	55	5.6	5.7	38.336	12.904	29.014
	74	5.8	5.9	38.429	12.861	29.095
	123	3.7	3.75	38.467	12.917	29.113
	178	2.35	2.4	38.466	12.886	29.119
	302	2.6	2.65	38.460	12.845	29.123
	598	1.95	2.0	38.457	12.819	29.126
	1990	2.35	2.4	38.449	12.736	29.137
ETE	32	5.8	5.9	37.301	15.313	27.692
	42	6.6	6.7	37.423	14.130	28.048
	52	6.6	6.7	37.495	13.751	28.185
	62	5.9	6.0	37.600	13.600	28.200
	77	7.1	7.2	37.743	13.449	28.441
	88	6.7	6.8	37.900	13.300	28.600
	125	7.0	7.1	38.175	13.219	28.824
	139	6.95	7.05	38.200	13.170	28.870
	176	7.55	7.7	38.280	13.139	28.922
	299	4.0	4.05	38.467	13.068	29.082
	348	4.4	4.45	38.479	13.035	29.098
	399	3.8	3.85	38.483	13.014	29.105
	449	3.45	3.5	38.489	13.012	29.110

Table 2. Continued

Station	Depth (m)	TU	TU81N	Salinity (‰)	Potential temperature (°C)	Sigma-θ
	498	3.4	3.45	38.485	12.999	29.111
	596	2.6	2.65	38.461	12.885	29.122
	645	2.8	2.85	38.461	12.847	29.123
	695	2.6	2.65	38.463	12.846	29.125
	796	2.1	2.15	38.457	12.818	29.126
	894	1.75	1.8	38.454	12.805	29.127
	993	2.05	2.1	38.446	12.769	29.128
	1192	2.6	2.65	38.446	12.740	29.134
	1485	3.55	3.6	38.423	12.618	29.141
	1618	3.61	3.65	38.420	12.605	29.141
SRG2	51	5.6	5.7	36.820	14.648	27.469
	76.5	5.0	5.1	37.045	14.357	27.707
	149	5.45	5.55	38.022	13.465	28.654
	197	6.5	6.6	38.233	13.141	28.886
	300	5.8	5.9	38.443	13.202	29.035
	398	4.1	4.15	38.530	13.316	29.079
	801	1.9	1.95	38.483	12.935	29.122
	1000	1.85	1.9	38.467	12.865	29.124
	1200	1.2	1.2	38.456	12.803	29.128
	1500	1.2	1.2	38.450	12.774	29.130
	1992	1.2	1.2	38.446	12.753	29.131
	2508	1.3	1.35	38.441	12.731	29.131
	2643	1.3	1.35	38.439	12.731	29.130
SRS	32	6.65	6.8	37.394	13.925	28.070
	51	6.4	6.55	37.708	13.491	28.405
	77	6.45	6.6	37.983	13.221	28.675
	101	6.9	7.0	38.135	13.069	28.824
	150	6.8	6.9	38.226	13.080	28.892
	200	6.35	6.45	38.361	13.187	28.975
	299	6.3	6.35	38.419	13.206	29.015
	499	5.4	5.5	38.652	13.704	29.090
	1200	2.85	2.9	38.520	13.043	29.128
	1589	2.45	2.5	38.527	13.043	29.133
	1792	2.75	2.8	38.527	13.039	29.134
SRC	10	17.8	18.2	38.002	14.789	28.350
	20	11.1	11.3	38.035	14.782	28.377
	31	7.43	7.55	38.259	14.796	28.547
	50	7.1	7.2	38.158	13.388	28.806
	101	6.7	6.8	38.331	13.110	28.968
	149	6.7	6.8	38.397	13.001	29.041
	298	5.1	5.2	38.482	13.026	29.102
	405	4.8	4.9	38.545	13.191	29.117
	602	4.3	4.35	38.518	13.038	29.119
	942	3.0	3.05	38.492	12.948	29.126
GYL	50	4.55	4.65	38.451	13.158	29.051
	78	3.9	3.95	38.481	13.117	29.082
	100	4.05	4.1	38.489	13.049	29.103
	149	3.9	3.95	38.504	13.060	29.112
	203	3.3	3.35	38.497	13.002	29.119
	293	2.4	2.45	38.477	12.899	29.125
	392	2.3	2.35	38.470	12.870	29.125
	625	2.65	2.7	38.472	12.851	29.131
	949	2.85	2.9	38.474	12.854	29.131
	1006	2.75	2.8	38.476	12.858	29.132
	1182	2.45	2.5	38.479	12.876	29.131
	1491	1.7	1.7	38.470	12.833	29.133
	1982	1.35	1.35	38.446	12.750	29.132
	2465	1.75	1.75	38.453	12.771	29.133

3. HYDROLOGICAL BACKGROUND

The Western Basin of the Mediterranean Sea is bounded to the west by the Strait of Gibraltar (~284 m still depth) and to the east by the Straits of Sicily (~330 m sill depth). The general characteristics of water circulation in this part of the Mediterranean Sea are relatively well documented (WÜST, 1961; LACOMBE et TCHERNIA, 1972; BETHOUX, 1977, 1979; BETHOUX et PRIEUR, 1983). The largest influxes of water are from the Atlantic Ocean in surface and from the Eastern Basin in subsurface. The largest outflow occurs westward at depth through the Strait of Gibraltar and eastward in the surface layer in the Straits of Sicily.

The origin of water masses which circulate in the western Mediterranean Sea can be easily inferred from potential temperature vs salinity (T–S) diagrams (Fig. 2). Plotted as references are the end members, the Levantine Intermediate Water (LIW) when it enters through the Sicily Straits and the western Deep Water (DW). From the surface to the bottom, we successively observe:

(a) The surface layer composed of low-salinity Atlantic waters flowing in a generally cyclonic circulation.

(b) The intermediate layer, between 200 and 500 m, formed in the Eastern Basin near Rhodes and characterized by a hook in the T–S curves at the level of the salinity maximum. This LIW flows westward through the Straits of Sicily and follows the general cyclonic circulation in the northern part of the Western Basin. Historical data give the hydrological characteristics of this water mass when it enters the Straits of Sicily (potential temperature $T = 14.00°C$; salinity $S = 38.75‰$; sigma-theta or potential density $\sigma_\theta = 29.09$ (CORTECCI *et al.*, 1979; NYFFELER *et al.*, 1980; BETHOUX et PRIEUR, 1983). We observe the decrease of the LIW imprint from the Sicily Straits (LIW dot) to the Sardinia Strait (SRS curve) and then to the Alboran Sea (SRG2 curve), or the northern area of the Gulf of Lion (ETRI curve). This imprint is noticeable everywhere in the basin.

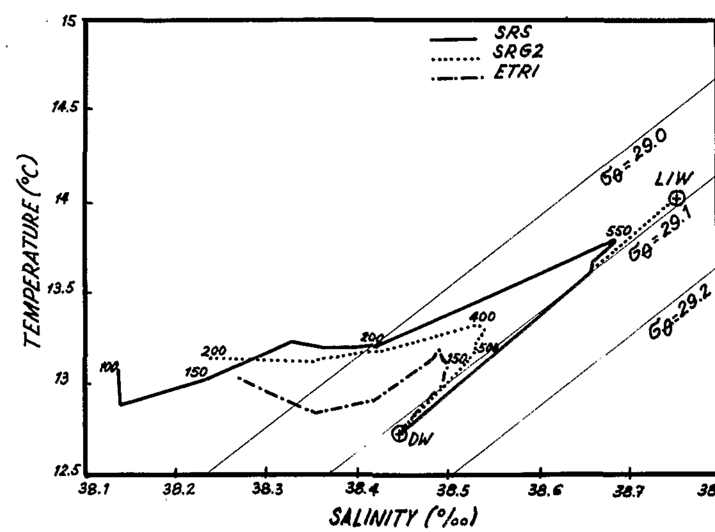


Fig. 2. T–S diagrams of the SRS, SRG2 and ETRI stations. (T–S curves are obtained using points every 50 m interval from 100 m to the bottom.)

(c) Below 600 m depth, a third water mass consists of a thick, colder and less saline layer with nearly constant hydrological characteristics. All the T–S curves converge at depth to the western DW characteristics. At the time of the cruise, they were, respectively, $T = 12.74°$, $S = 38.44‰$, $\sigma_\theta = 29.12$. This water mass is identified as the western DW. Its hydrological characteristics are similar to those recorded during the *Mediprod* IV cruise in November 1981 and the *Dyome* II cruise in March 1982 (LACOMBE *et al.*, 1985). For all the sampled stations, the deep water T–S characteristics are no more scattered than 0.04°C for temperature and 0.05‰ for salinity. Such a dispersion is well documented in LACOMBE *et al.* (1985) as a real variability of the bottom water characteristics. A scatter of the same order of magnitude is observed between *Phycemed* 1981 and historical data.

It is known that the deep water is formed in the northern area of the western basin (Gulf of Lion, Ligurian Sea) by convection of near-surface waters induced by strong cold winds (LACOMBE et TCHERNIA, 1972; GASCARD, 1978; BETHOUX et PRIEUR, 1983). The phenomenon can affect the whole water column.

Four stations from the Northern Sea (Gulf of Lion area, ETR stations; Ligurian Sea, GYL station) show how the use of tritium data can corroborate hydrological studies, thereby implementing our understanding of deep-water formation and the time-scale of the deep-water renewal (Section 4.1). We then examine how tritium data can reflect a peculiar deep-water formation process along the continental shelf off the Ebro River near the Spanish coast (ETE station) (Section 4.2). Finally, the discussion focus on water circulation in the Straits of the Alboran Sea (SRG2 station) and off the Sardinia Southern coast (SRS station) (Section 4.3).

4. RESULTS AND DISCUSSION

4.1. *Deep-water formation in the northern area of the Western Basin*

ETR stations (Medoc area of the Gulf of Lion). Figure 3 shows the deep T–S diagrams of the ETRI, ETR1 and ETR2 stations for depths below the intermediate level, sampled over a 48-h period. The T–S curve for ETRI reflects a typical hydrological structure in the absence of convection. Very similar structures have been observed in the Medoc area by other workers (e.g. LACOMBE et TCHERNIA, 1972; NYFFELER *et al.*, 1980) as well as in the T–S diagrams in the same area during the Phycemed cruise II in October 1983 (MAGENHAM et BRUN-COTTAN, 1986).

We assume that the tritium vs depth profile for the ETRI station (Fig. 4) represents the normal tritium distribution in the water column of the northern area. This assumption is supported by the shape of the profile measured in summer 1971 in the ETRI area (J. JOUZEL, personal communication) (Fig. 5). In addition, similar quasi-exponential profiles have been reported for the BORHA station (42°N, 4°45E) during six different cruises from December 1976 to April 1977 (ROETHER *et al.*, 1987).

The great variability of the deep tritium content between our three ETR stations (Fig. 4, Table 2) is due to the patchy and temporary character of deep convection observed in ETR1 and ETR2. After dilution, these processes do not affect the deep tritium concentration of the surrounding waters. So, we assume that the deep-water tritium concentration for ETRI (1.3 TU) represents the mean tritium concentration of the deep water in the Gulf of Lion.

We can evaluate the residence time of the deep waters in the northern western basin

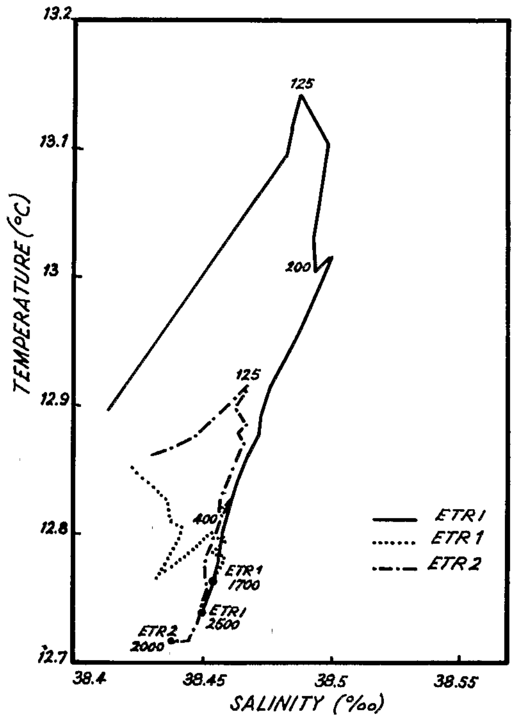


Fig. 3. T–S diagrams for the deep waters of the ETRI, ETR1 and ETR2 stations.

using the respective tritium data in the ETRI area during July 1971 and April 1981 (Fig. 5) and a box-model. In this calculation, we consider two boxes. The upper box from the surface to 450 m depth is located above the intermediate layer where horizontal motions are dominant. The second box extends from 450 m to the seafloor. The depth of the interface between the two reservoirs is chosen referring to the T–S profiles (see Fig. 2): we consider no horizontal advection of waters below this level. The tritium content at the top of the interface had the same value in 1971 and 1981 (3.3 TU). This was equally true in 1976 as observed by ROETHER *et al.* (1987). In the deep box, on the other hand, tritium content between 1971 and 1981 increased from 1.6 TU to 2.2 TU (Fig. 5).

We assume that the tritium content of the deep reservoir is governed by vertical advective diffusive processes.

We write the tritium balance for the deep reservoir using the approximations usually done in box models (SARMIENTO, 1986); the change of the mean tritium content Cp over 10 years results from the exchange flux at the upper limit of the box and the radioactive decay of tritium with time:

$$\Delta Cp = \frac{1}{\tau}\,(Cu - Cp)\,\Delta t - \lambda Cp \Delta t. \qquad (1)$$

A time step Δt equal to 1 year has been used in the calculation where λ is the decay constant for tritium equal to 0.055764 y^{-1}, τ is the renewal time of the deep reservoir, Cu

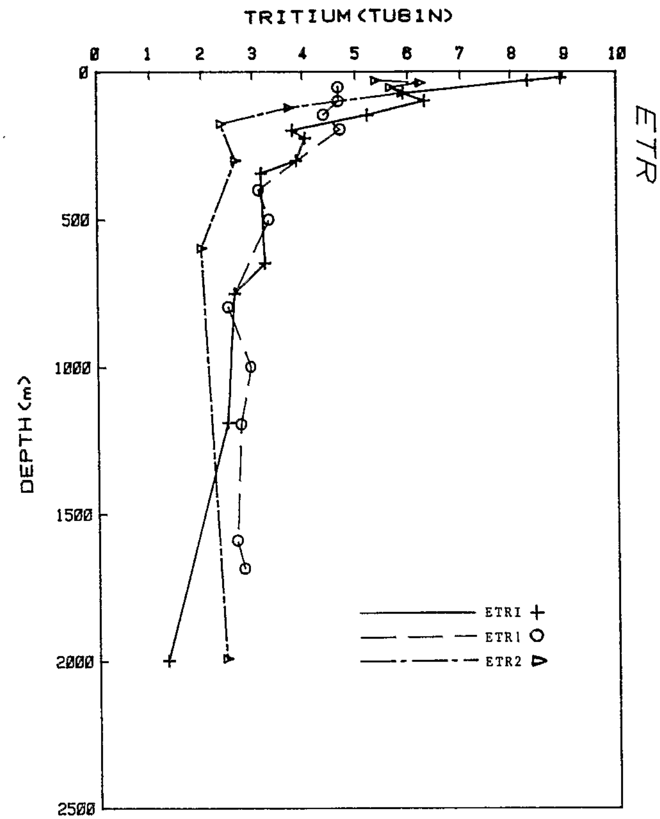


Fig. 4. Tritium (TU81N) vs depth profiles of Stas ETRI, ETR1, ETR2 in the Gulf of Lions.

is the tritium concentration at the interface (3.3 TU at the 450 m level), Cp is the mean tritium content of the deep reservoir, ($Cp_{1971} = 1.6 \pm 0.2$ TU, $Cp_{1981} = 2.2 \pm 0.1$ TU), ΔCp is the tritium content increase of the deep reservoir from 1971 to 1981 ($\Delta Cp = 0.6$ TU).

We compute a renewal time of the deep waters in the Gulf of Lion to equal 11 ± 2 years. This renewal time τ results in the vertical model assumption (equation 1) from the combination of one advective term and one diffusive term:

$$\frac{1}{\tau} = \frac{1}{H}\left(W + \frac{K}{H}\right),$$

where W is the mean vertical advection rate, K is the mean vertical diffusivity, and H is the height of the deep reservoir ($H = 1780$ m). Considering a vertical diffusivity K of the order of 10^{-4} m^2 s^{-1} (ROETHER *et al.*, 1987) it appears that advection is the dominant process in the deep-water renewal. From the renewal time of 11 ± 2 years, the mean advection rate is calculated to be 160 ± 25 m y^{-1}.

Our estimation of the renewal time appears consistent with the value reported by BETHOUX (1977) who calculated a mean residence time for the western deep basin of 16 years; this value was computed from water, salt and energy balances. Our estimate may

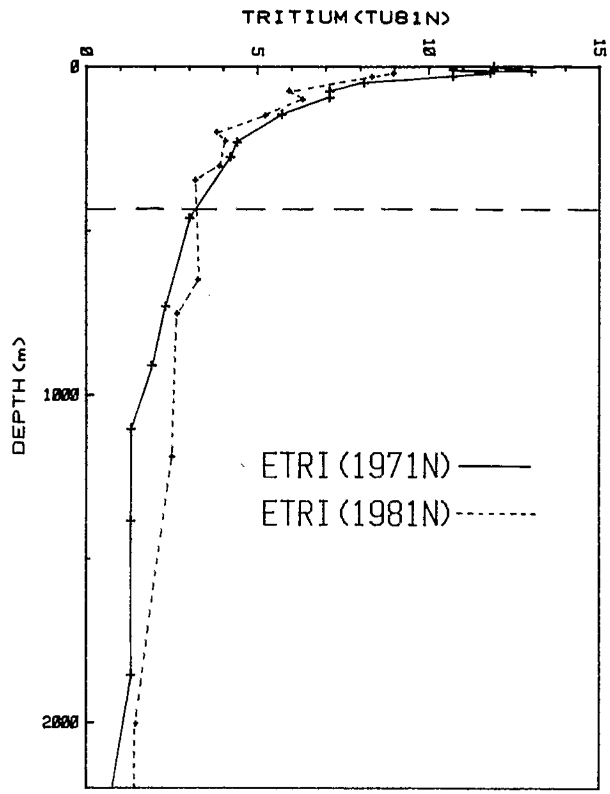


Fig. 5. Tritium vs depth profiles of the *Origny* cruise (1971N) and *Phycemed* cruise (1981N). The dashed horizontal line corresponds to the upper level of the deep reservoir used in our box-model.

be lower because the Gulf of Lion is the area in which advective processes are the most efficient.

Simultaneous tritium and helium-3 measurements in the western Mediterranean should be of great interest for a more precise calculation of the renewal time of the deep basin.

As shown in Figs 3 and 4, the ETR1 and ETR2 stations are very different from the ETRI station, the latter reflecting the usual hydrological situation in the Gulf of Lion. The imprint of the LIW decreases for the ETR2 station and is completely absent in the ETR1 station due to mixing (Fig. 3). In addition, the tritium vs depth profile (Fig. 4) for the ETR1 station indicates a very homogeneous tritium content throughout the water column. The deep tritium concentration (2.8 TU at the bottom) is the highest observed in the Medoc area and reflects a very newly formed water mass.

The deep water from ETR1 is warm (T = 12.764°C) and saline (S = 38.45‰), the result of local convection which downwells relatively warm and saline surface and subsurface waters to the bottom. This area, located near 42°N–5°E, has been described previously as being centered in a general cyclonic gyre (Lacombe et Tchernia, 1972). Evaporation and cooling due to the dry continental winds (particularly strong during the winter) are responsible for the convective mixing. GASCARD (1978) has described this convection process as resulting from baroclinic instability characterized by an upward motion of intermediate waters and a downward motion of dense waters associated with cyclonic and anticyclonic eddies, respectively. Two processes of very different scales are responsible for the mixing: an advective process associated to a slow downward motion of new homogeneous and dense water and an upward motion of intermediate water into the surface layer; a "convective process", or "violent mixing phase", when strong winds produce rapid downward motions ("chimneys") with velocities up to 10 cm s^{-1}.

The tritium vs depth profile of the ETR1 station (Fig. 4), as well as the T–S diagram (Fig. 3) and the relatively high surface salinity (38.365‰ to compare to 38.032‰ at 20 m depth in ETRI) seem to reflect such mixing processes. The newly formed water can sink from the surface to the bottom and then mix in all directions with "old" water masses previously identified as the western DW (T = 12.74°C, S = 38.44‰).

Density vs depth profiles in Fig. 6 indicate that convection has been more active in ETR1 than in ETR2 and ETRI, but the hydrological structure of the stations seems to return to a more stable situation.

The few data available in the depth range 600–2000 m at ETR2 suggest that the high deep tritium concentration (2.4 TU near the bottom) may be the result of the southward spreading of newly formed water in the ETR1 station. The sea-beam map of the Rhône

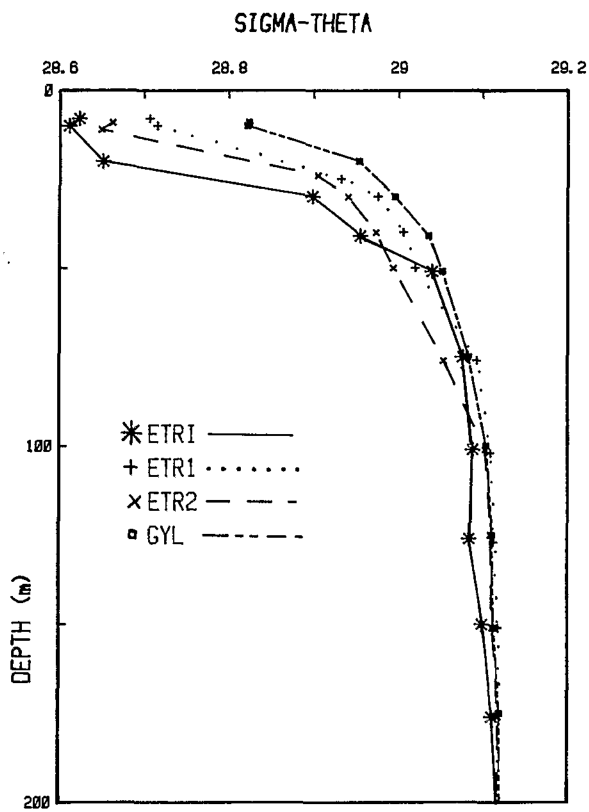


Fig. 6. Sigma-theta vs depth profiles of the northern stations ETR and GYL.

deep-sea fan (Bellaiche *et al.*, 1986) clearly shows that the bottom of the ETR2 station is located just 50 km downstream of the ETR1 station along the "Petit-Rhône canyon". The fresh and cool character of the ETR2 deep waters, suggest that the high deep tritium content in ETR2 can be due to local turbidity currents from ETR1 along the canyon. There is no indication if the differences in surface and subsurface concentrations of tritium at ETR1 and ETR2 are due to differences in the Rhône Estuary input, or to the variability in the uplifting of the intermediate water and mixing between 200 and 600 m water depth (Gascard, 1978; Roether *et al.*, 1987).

GYL area: (Ligurian Sea). The Ligurian Sea, about half way between the French Riviera and the Corsican coast, is described by a doming structure of temperature and density at the center of a cyclonic gyre (Lacombe et Tchernia, 1972; Bethoux *et al.*, 1982; Bethoux et Prieur, 1983). A tritium vs depth profile (Fig. 7a) shows a decrease from the surface to 400 m depth, below which concentration increases to a maximum of 2.9 TU at 1000 m depth. The deep tritium content decreases consistently over the next 1000 m depth range, with a somewhat higher value at the bottom (1.75 TU).

The more or less constant tritium content vs salinity between 400 and 1200 m (Fig. 7b) agrees with the heterogeneity of water mass hydrological characteristics between 400 and 1500 m (Fig. 7c).

The density vs depth profile (Fig. 6) indicates that convection has been efficient as well as for the ETR1 profile. In addition, we observe a high salinity in surface waters. The

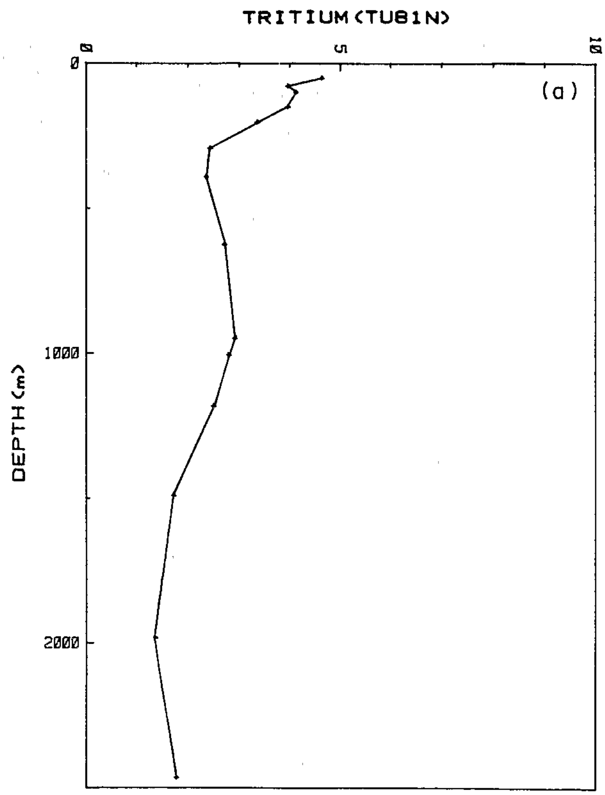
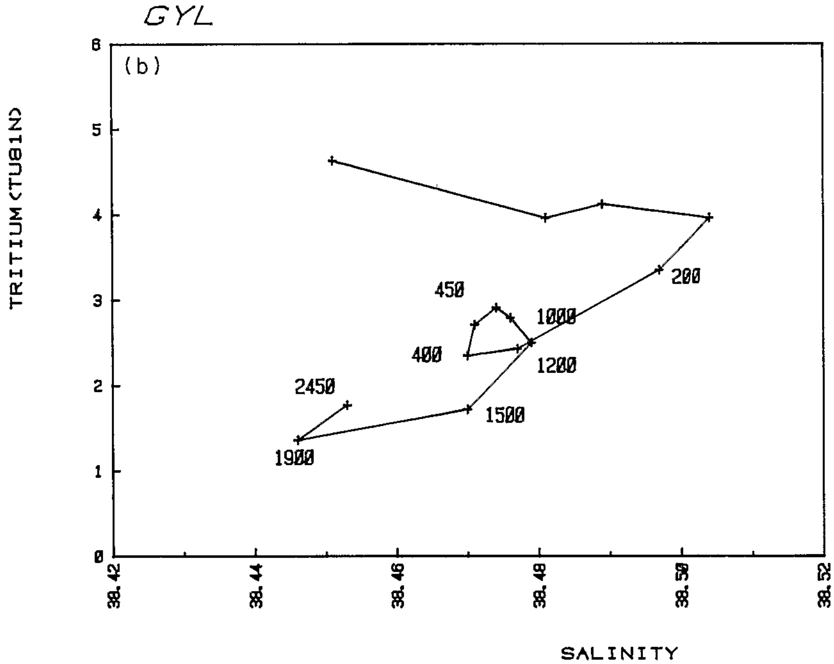


Fig. 7a.



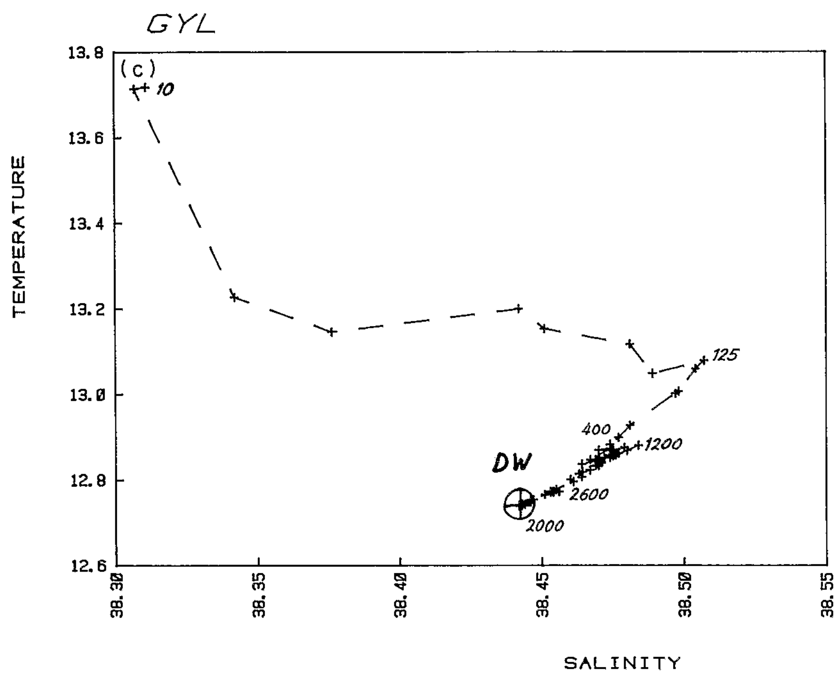


Fig. 7. GYL station (Ligurian Sea). (a) Tritium vs depth profile. (b) Tritium vs salinity diagram. (c) T–S diagram.

T–S diagram (Fig. 7b) shows the imprint of the intermediate water around 150 m depth rather than the usual depth of 400 m (BETHOUX et PRIEUR, 1983). MARULLO *et al.* (1985) have observed small-scale baroclinic eddies in the Ligurian Sea (between 43°50′–44°4′N and 8°45′–9°15′E) and BETHOUX and PRIEUR (1983) previously described important hydrological fronts and convection mixing processes in this area. Our observations of uplifting of intermediate water and tritium enrichment in the range 400–1200 m seem to be the result of the baroclinic instabilities and the convection processes observed at the time of sampling.

The higher tritium concentration near the bottom (1.75 TU compared to 1.35 TU at 2000 m depth; Fig. 7a) coincides with relatively warmer and more saline water than in the overlying waters (Fig. 7b). In reporting similar observations from *Dome* II (March 1982) and *Mediprod* IV (November 1981), LACOMBE *et al.* (1985) have concluded that this bottom layer results from convection processes near the center of the cyclonic gyre. Moreover, the tritium concentration at 2000 m depth (1.35 TU) in the GYL station is nearly the same as in the depth of the ETRI station (1.3 TU). This similarity agrees with the same hydrological data which identify the western Deep Water (plotted as DW on the T–S curve, Fig. 7b).

4.2. *Dense water formation on the Spanish continental slope off the Ebro Estuary*

Station ETE off the Ebro Estuary has an unusual tritium profile, with a sharp increase from 900 m to the bottom (Fig. 8a). The hydrological data reported on the T–S diagram

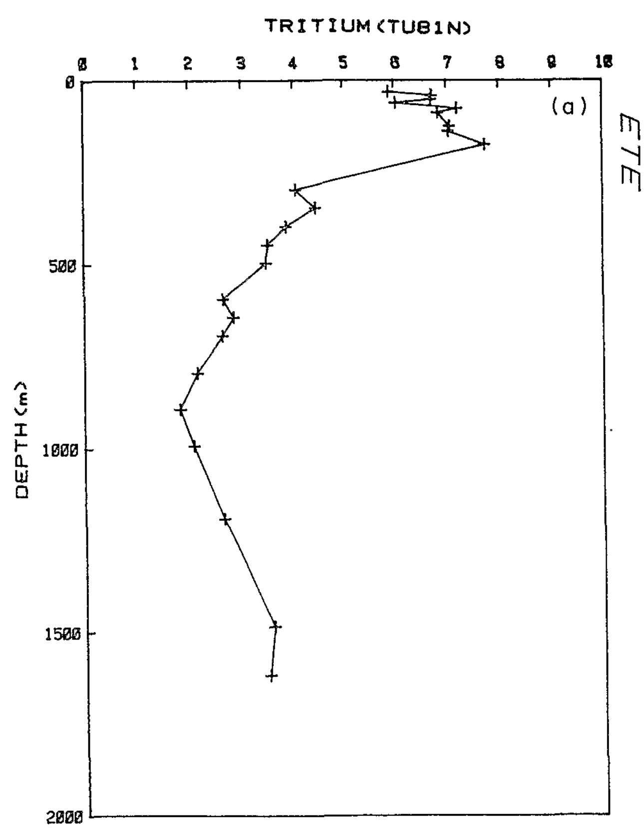


Fig. 8a.

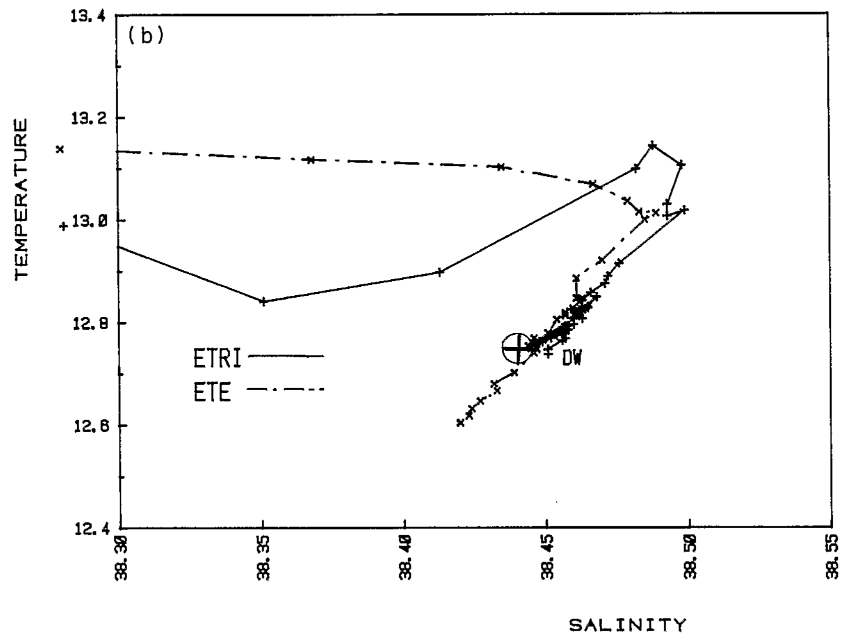


Fig. 8. ETE station (off the Spanish coast). (a) Tritium vs depth profile. (b) T–S diagram. (The T–S diagram for the ETRI station is reported as reference.)

(Fig. 8b) indicate that the deep waters are colder and fresher than the surrounding waters (plotted as DW). The deep waters are the densest observed during the entire *Phycemed* cruise ($\sigma_\theta = 29.141$). In addition, oxygen concentrations are abnormally high in deep waters (5.1 ml l^{-1} at 10 m depth, 4.53 ml l^{-1} at 1000 m depth, 4.91 ml l^{-1} at the bottom).

These observations suggest that the water from the Ebro River is cooled by wind action and deepens along the continental slope. A similar phenomenon of dense water formation on the continental shelf has been described by FIEUX (1974) and PERSON (1974). The tritium profile in this area (Fig. 8a) supports this concept of "cascading". High tritium concentrations near the bottom are linked to the significantly higher tritium concentrations measured in rivers.

At a density level $\sigma_\theta = 29.3$ (around 1000 m depth) the tritium concentrations at ETE (2.1 – 2.65 TU) are similar to these of the ETRI station (2.5 — 2.6 TU). In contrast, the deep tritium content in the ETRI station (1.3 TU) is significantly lower than in the ETE area (3.6 TU), which is logical as the mechanisms involved in deep-water formation are totally different in the two areas.

4.3. *Water circulation in the southern Western Basin*

SRS and SRSB stations (Straits of Sardinia). The location and depth of the SRS1 station sampled for tritium is given in Table 3. The tritium profile for the SRS1 station (Fig. 9) suggests an increase in tritium near 100 m. This characteristic subsurface maximum agrees with an exchange of high tritium water from the eastern Mediterranean Sea, shallower than the LIW, as previously mentioned by ROETHER *et al.* (1987). The line on the T–S diagram (Fig. 2) describing the subsuperficial waters between 200 and 500 m extrapolates to the characteristics of LIW, indicating a mixing between two types of

Table 3. *Positions, sampling dates and depths of the SRS and SRSB stations*

Station	Position	Date (1987)	Depths (m)
SRS1	38°229′N–9°249′E	20 April 4 h 15 a.m.	1811
SRS2	38°210′N–9°235′E	20 April 2 h 24 p.m.	1968
SRS3	38°207′N–9°237′E	21 April 2 h 11 a.m.	1940
SRS4	38°228′N–9°247′E	21 April 11 h 38 a.m.	1825
SRSB	38°359′N–9°508′E	21 April 7 h 10 a.m.	2082

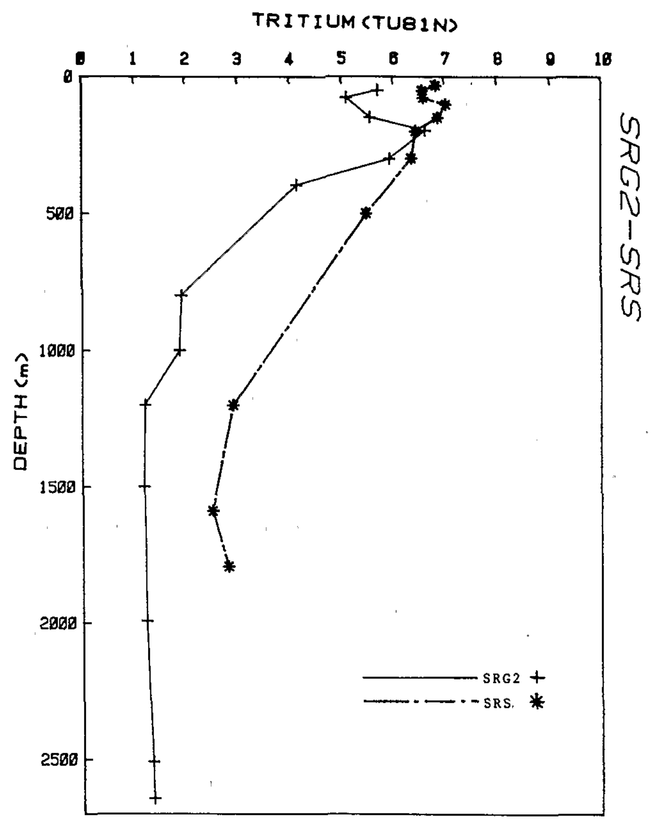


Fig. 9. Tritium (TU81N) vs depth profiles of the SRG 2 and SRS stations.

water (LIW and subsurface waters) at 150–200 m. An analog trend is observed on the ^{3}H–S diagram (Fig. 10), which suggests that mixing is very efficient between 500 and 100 m depths. The linearity of the trend is remarkable and identifies two end-members for the mixing process: the intermediate water mass (5.5 TU, S = 38.652‰) and a tritium-enriched subsurface water mass flowing from the east. Therefore the eastward surface flow of low tritium water apparently occurs within a very shallow layer. This agrees with GARZOLI and MAILLARD (1979) who indicated great variability in the surface

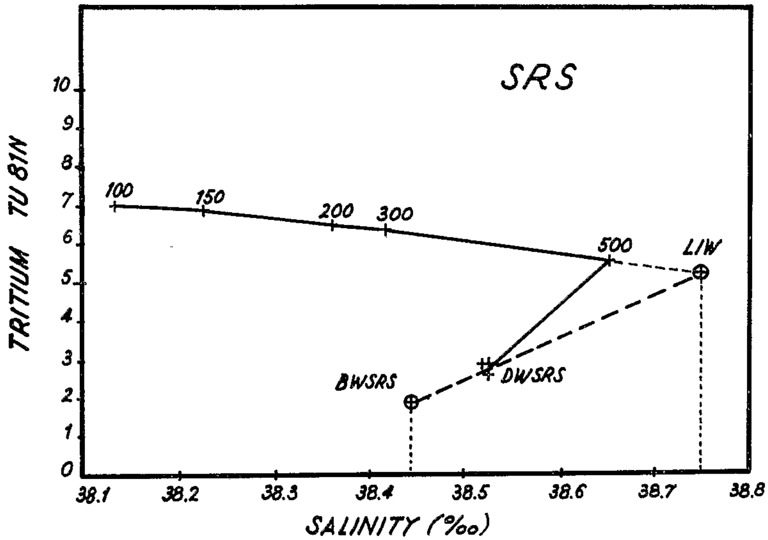


Fig. 10. Tritium (TU81N)–salinity diagram of the SRS1 station. The DWSRS and BWSRS points are, respectively, relative to the deepest samples for tritium and the extrapolated value for the salinity of the occidental deep water using the line LIW–DWSRS.

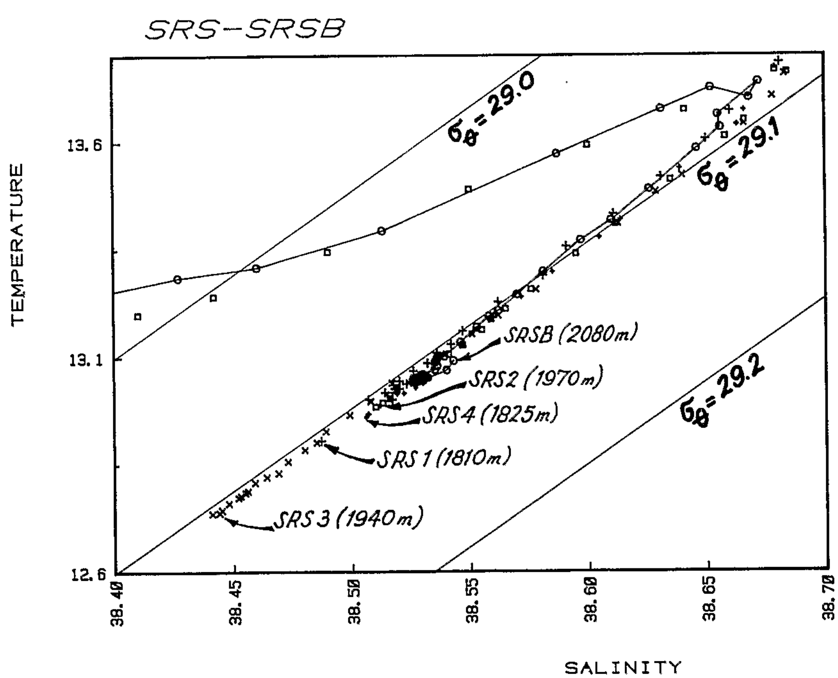


Fig. 11. T–S diagrams for the four SRS stations (SRS1–SRS4, see Table 3) and the SRSB station from 200 m to the bottom.

water fluxes in the Straits of Sardinia (mean geostrophic velocities in an area somewhat southwest of the SRS station can be westward in the upper 0–100 m). By extrapolation of the mixing line between the subsurface water mass and the intermediate water, we can evaluate the tritium content of the LIW when it enters the Straits of Sicily (5.15 TU for S = 38.78‰).

Several CTD casts have been performed in the Sardinia Channel. Four of them are relative to the SRS station and the fifth one corresponds to an area somewhat more to the east (SRSB station; Table 3). The deep T–S diagrams for these stations (Fig. 11) show that the different characteristics of the bottom waters are due to marked topographical changes in the Sardinia Channel (GARZOLI and MAILLARD, 1979). The characteristics of the bottom waters of the five stations fall along a very well-defined line from SRSB to SRS3. They are those of the western Deep Water previously defined (DW, T = 12.74°C, S = 38.44‰). For each station, there appears a very homogeneous and thick layer of temperature around 13.0°C and salinity around 38.52‰ between 1200 and 1900 m depths. It is likely that this layer originates from a high salinity water mass formed in the Tyrrhenian Sea.

The same homogeneity is noticeable for the tritium data relative to the SRS1 station (Fig. 9 and Table 2) in the depth range 1200–1800 m. The hydrographic homogeneity of water at Stas SRSB, SRS1, SRS2 and SRS4, as well as homogeneous tritium content at the SRS1 station, suggests an input of Tyrrhenian water at this depth range.

MOLCARD and TAIT (1977) described a remarkable step structure in the Tyrrhenian Sea resulting from a double-diffusion process or "salt fingering" which induces convection in the water column. A "step" structure exists between 600 m (Levantine Intermediate level) and 1500 m. The simultaneous homogeneity in hydrological data and in tritium data (SRS station, Table 2) suggests that this structure can occur down to 2000 m. MOLCARD and TAIT (1977) observed that the deep Tyrrhenian water had the same hydrological characteristics as those observed by GARZOLI and MAILLARD (1976; T = 12.7°C, S = 38.40‰). The noticeable discrepancy between these characteristics (for the years 1972–1976) and those of the western DW observed during the *Phycemed* cruise can be explained by the variability with time of the deep hydrological characteristics of the western water (LACOMBE *et al.*, 1985). The observed increase in salinity is equal to 0.04‰ between 1972 and 1981. Tritium measurements of CORTECCI *et al.* (1974) also indicate step structures at most stations. A mean value of (2.8 ± 0.5 TU) has been observed during May 1972 between 864 and 1236 m at the 19B1 station. It is unfortunate that the deep water at SRS3 has not been sampled for tritium.

From these observations (i.e. double diffusion in the Tyrrhenian Sea starting from the LIW and dilution with a deep water of the same hydrological characteristics as the western DW) we can extrapolate the mixing line between the points LIW (tritium content of the Levantine Water when it enters in the Sicily Straits) and DWSRS (tritium data relative to the depth range 1200–1800 m for the SRS1 station) to evaluate the deep tritium content of the waters near the bottom of the Sardinia Channel (BWSRS with a 38.44‰ salinity, i.e. the tritium content in SRS3). This gives a tritium content equal to 1.8 TU for the western DW in the Sardinia Straits (SRS3 or BWSRS or DW). In the following, we shall see that this deep tritium content (relatively tritium enriched due to a tyrrhenian input) can be used to estimate the horizontal advection rate of the deep waters in the western basin.

SRG2 station (Alboran Sea). The inflowing Atlantic water at 50 m displays hydrological characteristics of an Atlantic origin (salinity = 36.74‰), with a tritium content equal

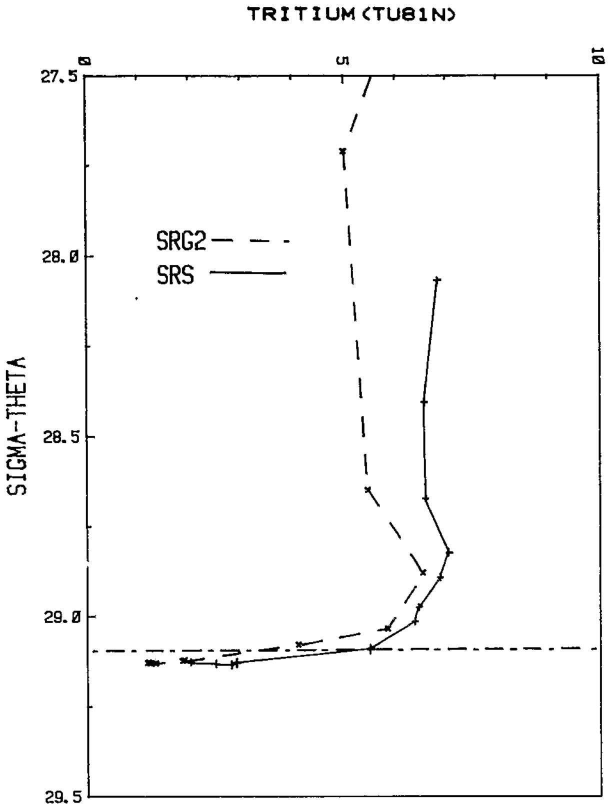


Fig. 12. Tritium (TU81N) vs sigma-theta diagram for the two stations SRG2 and SRS. The dashed horizontal line corresponds to the level of the intermediate layer.

to 5.6 TU (Fig. 9). This value is close to the one observed during *Meteor* 1978 at Sta. 454 (around 6 TU, i.e. 5.3 TU81N) (ROETHER *et al.*, 1987). In the subsurface, a maximum in the tritium vs depth profile (~200 m depth) is apparent above the intermediate layer (at 400–500 m depth from Fig. 2). This subsurface tritium maximum coincides with the previously mentioned subsurface maximum at the SRS station (Fig. 12). This suggests that at the density level (σ_θ = 28.8) a tritium-enriched water mass flows from the east, well above the intermediate layer. The tritium content of this layer decreases westward (7 TU at SRS and 6.6 TU at SRG2). ROETHER *et al.* (1987) previously have described such a tongue of high tritium water flowing from the Sicily Straits towards the Sardinia Straits, overlying the LIW.

In the SRG2 area, we observe (Fig. 9) a remarkable steadiness of the tritium content of the water column between 1200 m depth and the bottom (1.25 ± 0.1 TU). The shape of our profile is very similar to the data reported by ROETHER and WEISS (1975) from the Gibraltar area (4°W to 6°E).

The Mediterranean outflow at Gibraltar has been described as an upward motion of the deep waters in the Alboran Sea associated with a westward motion of the deep waters along the Moroccan continental slope (BRYDEN and STOMMEL, 1984; GASCARD and RICHEZ, 1985; PISTEK *et al.*, 1985; WHITEHEAD, 1985; PARILLA *et al.*, 1986). BRYDEN and

STOMMEL (1982) observed that, close to the Gibraltar Strait (36°N, 5°W), the hydrological characteristics in the water column at 450 m depth are identical to the data measured in the vicinity of SRG2 location at a depth of 1200 m. They suggested that a "suction" of deep waters occurs at least as deep as 1200 m.

It seems that the homogenization of the deep-water tritium content between 1200 and 2500 m results from two combined causes: an upward motion of the waters occurring from a level deeper than 1200 m, and a lateral input from waters from the east. This last assumption, for a westward circulation of the western deep waters in the south, is supported by two observations: (1) The east–west tritium content of the bottom waters decreases from SRS (1.8 TU for DWSRS) to SRG2 (1.25 TU). (2) The deep tritium content in the SRG2 area increases with time: 0.4 TU for *Meteor* 1974 cruise and 0.9 TU for *Meteor* 1978 cruise (ROETHER *et al.*, 1987), 1.25 TU for *Phycemed* 1981 cruise. Considering the upward motion of the deep waters, this increase involves either a lateral tritium input from the east or a very rapid input from the Gulf of Lion deep waters.

As mentioned by ROETHER *et al.* (1987), the tritium source function for deep waters cannot be computed easily for the entire western Mediterranean Sea. However, we can tentatively use our isotopic data to evaluate the approximate time constants relative to the deep circulation. With our first assumption of a deep westward horizontal advection between the Sardinia and Gibraltar Straits [respective deep tritium concentrations of 1.8 TU(81N) and 1.25 TU(81N) for SRS and SRG2 stations], we calculate a transit time of 6.5 years, i.e. a deep advection rate of approximately 0.5 cm s^{-1}. This is a maximal value as we do not consider the input of the ETR deep water (1.3 TU) in this calculation. On the other hand, the similar deep-water tritium concentrations in the Alboran Sea (1.25 TU) and in the northern occidental area (1.3 TU) suggest that the transit time necessary for the "new" western deep waters to feed the Gibraltar outflow is very short. This transit time cannot be computed, as the difference between the two members (ETRI and SRG2 deep waters) is of the order of the analytical precision. Here again, tritium data strongly confirm a feature previously mentioned by the MEDOC GROUP (1975).

5. CONCLUSION

The combination of hydrographic tracers, such as salinity and potential temperature, and radioactive tracers such as tritium can provide information relative to the residence time of waters in the western Mediterranean.

(1) The tritium data relative to three different stations in the Gulf of Lions corroborate the previously mentioned spatio-temporal variations of the deep-water formation processes in this area. The mean residence time of the deep waters in this area is calculated to be 11 ± 2 years using a box-model. The "violent" mixing that we have observed at one station in the Medoc area seems to represent the active center of the cyclonic gyre of the northern western basin. The deep tritium content in this area is 1.3 TU.

(2) The waters in the Sardinia Straits are mixed both above and under the LIW (500 m depth). In the range 100–500 m mixing affects the LIW and an overlying layer flowing westward above the LIW layer. There is evidence for a tritium-enriched subsurface layer. We determine the tritium content of the LIW when it enters the Sicily Straits to 5.1 TU. From 500 m to the bottom an active mixing occurs between the deep water and the LIW via an intermediate water mass from the Tyrrhenian Sea by a "salt-fingering" process. With an assumption of the two end-members mixing, we determine that the deep tritium content in the Sardinia Straits equals 1.8 TU.

(3) Data relative to the Gibraltar Strait show a remarkable steadiness of the tritium content in the water column at depths greater than 1200 m (1.25 ± 0.1 TU). This feature is the result of a combined upward "suction" of the waters lying under 1200 m depth and feeding the outflow, and a lateral advection of deep waters from the northern and the eastern areas. We estimate that the transit time for the deep waters to flow westward along the continental slope of the north African coast between the Sardinia Straits and the Alboran Sea is at least 6 years, leading to an upper limit of the advection rate around 0.5 cm s^{-1}.

(4) Tritium data indicate some local phenomena of deep-water formation along the continental shelf, as well as the particular characteristics of deep layers near the bottom at several locations.

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