Mixing between oxic and anoxic waters of the Black Sea as traced by Chernobyl cesium isotopes

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Abstract—The Chernobyl nuclear power station accident in 1986 released readily measureable quantities of fallout [134]Cs and ^{137}Cs to Black Sea surface waters. This pulse-like input of tracers can be used to follow the physical mixing of the surface oxic waters, now labeled with the Chernobyl tracers, and the deeper anoxic waters, which were initially Chernobyl free. By 1988, there is clear evidence of Chernobyl Cs penetration below the oxic/anoxic interface at deep water stations in the western and eastern basins of the Black Sea. This rapid penetration of surface waters across the pycnocline cannot be explained by vertical mixing processes alone. Data from profiles at the mouth of the Bosporus suggest that significant ventilation of intermediate depths can occur as the outflowing Black Sea waters are entrained with the inflowing Mediterranean waters, forming a sub-surface water mass which is recognized by its surface water characteristics, i.e. initially a relatively high oxygen content and Chernobyl Cs signal. The lateral propagation of this signal along isopycnals into the basin interior would provide a rapid and effective mechanism for ventilating intermediate depths of the Black Sea. This process could also account for the lateral injection of resuspended margin sediments into the basin interior. The temperature and salinity data suggest that the entrainment process occurs at depths of 50–80 m, mixing waters from the Cold Intermediate Layer with the incoming, denser Mediterranean waters.

INTRODUCTION

THE deep waters of the Black Sea currently form the largest reservoir of permanently anoxic waters in the oceans. This feature is primarily a result of restricted mixing between the surface and deep waters. Vertical mixing is limited due to a strong density gradient which exists between the upper less saline waters (≈18‰) and the saltier deep waters (≈22‰). The pycnocline which separates these two layers is generally dome-shaped, being found at greater depths near the margins (150–200 m) than in the center of the eastern and western basins (80–120 m; MURRAY *et al.*, 1991). The salinity gradient is maintained through a balance between continued fluvial and fresh water inputs, evaporative losses, and the restricted outflow of surface waters from the basin and the inflow of high density Mediterranean waters into the basin through the narrow and shallow Bosporus Straits (GUNNERSON and ÖZTURGUT, 1974; LATIF *et al.*, 1991).

The boundary that exists between the surface oxic waters and the deep anoxic waters is a site of considerable scientific interest, since it is here that the sharpest chemical, biological and physical gradients exist. One of the most basic questions which can be asked is to what

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extent and under what conditions does mixing occur between the oxic and anoxic layers. On a geological time-scale we know from sediment cores that anoxic conditions were likely established in the Black Sea some 5000–7000 years ago (ROSS *et al.*, 1970; DEUSER, 1972; DEGENS *et al.*, 1978; CALVERT *et al.*, 1987). On shorter time-scales there is considerable debate about changes in the last few decades in the depth and properties at the oxic/anoxic interface (TOLMAZIN, 1985; FASHCHUK and AYZATULLIN, 1986; BRYANTSEV *et al.*, 1988; MURRAY *et al.*, 1989; MURRAY and IZDAR, 1989).

In this manuscript, we present data on the depth distribution of the Cs isotopes, ^{134}Cs ($t_{1/2}$ = 2.07 y) and ^{137}Cs ($t_{1/2}$ = 30.17 y) in the Black Sea. These radioactive tracers have been introduced to this basin primarily from fallout due to the Chernobyl nuclear power station accident which started on 26 April 1986, as well as from fallout due to atmospheric nuclear weapons testing programs which occurred predominantly in the 1950s and 1960s. The samples were collected as part of a larger geochemical study wherein the Cs isotopic data are used to separate physical mixing from scavenging and removal processes of the more particle-reactive Chernobyl tracers, such as ^{144}Ce and ^{106}Ru. The sampling scheme is therefore focused around the oxic/anoxic interface and was limited by the ship time available on short notice after the accident. While the Cs data were not collected as part of a detailed physical oceanographic study of the Black Sea, the features in this data set alone allow us to make some basic and important conclusions regarding the mixing of surface Black Sea waters to depth on annual time-scales, which are presented here.

BACKGROUND

Cesium isotopes have been used in a variety of oceanographic studies as tracers of physical mixing. The studies began after atmospheric nuclear weapons testing programs delivered approximately 1.3×10^{18} Bq of ^{137}Cs worldwide (JOSEPH *et al.*, 1971). The delivery of Cs isotopes from weapons testing sources peaked in the early 1960s. In general, oceanic residence times for Cs are long, and fallout ^{137}Cs has been used along with ^{90}Sr and tritium as a tracer of physical mixing processes (VOLCHOK *et al.*, 1971; BOWEN and ROETHER, 1973; BOWEN *et al.*, 1980; COCHRAN *et al.*, 1987). In addition to the fallout sources, localized releases of Cs isotopes from the Sellafield nuclear fuel reprocessing plant in the U.K. have been used to follow the mixing of waters from the Irish Sea into the Norwegian/Greenland Seas and the Arctic basin (LIVINGSTON *et al.*, 1982a,b, 1985).

With the Chernobyl accident in April 1986, a new pulse of fallout Cs was added to the environment. The bulk of the Chernobyl Cs fallout appears to have originated during the reactor fire due to volatilization of Cs. A second possible release pathway would have been direct fallout deposition of particulate reactor material originating from the explosion which occurred at the onset of the accident. Infrequent hot particles (20–100 μm) have been found which are thought to originate from this latter source (VAN DER VEEN *et al.*, 1986), but data are scarce and particle deposition would be highly localized. The behavior of Cs in the Black Sea carried by intact hot particles may be different than the bulk Cs fallout; for instance, the hot particles may not release soluble Cs but rather sink unaltered to the sea floor. This study focuses on soluble Cs in the water column and as such is concerned with the bulk fallout and the evolution of Cs water column distributions.

The total quantity of ^{137}Cs released from Chernobyl is an order of magnitude smaller than that from weapons testing sources (1×10^{17} Bq; GOLDMAN, 1987). The radioactive fallout from this accident is a significant source of activity to the environment due to the

high fallout activities in localized tropospheric fallout deposition observed during the relatively short duration of the releases (10 days from Chernobyl vs more than 15 years from weapons testing). In our studies the ^{134}Cs isotope provides a highly specific tracer of the Chernobyl fallout for two main reasons. First, there is essentially no ^{134}Cs in the environment from the 1960s weapons testing inputs due to its low production ratio in weapons sources and its relatively short half-life (0.02% remains after 25 years). Secondly, the ^{134}Cs/^{137}Cs ratio of the Chernobyl releases remained fairly constant during the accident, such that a pure Chernobyl fallout signal will have an easily identifiable ^{134}Cs/^{137}Cs activity ratio—approximately 0.5 at the time of input in 1986 (DEVELL et al., 1986; AARKROG, 1988; MITCHELL and STEELE, 1988; and following discussion). Also, given that Cs is efficiently removed in fresh-water systems, the pulse of Chernobyl atmospheric fallout that reached the Black Sea between ~1–5 May 1986 (ALEXANDRAPOULOS et al., 1986; WIRTH et al., 1987; MISAELIDES et al., 1987), would be the only significant source of this tracer to Black Sea surface waters, i.e. runoff and riverine Cs inputs are negligible (POLIKARPOV et al., 1991).

In this manuscript all Cs tracer activity data will be decay corrected to an input date of 1 May 1986, such that waters labeled with Cs isotopes of a predominantly Chernobyl origin would have a high ^{134}Cs/^{137}Cs activity ratio (approaching one-half) and those waters labeled by earlier weapons testing sources would have a ^{134}Cs/^{137}Cs ratio of zero. Waters which had remained isolated from surface fallout inputs since the early 1950s would show neither tracer. The ^{134}Cs/^{137}Cs ratio will always refer to an activity ratio (in contrast to a mass or atom abundance ratio) and the units of activity will be Bq (= Becquerel, or disintegrations per second).

SAMPLING AND ANALYSES

The samples for the Cs isotopic profiles discussed here were collected on three cruises. The first and second cruises were conducted aboard the R.V. *K. Piri Reis* of the Dokuz Eylül Üniversitesi in Izmir, Turkey during 19–23 September 1986 and 11–13 May 1987. The third cruise occurred during 21 June–8 July 1988 as part of cruise 4 of the R.V. *Knorr* Black Sea Expedition.

Cesium samples were collected in one of two ways. The first method involved a large volume pumping system, whereby 200–1500 l of sea water were passed first through a prefilter cartridge (0.5-μm polypropylene CUNO Microwynd) and then sequentially through two CuFe(CN)$_6$ adsorber cartridges for the collection of dissolved Cs. Once collected, these Cs adsorbers are ashed and gamma-counted at Woods Hole for 1–3 days on a Ge(Li) detector. ^{134}Cs and ^{137}Cs are measured directly by their corresponding gamma peaks at 796 keV and 662 keV, respectively (the ^{134}Cs peak is corrected for background contribution from ^{228}Ac at 795 keV by the measurement of ^{228}Ac at 911 keV). The second Cs adsorber in-line is used to calculate the absolute collection efficiency of the Cs adsorbers, using the equation: collection eff. $= 1 - B/A$, where A and B are the Cs activities on the first and second adsorbers, respectively (MANN and CASSO, 1984; LIVINGSTON and COCHRAN, 1987). Absolute activities are obtained by comparison to standards of known activity and similar geometry. This technique is described in detail in BUESSELER et al. (1990a). This procedure has been calibrated against existing beta-counting techniques and in international calibration exercises conducted by the IAEA (BALLESTRA et al., 1989). In 1986 and 1987 this chemisorption procedure was carried out

only in surface waters using a deck mounted pumping system. On the R.V. *Knorr* cruise in 1988, seven *in situ* battery powered pumps with Cs adsorbers were used, which when hung on the trawlwire allowed for the collection of samples from multiple depths on a single cast (flow rates averaged 5 l min^{-1} over 4-h pumping intervals).

The second technique for obtaining the Cs isotopic distributions is based upon radiochemical procedures developed during the 1960s (Yamagata, 1965; Wong *et al.*, 1970), and uses discrete 10–20-l water samples collected from wire mounted sampling bottles (10- or 30-l Niskins in 1986 and 1987). The unfiltered Niskin samples are transferred into clean sample containers and processed by radiochemical techniques to separate and purify the Cs isotopes. The samples are mounted on a filter as Cs chloroplatinate precipitates and counted by radiometric techniques (details can be found in Buesseler *et al.*, 1990a). Given the relatively high activities of the Chernobyl-labeled samples, the purified Cs samples mounted in this manner can be counted on a gamma detector for the ^{134}Cs and ^{137}Cs isotopes similar to that described above for the ashed adsorbers, but with a higher gamma detection efficiency due to geometry considerations. A more sensitive determination of total Cs activity is obtained by beta counting the precipitate. With beta counting the ^{134}Cs/^{137}Cs ratio cannot be determined as the beta signals from the two Cs isotopes are not resolved. We used beta counting primarily on those samples from the deep waters which were free of Chernobyl ^{134}Cs. Typically, the highest precision was obtained using the Cs adsorber cartridges due to the much larger sample size, and hence larger total sample signal.

In addition to the Cs isotopic analyses, comparisons will be made to salinities, temperatures and densities as well as to the basic chemical parameters, oxygen and sulfide. In these measurements considerable differences exist between the cruises, due to the nature of the sampling programs and the capabilities of the Turkish and U.S. research vessels. In 1986 and 1987, salinities were obtained from the same Niskin bottles which were used to collect the Cs samples. In this case, 125-ml salinity bottles were filled, sealed and transported to WHOI for subsequent salinity analysis using an autosalinometer facility at Woods Hole. On the same cruises, our Turkish colleagues from Izmir deployed a separate CTD package either before or after the Niskin casts at three of the four stations (within a few hours of the Niskin cast). The oxygen and sulfide data in 1986 and 1987 were obtained by standard titrimetric techniques and via an oxygen probe on the Turkish CTD package. The data are somewhat limited and are only used to define the relative depths of the oxygen and sulfide boundaries.

The 1988 hydrographic data which are used here are described in this volume (Murray *et al.*, 1991). As in the earlier years, the CTD data were collected on a separate cast from the Cs casts. The 1988 oxygen and sulfide determinations were made using the deck mounted pumping system and techniques described by Codispoti *et al.* (1991).

It should be noted that the hydrographic and Cs data were collected on casts separated in time by up to 2–3 h at a given station. This may be especially important near the mouth of the Bosporus (Sta. 24; Fig. 1), where spatial and temporal variability in physical processes can make comparisons between replicate casts quite difficult. Fortunately, the features to be examined here across the pycnocline are so strong in this basin that errors introduced in comparing separate CTD and Niskin casts are not of major significance in the interpretation of our data set.

Particulate ^{234}Th, Mn and Fe data also will be shown from one station in 1988 where a strong minimum in light transmission was found during the CTD cast. In this case, the
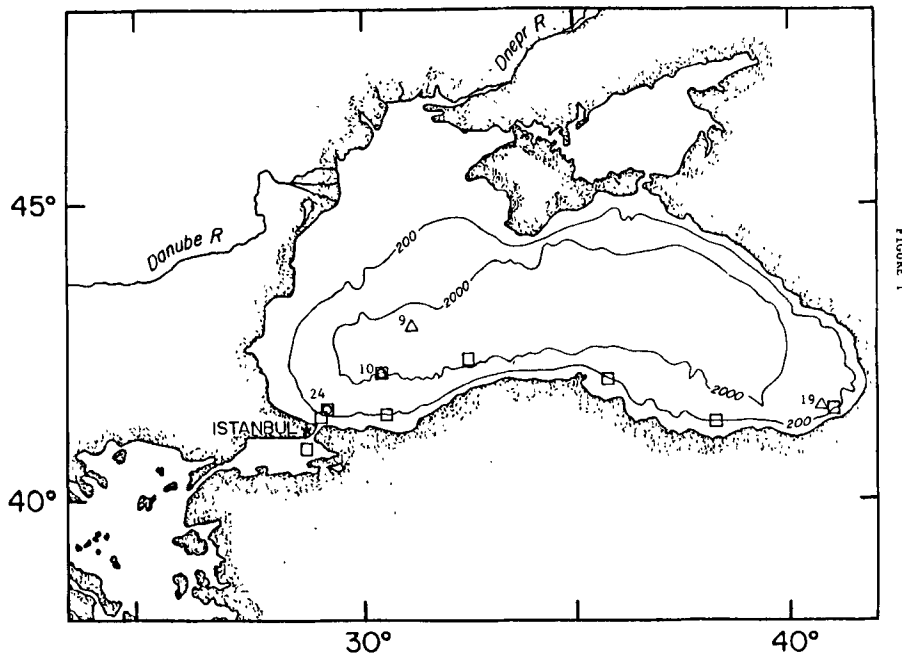
Fig. 1. Station location map. Locations sampled for surface water $^{134}Cs/^{137}Cs$ ratios in 1986 are shown by open squares. The 1987 and 1988 sampling sites are shown by open circles and triangles, respectively. Stations 24, 10, 9 and 19 were the primary locations sampled for the vertical distributions of the Chernobyl radionuclides.

particulate ^{234}Th data were obtained by direct gamma counting of the ashed prefilters from the large volume samples. Particulate Mn and Fe samples came from a 1% by weight split of the same ashed prefilter samples and were analysed using an Inductively Coupled Plasma–Atomic Emission Spectrometer at Woods Hole.

RESULTS

Surface waters

Surface water data were used to calculate the pure Chernobyl end-member $^{134}Cs/^{137}Cs$ ratio (which was reported to be around one-half) and the pre-Chernobyl level of surface water ^{137}Cs from weapons testing. The coverage of stations used in this analysis is shown in Fig. 1, and the total surface water ^{137}Cs activity is plotted vs the measured $^{134}Cs/^{137}Cs$ ratio in Fig. 2. As discussed in the previous section, there are only two significant sources of fallout Cs in the Black Sea: weapons testing fallout ($^{137}Cs_{wt}$) and Chernobyl fallout ($^{137}Cs_{Ch}$). Furthermore, the $^{134}Cs/^{137}Cs$ ratio in weapons testing fallout today is zero, and in Chernobyl fallout (decay corrected to 1 May 1986) some constant value ($^{134}Cs/^{137}Cs_{Ch} = R_{Ch}$). Therefore, the measured Cs isotopic ratio ($^{134}Cs/^{137}Cs$ of sample $= R_{tot}$) is related to these quantities by the equation:

$$R_{tot} = R_{Ch}\left(^{137}Cs_{Ch}/^{137}Cs_{tot}\right). \tag{1}$$

Substituting $[1 - ({}^{137}Cs_{wt}/{}^{137}Cs_{tot})]$ in equation (1) for the percentage of Chernobyl ${}^{137}Cs$ in the total, and rearranging we have:

$$R_{tot} = R_{Ch} - [(R_{Ch} * {}^{137}Cs_{wt})/{}^{137}Cs_{tot}]. \tag{2}$$

A best fit through the data in Fig. 2 (${}^{137}Cs_{tot}$ vs R_{tot}) will therefore provide an estimate of the two constants in this equation, R_{Ch} and ${}^{137}Cs_{wt}$, since we assume that the ${}^{137}Cs_{wt}$ signal was constant in southern Black Sea surface waters prior to the Chernobyl accident. We fit the data (using a statistical package in the software program "RS1" from BBN Software Prod. Corp.) in this manner from 28 surface water samples collected during 1986 (Fig. 2) and found R_{Ch}, i.e. the end-member ${}^{134}Cs/{}^{137}Cs$ ratio in Chernobyl fallout, to be 0.53 ± 0.01. This agrees very well with other measurements of this ratio in fallout samples directly after the accident (Devell *et al.*, 1986; Aarkrog, 1988). The pre-existing surface water ${}^{137}Cs$ activity (${}^{137}Cs_{wt}$) was found to be 9 ± 1 Bq m^{-3}. This also agrees well with earlier estimates of the Black Sea surface water ${}^{137}Cs$ signal prior to the Chernobyl accident (10–12 Bq m^{-3} corrected to May 1986; Vakulovskiy *et al.*, 1982). Note that the total ${}^{137}Cs$ signal post-Chernobyl can be as high as 360 Bq m^{-3}, and samples above 100 Bq m^{-3} have ${}^{134}Cs/{}^{137}Cs$ ratios very close to the 0.53 end-member (Fig. 2).

Vertical distributions

Vertical profiles of Cs isotopes were obtained in 1986 and 1987 at two stations: Sta. 24 at the mouth of the Bosporus north of the shelf break at a water depth of roughly 500 m, and Sta. 10, at a depth of 2100 m in the interior of the SW Black Sea (Fig. 1). Station 10 was resampled in 1988 (=BS4 Sta. 7) along with two other deep water stations (BS4 Stas 9 and 19; Fig. 1). Station 24 was not resampled for Cs isotopes in 1988.
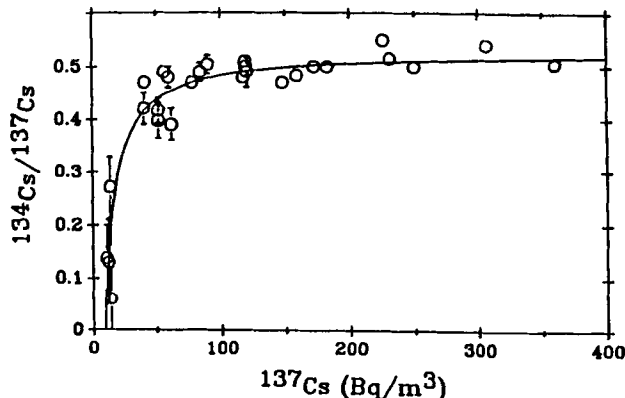

Fig. 2. Total ${}^{137}Cs$ vs ${}^{134}Cs/{}^{137}Cs$ ratios in surface waters of the Black Sea in 1986. The one sigma errors on the ${}^{134}Cs/{}^{137}Cs$ ratio are shown if larger than the symbol. All ${}^{137}Cs$ activity errors are smaller than the symbol size. The solid line represents a model fit to a two end-member fallout Cs source model as described in the text.

The vertical ^{137}Cs distributions and ^{134}Cs/^{137}Cs ratios from these cruises are shown in Fig. 3a–f, and the data are provided in Table 1. The Cs data are compared to the ancillary hydrographic, oxygen and sulfide data in the same figures and tables.

In 1986, at the interior Sta. 10, Chernobyl Cs, as defined by the presence of ^{134}Cs, had not penetrated below the upper 50 m (Fig. 3a). The depth resolution and sensitivity in the ratio data (detection limit = 0.05) is not sufficient to estimate the exact depth of Chernobyl tracer penetration. The total ^{137}Cs activities of 10–11 Bq m^{-3} in the ^{134}Cs free waters between 70 and 100 m support our earlier estimate of a pre-Chernobyl weapons testing ^{137}Cs activity in surface waters of 9 ± 1 Bq m^{-3}.

In the upper 50 m at the margin Sta. 24, the picture looks very similar, with a strong Chernobyl signal in the upper 20 m, a hint of ^{134}Cs at 50 m, and no evidence of Chernobyl ^{134}Cs by the 80 m sample (Fig. 3b). The CTD temperature data suggest that the depth of the summer thermocline was 35 m at this site. A somewhat different feature is seen in the data below 100 m at this margin site, however. The 150 m sample had a ^{134}Cs/^{137}Cs ratio of 0.13 ± 0.08. The large associated error is due to the small sample size and relatively low total activity observed. The water samples directly above and below this depth did not show any evidence of Chernobyl ^{134}Cs (^{134}Cs/^{137}Cs < 0.05). The CTD data also showed a sub-surface oxygen peak at a depth of 110 m (Fig. 3b). Since the CTD data were taken on a separate cast from the Cs cast, the significance in the difference in absolute depth of this feature (40 m) cannot be evaluated at this time. With a strongly varying hydrographic structure in this region with space and time, the depth of specific features seen on replicate casts may be quite different. The main point is that in both the ^{134}Cs/^{137}Cs data and the oxygen profile at this margin station in 1986, there is an indication of sub-surface injection of waters with surface water characteristics at intermediate depths.

By May of 1987, ^{134}Cs/^{137}Cs ratios indicate deeper penetration of the Chernobyl labeled waters. At Sta. 10, ^{134}Cs/^{137}Cs ratios of close to the 0.53 end-member are found down to 65 m (Fig. 3c). By the next sample at 80 m, ^{134}Cs/^{137}Cs ratios are again below detection. These data suggest that winter mixing alone between 1986 and 1987 was insufficient to cause the penetration of surface waters across oxygen zero (here at somewhere between 80 and 90 m). Total surface water ^{137}Cs levels also have decreased between 1986 and 1987 (note the scale change in ^{137}Cs between Fig. 3a,b and 3c–f) due to continued mixing of the Chernobyl-labeled waters to depth.

In 1987 at the margin site, the surface waters show deeper ^{134}Cs/^{137}Cs penetration, similar to Sta. 10 (down to at least 50 m; Fig. 3d). As in the previous fall, we also see a subsurface ^{134}Cs peak at 150 m, this time with a ^{134}Cs/^{137}Cs ratio of 0.41 ± 0.08. The total ^{137}Cs activity profile at this depth also shows a significant increase in activity compared to samples just above and below this 150 m feature. The Sta. 24 CTD data in 1987 show a secondary oxygen maximum (at 135–145 m), consistent with the sub-surface ^{134}Cs peak, and accompanied by slightly cooler temperatures.

The 1988 Cs data are more precise, due to the larger sample size obtained by our *in situ* pumps. A surprising feature in the 1988 data was the penetration of ^{134}Cs down to depths of at least 150 m, much deeper than in previous years (Fig. 3e,f). The ^{134}Cs/^{137}Cs profiles and activity data in the upper 150 m at the two stations in the western basin are very similar. The sample spacing below 150 m does not allow us to accurately estimate the depth of zero ^{134}Cs. By 400 m at Sta. 9 and 600 m at Sta. 10 the ^{134}Cs/^{137}Cs ratio was below detection. The supporting data suggest that oxygen had reached zero by 80 m at Sta. 10 and 90 m at Sta. 9, with the onset of sulfide occurring about 15–20 m below oxygen zero. At Sta. 19,
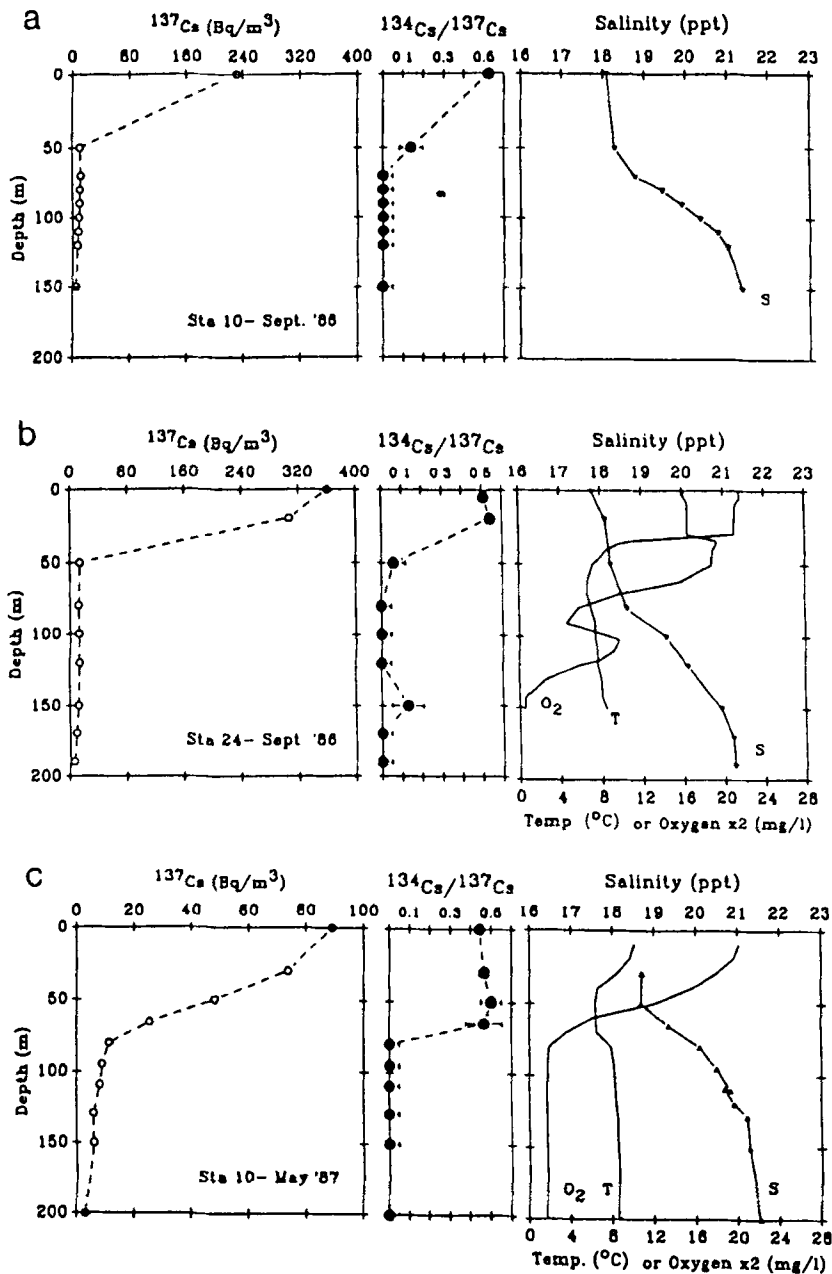
Fig. 3. Composite figure showing all Cs and ancillary data at Stas 24, 10 and 9. In a–f, the left panel represents total ^{137}Cs activity vs depth, the middle panel [134]Cs/^{137}Cs ratio vs depth, and the right panel ancillary hydrographic and oxygen data when available. The data are provided in Table 1, and the errors are plotted if larger than the symbol size. The 1986 data are shown for Sta. 10 (a) and 24 (b), the 1987 data for Sta. 10 (c) and 24 (d), and the 1988 data for Stas 10 (e) and 9 (f); see Fig. 1 for station locations. The salinity data in all years are from bottle casts, potential temperature data are from the CTD, and oxygen profiles in 1986 and 1987 are from an oxygen probe on the Turkish CTD package. Note that the oxygen zero is offset, due to calibration problems with the probe.
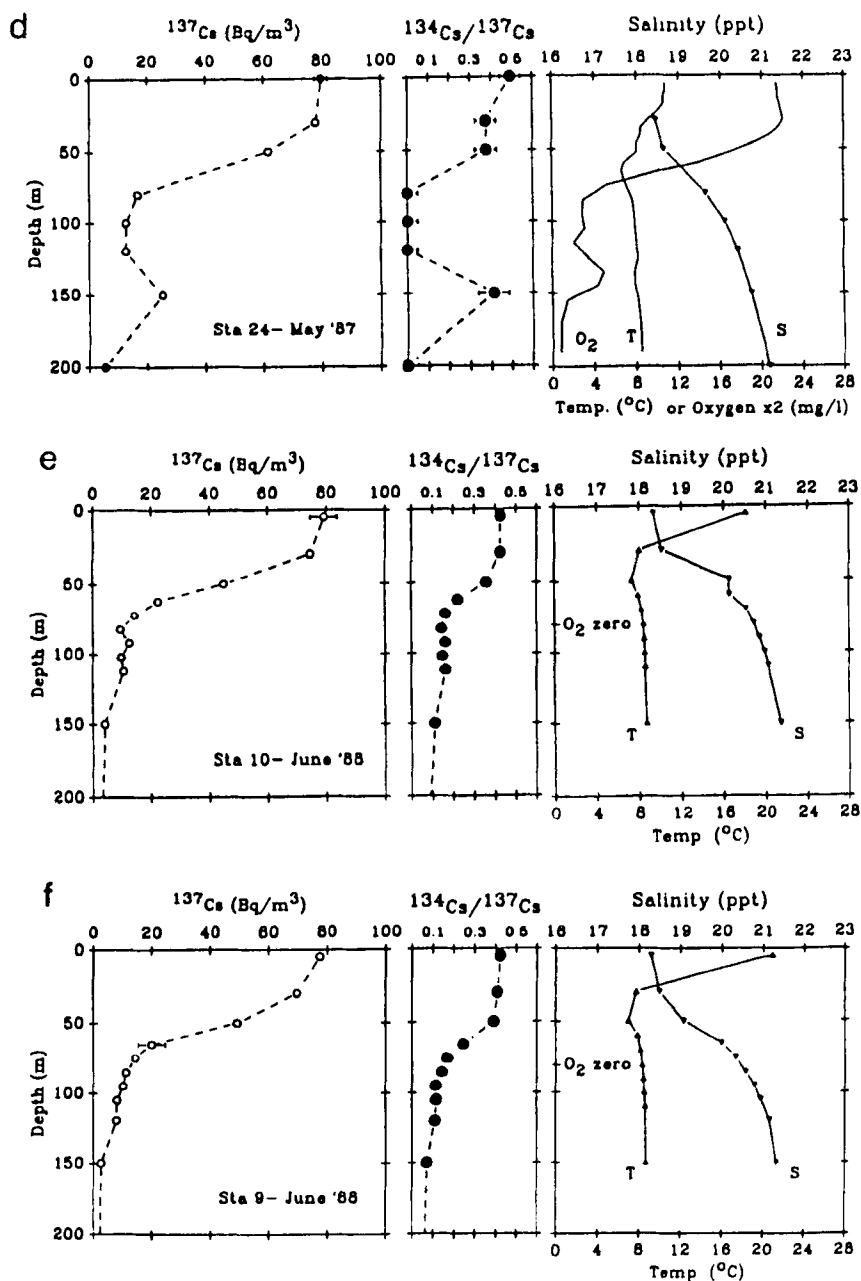
Fig. 3.   *Continued*.

near the edge of the eastern basin, [134]Cs is clearly evident down to 185 m (Table 1). The sample spacing at Sta. 19 was not as dense as at the other two 1988 sites, and the data are not plotted in Fig. 3. Slightly higher [134]Cs activities were found vs depth, but if plotted vs density, Sta. 19 is very similar to Sta. 7.

Table 1.   *Black Sea cesium and hydrographic data*

Z (m)	Pot. T (°C)	Salinity (‰)	Density (sigma θ)	$^{137}Cs \pm$ error (Bq m^{-3})	$(^{134}Cs/^{137}Cs) \pm$ error	Comments
Sta. 10: 19/09/86; 40°48.97′N, 30°25.48′E						
2		18.100		230.83 ± 1.67	0.52 ± 0.01	No CTD data
50		18.299		10.88 ± 0.50	0.54 ± 0.01	
70		18.775		11.83 ± 0.62	b.d.	
80		19.435		10.47 ± 0.32	b.d.	
90		19.895		9.97 ± 0.23	b.d.	
100		20.343		8.85 ± 0.22	b.d.	
110		20.773		8.33 ± 0.23	b.d.	
120		21.018		7.07 ± 0.22	b.d.	
150		21.358		5.35 ± 0.22	b.d.	
Sta. 24: 23/09/86; 41°24.49′N, 29°19.18′E						
2	21.46	17.800	11.34	360.33 ± 2.83	0.51 ± 0.01	
20	21.03	18.115	11.69	306.67 ± 3.50	0.54 ± 0.01	35 m mixed layer
50	7.21	18.238	14.23	13.77 ± 0.87	0.06 ± 0.06	T min. 60–70 m (T < 7°C)
80	7.03	18.637	14.56	12.00 ± 0.35	b.d.	
100	7.40	19.579	15.26	12.27 ± 0.28	b.d.	
120	7.66	20.113	15.65	13.77 ± 0.30	b.d.	
150	7.4*	20.922	16.3 est	12.30 ± 0.77	0.13 ± 0.08	Sub-surface oxygen peak
170	8.5*	21.201	16.4 est	9.30 ± 0.20	b.d.	O$_2$ zero approx. 140 m
190	8.5*	21.241	16.4 est	6.12 ± 0.32	b.d.	
Sta. 10: 12/05/87; 41°48.49′N, 30°26.27′E						
2	10.15	18.3*	13.9 est	89.00 ± 1.83	0.44 ± 0.03	10–15 m mixed layer
30	8.39	18.710	14.47	73.50 ± 1.50	0.46 ± 0.03	
50	6.32	18.686	14.66	47.83 ± 1.33	0.50 ± 0.05	T min. 40–50 m (T < 7°C)
65	6.48	19.354	15.17	22.50 ± 1.00	0.46 ± 0.09	
80	7.88	20.091	15.61	11.43 ± 0.38	b.d.	
95	8.14	20.504	15.90	8.85 ± 0.30	b.d.	O$_2$ zero between 80 and 90 m
109	8.29	20.700	16.03	8.07 ± 0.40	b.d.	
129	8.48	21.226	16.42	5.80 ± 0.28	b.d.	H$_2$S measured 0–130 m
150	8.51	21.282	16.46	5.95 ± 0.37	b.d.	
200	8.59	21.549	16.66	3.02 ± 0.30	b.d.	
Sta. 24: 12/05/87; 41°25.0′N, 29°17.5′E						
2	10.70	17.7*	13.4 est	79.67 ± 2.33	0.49 ± 0.05	
30	9.02	18.457	14.20	77.33 ± 1.83	0.37 ± 0.05	20 m mixed layer
50	8.00	18.637	14.46	61.67 ± 1.83	0.38 ± 0.06	T min. 60–70 m (T < 7°C)
80	7.29	19.634	15.31	16.67 ± 0.50	b.d.	
100	7.79	20.088	15.61	12.45 ± 0.32	b.d.	
120	8.07	20.423	15.84	11.88 ± 0.27	b.d.	
150	8.15	20.759	16.10	25.17 ± 1.17	0.41 ± 0.08	Sub-surface oxygen peak
200	8.48	21.189	16.39	5.47 ± 0.30	b.d.	O$_2$ zero by 170 m
250	8.48	21.414	16.57	6.23 ± 0.25	b.d.	H$_2$S onset 250 m

(Continued)

Table 1. *Continued*

Z (m)	Pot. T (°C)	Salinity (‰)	Density (sigma θ)	^{137}Cs ± error (Bq m^{-3})	(^{134}Cs/^{137}Cs) ± error	Comments
Sta. 10 (=BS47): 24/06/88; 41°50.5′N, 30°21.04′E						
5	20.191	18.348	12.065	77.94 ± 0.86	0.431 ± 0.005	7 m mixed layer
30	9.495	18.494	14.165	68.06 ± 0.55	0.424 ± 0.005	
50	6.991	18.944	14.801	41.26 ± 0.40	0.361 ± 0.005	T min. 44–51 m (T < 7°C)
62	7.782	19.891	15.460	20.46 ± 0.35	0.224 ± 0.008	
72	8.138	20.318	15.754	13.15 ± 0.22	0.162 ± 0.007	
82	8.304	20.587	15.945	8.73 ± 0.20	0.144 ± 0.011	O$_2$ zero 80 m
92	8.429	20.778	16.078	11.94 ± 0.27	0.163 ± 0.012	
102	8.451	20.914	16.182	9.05 ± 0.28	0.147 ± 0.013	H$_2$S onset 100 m
112	8.519	21.034	16.268	9.88 ± 0.18	0.163 ± 0.009	
150	8.673	21.338	16.486	3.57 ± 0.32	0.112 ± 0.019	
400	8.846	21.982	16.966	0.15 ± 0.07	b.d.	
Sta 9: 26/06/88; 42°09.62′N, 31°18.0′E						
5	20.941	18.294	11.842	73.08 ± 0.66	0.427 ± 0.006	9 m mixed layer
30	7.820	18.485	14.356	67.03 ± 0.60	0.414 ± 0.004	
50	6.989	19.046	14.882	43.99 ± 0.31	0.395 ± 0.004	T min. 35–50 m (T < 7°C)
65	7.846	19.951	15.500	18.77 ± 3.92	0.250 ± 0.006	
75	8.120	20.294	15.737	13.55 ± 0.35	0.170 ± 0.009	
85	8.301	20.558	15.922	10.42 ± 0.28	0.143 ± 0.012	O$_2$ zero 90 m
95	8.419	20.769	16.073	9.29 ± 0.25	0.113 ± 0.010	
105	8.514	20.942	16.196	12.02 ± 0.19	0.109 ± 0.007	
120	8.606	21.146	16.344	5.66 ± 0.22	0.114 ± 0.017	H$_2$S onset 110 m
150	8.674	21.334	16.483	2.46 ± 0.12	0.078 ± 0.018	
600	8.845	22.148	17.096	b.d.	b.d.	
Sta. 19: 01/07/88; 41°30.28′N, 40°44.47′E						
3	22.866	17.516	10.766	63.48 ± 0.57	0.438 ± 0.006	5 m mixed layer
30	7.922	18.187	14.112	77.31 ± 0.46	0.428 ± 0.004	
80	6.833	18.464	14.440	63.44 ± 0.57	0.432 ± 0.005	T min. 55–105 m (T < 7°C)
110	7.094	19.068	14.888	42.47 ± 0.47	0.416 ± 0.006	
135	7.850	20.047	15.575	23.69 ± 0.95	0.311 ± 0.006	O$_2$ zero 175 m
185	8.519	21.005	16.245	9.16 ± 0.23	0.141 ± 0.009	H$_2$S onset 109 m

All activity data decay corrected to 1 May 1986.

Error on ^{137}Cs activity reported as 2 sigma calculated from counting statistics and sample collecting efficiency; error on ^{134}Cs/^{137}Cs ratio reported as 1 sigma counting uncertainty.

b.d. = below detection.

*est = In many cases hydrographic data in 1986 and 1987 were not complete. Those data marked with an * were estimated from other sources, and hence the calculated densities are listed as "est", or estimated values.

Specific comments on each cruise are as follows:

1986 Sta. 24 pot. temp. from >150 m were estimated from 1987 data at these depths.

1987 Sta. 10 surface water salinity is estimated from 1988 data.

1987 Sta. 24 surface water salinity is estimated from 1988 data.

1988 Sta. 10 hydrographic data from BS47 cast 3 (WHITE *et al.*, 1989).

1988 Sta. 9 hydrographic data from BS49 cast 1.

1988 Sta. 19 hydrographic data from BS419 cast 1.

DISCUSSION

We believe the data presented above provide direct evidence of two main processes. First, the depth of winter mixing at the interior Sta. 10 can be shown to be no deeper than 50–65 m as evidenced by the changes in the upper water column Cs distributions between 1986 and 1987. Secondly, and on which the remainder of this manuscript will focus, is the evidence for the rapid penetration of surface water to depths well below the pycnocline between 1987 and 1988 at all of the sites.

Between May 1987 and July 1988, the data at the interior Sta. 10 clearly show a change in the depth of ^{134}Cs penetration by about 85 m (from 65 m in 1987 to 150 m in 1988). We propose that this vertical propagation of the Chernobyl Cs signal is driven by physical transport processes and not particle removal processes for the following reasons. First, the total percentage of the Cs isotopes found on particles in the Black Sea has been shown to be quite small (<0.2% of total retained on 0.5-μm filter; LIVINGSTON *et al.*, 1988). Also, a sediment trap moored at this same Sta. 10, showed that less than 0.1% of the ^{137}Cs inventory in the upper water column was removed by large-particle scavenging processes within the first year since the tracers were introduced (BUESSELER *et al.*, 1990b). Furthermore, in this same study it was found that there was no evidence of the release of Cs isotopes back into the water column from sinking material which carries the ^{137}Cs signal. So while a small percentage of Cs may be removed to sediments (particularly at ocean margins), the behavior of fallout Cs is dominated by advection and diffusion over time-scales of years to decades.

The observed penetration of Chernobyl Cs into the deep anoxic waters would appear to follow a physical process which rapidly transports and mixes surface waters to intermediate depths on an annual time-scale. Strictly vertical advective processes seem unlikely due to the strong vertical gradient in density which must be overcome. The density gradient between 65 and 150 m is close to one sigma theta unit (15.5–16.5 sigma θ, Table 1) and quite stable over this time-scale. The absolute magnitude of this subsurface mixing event can be calculated (equation 1) from the measured ^{134}Cs/^{137}Cs ratios at depth in 1988, our end-member ^{134}Cs/^{137}Cs ratios of 0.53 for pure Chernobyl-labeled waters in 1986, and 0 for pre-Chernobyl waters. With these end-members, the percentage of total ^{137}Cs originating from Chernobyl and found at depth at Stas 10 and 9 in 1988 is 28–38% between 65–85 m (^{134}Cs/^{137}Cs ratios of 0.15–0.20) and 15–27% for the waters between 85 and 150 m (^{134}Cs/^{137}Cs ratios of 0.08–0.14).

The flushing of these intermediate depths with surface waters would have major implications for other non-conservative water properties as well, such as oxygen and sulfide. The 20–30 m gap found in 1988 between oxygen zero and the sulfide interface at these sites would be consistent with a recent flushing event (MURRAY *et al.*, 1989; CODISPOTI *et al.*, 1991). Surface waters carrying the ^{134}Cs signal to depth would also carry oxygen with them, which would be consumed in the conversion of sulfide to sulfate. This type of flushing event has been used to account for the separation of the oxygen and sulfide interfaces in similar studies of anoxic fjords (EMERSON *et al.*, 1982). Although detailed oxygen and sulfide profiles are not available for 1986 and 1987, the CTD oxygen data and sulfide analyses from the R.V. *K. Piri Reis* suggest a separation of 40 m in the oxygen and sulfide boundaries at Sta. 10 in 1987 and even greater separation at Sta. 24 (Table 1 comments). This feature may be quite transient, and without more complete time-series

data it will be difficult to establish if this process occurs throughout the year, and how long it takes for the interface to re-establish itself.

We propose that the physical mixing event traced by the Cs isotopes is one that occurs predominantly at the Bosporus region along the SW margin and is transported laterally across the entire Black Sea basin. The process which is envisioned is one whereby the outflowing surface waters are entrained in a return flow by the inflowing Mediterranean waters, forming plumes of water with intermediate densities which are then laterally transported into the basin along density gradients. The evidence for this process can be seen in the margin Sta. 24 data in 1986 and 1987, where a sub-surface signal of Chernobyl-labeled waters is seen at intermediate depths. The densities of the samples at 150 m at Sta. 24 which contain the Chernobyl signal in 1986 and 1987 are within the range of 16–16.5 sigma theta (Table 1). If the feature followed isopycnal surfaces into the interior, these waters would correspond to depths between 80 and 150 m at Stas 9 and 10, precisely the depths where in 1988 we find evidence of recent surface water injection. The measured sub-surface currents in the range of tens of centimeters per second (BOGUSLAVSKIY *et al.*, 1976; SOROKIN, 1983) would easily be sufficient to transport the margin-derived signal to the interior stations within 1 year.

Given the measured properties of the waters at the margin Sta. 24 that show the sub-surface Chernobyl signal, it should be possible to estimate the simple end-members of a two-component mixing process which results in the observed sub-surface feature. This two-component model must hold for the Cs isotopes as well as other conservative properties such as salinity and temperature. The equation for a two component conservative mixing process is simply:

$$P_{ss} = F_o P_o + (1 - F_o)P_i, \qquad (3)$$

where
$\quad P_{ss}$ = the property measured in the sub-surface feature,
$\quad P_o$ = the property in the outflowing end-member waters,
$\quad P_i$ = the property in the inflowing end-member waters,
$\quad F_o$ = the fraction of outflowing waters in the sub-surface feature,
$1 - F_o$ = the fraction of inflowing waters in the sub-surface feature.

In Table 2, we have used this equation and a range of measured salinities to estimate the mixing ratio between the inflowing and outflowing waters. The wide range of salinities between the two end-members and the observed salinity in the sub-surface Cs peak allows us to tightly constrain the mixing ratio, F_o, which is 88.92% (Table 2). On a T–S plot (Fig. 4), it becomes clear that in order to have the final salinities measured in the sub-surface oxygen and Cs peak, the outward flowing water which is entrained must be relatively cool. The only waters with the correct salinity and low temperature are those at depths of 40–80 m at Sta. 24, at depths of the so-called Cold Intermediate Layer (CIL). While it is beyond the scope of this work to postulate on the origin of the CIL, it would appear from this simple calculation that entrainment occurs at the base of the outward-flowing Black Sea waters (at depths of the CIL) and the inward-flowing Mediterranean waters. This process would be entirely consistent with the observed Bosporus sill depth of 35 m. The [134]Cs/^{137}Cs data in the sub-surface peak have a rather large associated error, and hence cannot be used to tightly constrain the mixing ratio, F_o. It can be seen, though, that waters from depths in the range of 50–60 m would have the necessary Cs isotopic signature, salt and temperature needed for this simple mixing model to hold.

Table 2. *Calculated mixing ratios and properties from two-component conservative mixing model*

	Measured*			Calculated†
	P_o‡	P_i	P_{ss}	F_o
Salinity:	18.5–19.2 ppt.	38.1–38.6 ppt.	20.76 ppt.	88–92%

	From salinity	Measured*		Calculated†
	F_o	P_i	P_{ss}	P_o
^{134}Cs/^{137}Cs:	88–92%	0	0.41 ± 0.08	0.36 ± 0.56
Temperature:	88–92%	14.7–14.9°C	7.8–8.1°C	6.8–7.5°C

*Measured properties for P_o and P_{ss} are from Sta. 24, 1987 (Table 1). Sea of Marmara properties are used for P_i [values from 30–100 m, 1986 (unpublished Cs results and CTD data R.V. *K. Piri Reis*) and 1988 (Murray *et al.*, 1991)].

†Calculated from equation (3) in text.

‡P_o, P_i and P_{ss} are the property of outflowing, inflowing and sub-surface waters, respectively. F_o is the fraction of outflowing surface waters entrained in the sub-surface feature. See equation (3) in text for details.

The entrainment process we are proposing need not be continuous, nor is it likely to be limited to a single mixing ratio and density. It would appear that this is just one facet of deep-water renewal in the Black Sea. The major implications of this process are numerous. For instance, since rapid ventilation across the oxic/anoxic interface can occur on quite short time-scales, this will necessitate a lateral, rather than a one-dimensional vertical interpretation of much of the biological and geochemical water column data. Therefore, features in vertical profiles may be related to margin sources and sinks and not *in situ* processes. Depending upon the relative reaction vs transport rates, with increasing distance from the SW margin entrainment region, biological and chemical mechanisms would work on erasing, for example, the sub-surface oxygen peaks. Only the more
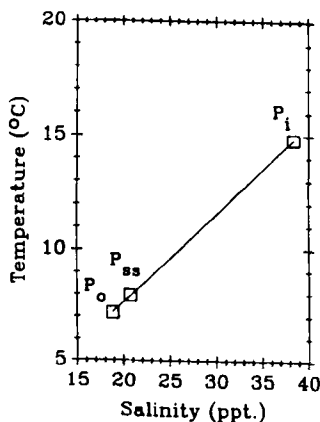

Fig. 4. Temperature and salinity plot for Sta. 24 data in 1987. P_i represents the inflowing Mediterranean waters, P_{ss} the entrained waters at 150 m which show a sub-surface peak in ^{134}Cs/^{137}Cs, and P_o the outflowing Black Sea waters. See text and Table 2 for details.

conservative tracers of this mixing process, such as the Cs isotopes, would remain unaltered. Not only may waters move laterally quite rapidly, but suspended sediment from the margin may be transported into the interior by the same mechanism.

Assuming our hypothesis is correct and entrainment of surface waters occurs in the Bosporus region, then one would expect the other R.V. *Knorr* data to show similar entrainment features. In an analysis of hydrographic data from R.V. *Knorr* cruise 4 in 1988, Özsoy *et al.* (1991) examined the complete set of potential temperatures and salinity data and found cold anomalies at Sta. 7 between 70 and 200 m consistent with the injection of CIL oxic waters into anoxic intermediate depths. Özsoy *et al.* (1991) claim to have found similar cold anomalies at intermediate depths at four stations near the SW margin. Using a recent data set from a large number of Turkish cruises in 1987–1989 along the SW margin, Oguz *et al.* (1991) also report evidence of similar hydrographic anomalies. These workers spotted the entrained waters both by the observed temperature anomaly and by using an oxygen probe mounted on the CTD. They found over 35 sites between the Bosporus and 32°E where relatively cold and/or oxygen-rich waters were found at depths between 100 and 500 m. In general, since the entrained waters would tend to seek out their own density level, searching for hydrographic evidence of sub-surface mixing is only possible near the source region.

As mentioned earlier, the evidence of CODISPOTI *et al.* (1991) showing an oxygen "null zone" basin-wide during the R.V. *Knorr* cruises is consistent with our Cs data. Upon examination of Codispoti's detailed oxygen, sulfide and nutrient profiles, these authors also find direct evidence of interleaving of waters in the observed wavy patterns of ammonium, phosphate, silicate and sulfide (CODISPOTI *et al.*, 1991). Interestingly, they see such features predominantly along the SW margin and at the BSK2 site which lies in the center of the Black Sea between the eastern and western gyres. This BSK2 site would appear to be strongly influenced by margin-related mixing processes which are then rapidly transported with the western gyre currents into this central basin site. Similar to the cold temperature anomalies, the nutrient and oxygen peaks are smoothed at the interior stations.

When the three R.V. *Knorr* stations sampled for Cs isotopes are compared, Sta. 10 stands out as having the strongest ancillary evidence (nutrients, CTD, etc.) in support of recent entrainment of surface waters to depth. When the $^{134}Cs/^{137}Cs$ ratios are examined vs density, Sta. 10 also stands out from Sta. 9 as having slightly higher $^{134}Cs/^{137}Cs$ ratios at equivalent densities. Interestingly, this site along the SW margin shows a strong suspended particulate maximum at depths of 95–125 m. These data are shown in Fig. 5 where light transmission and particulate Mn, Fe and ^{234}Th are plotted. The decrease in light transmission below oxygen zero and at the depth of H_2S onset stands out at this and other R.V. *Knorr* margin stations and is absent, or much diminished at the interior basin stations. The source of this feature could be related to *in situ* biological or chemical processes which are perhaps tied to the onset of H_2S in the water column. Equally plausible, and suggested here, is that this feature originates at the margins, and perhaps represents the resuspension of originally oxic margin sediments and subsequent lateral injection of this material along isopycnals into the basin interior. This would be consistent with the observed high particulate Mn and Fe content and elevated ^{234}Th activities. Özsoy and AYDIN (1991) provide evidence that suggests that abrupt changes in topography, such as the canyons along the SW margin, can trigger vertical motions or internal waves which lead to the resuspension of margin sediments.
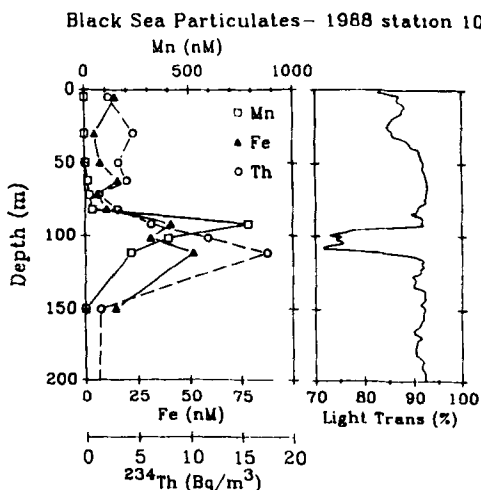
Black Sea Particulates— 1988 station 10

Fig. 5.   Particulate Mn, Fe and ^{234}Th (^{234}Th decay corrected to time of sampling) profiles and percentage transmission vs depth for Sta. 10 in 1988 (BS47).

Since Mn oxides would be expected to undergo reductive resolubilization in anoxic waters, the particulate Mn peak found below oxygen zero would not be expected to be stable over time. Indeed, Sta. 9 prefilters and light transmission profiles do not show a strong particle maximum in the region of H_2S onset. In a detailed trace metal study conducted on R.V. Knorr cruise 3, LEWIS and LANDING (1991) see more than an order of magnitude lower particulate Mn values at the interior stations where they performed their work relative to our Sta. 10. Their data show a peak in particulate Mn just above oxygen zero, consistent with in situ chemical processes and a smaller secondary particulate Mn peak some 20 m below. If our hypothesis is correct, then this lower peak would represent a relic Mn feature that originated at the margins but is much reduced at the interior stations due to reductive release of Mn and/or settling of the material during lateral transit into the basin.

It is interesting to note that in the 1969 R.V. Atlantis-II particulate trace metal data (SPENCER et al., 1972; BREWER and SPENCER, 1974), the stations closest to the Black Sea shelf showed particulate Mn peaks of similar magnitude as seen here in Fig. 5 and a similarly much reduced maximum at interior sites. Particulate Fe in the 1969 data was found to be especially elevated at a shelf station just off the mouth of the Bosporus. While the SPENCER et al. (1972) Fe peak was at or below oxygen zero, their Mn peak was typically shallower than oxygen zero. As suggested by SPENCER et al. (1972), the lower Fe at the margin may reflect detrital material and the upper Mn peak oxidation and precipitation of Mn oxides. The major difference, however, between our findings and those of SPENCER et al. (1972) is that both Fe and Mn peak below oxygen zero at our Sta. 10. This rules out in situ oxidation of Mn at this site driven by vertical advection diffusion as the source of Mn-rich particles. It does not rule out oxidation of Mn at the shelf-edge and subsequent lateral transport to this site.

We feel that the R.V. *Knorr* data discussed above, as well as the Turkish studies in the late 1980s, would all support the existence of significant entrainment and lateral transport of water and sediments. A final point to be addressed is whether or not this process is new, or is entrainment and lateral mixing a general feature consistent with earlier data.

While entrainment was not typically incorporated into earlier interpretations of Black Sea data, the general idea of ventilation of intermediate Black Sea waters by an entrainment process is not completely new. Early observations of hydrographic data in the Bosporus region, for example, led BOGDANOVA (1961) to postulate that the incoming Mediterranean water had to be mixed significantly with surface waters, and would not be expected to sink to the bottom but rather to intermediate depths. KOCZY and OSTLUND (1966), studying the hydrographic data from the R.V. *John Elliot Pillsbury* cruise in 1965 to the Black Sea, specifically suggest that entrainment occurs at a ratio of about 4–5 parts surface water between 40 and 60 m and 1 part incoming Mediterranean water. Certainly it has also been argued from theoretical grounds and early ^{14}C data that deep-water ventilation must include "entraining convective boundary currents with random termination depths" (ROOTH, 1986). Furthermore, ROOTH (1986) speculated that conditions for deep convection in the Black Sea occur only during a few months or less during the year, and that in other periods entrainment plume terminations would be in the region of significant density gradients (i.e. the oxic/anoxic interface).

Data in support of entrainment and the layering of water masses with differing lateral source terms are not obvious in earlier studies. This may simply be a result of the relatively coarse vertical sampling intervals over which much of the earlier data were collected. Modern CTDs allow for essentially continuous vertical sampling of hydrographic data, and the continuous pumping system of CODISPOTI *et al.* (1991) allows for water sampling on vertical scales of less than 1 m. Upon re-examination of oxygen profiles from the R.V. *Atlantis-II*, one does find sub-surface oxygen maxima at Sta. 1438 (GRASSHOFF, 1975, fig. 15.68). This station is located off the southern margin and contrasts with his smooth oxygen profile at interior sites. In an early tracer data set, TOP and CLARKE (1983) saw distinct sub-surface maxima in both helium and neon data at 65, 215 and 322 m at their Sta. 1355 in the central Black Sea. These features were not believed to be artifacts, but rather to have resulted from distinct plumes of water masses related again to the input of Mediterranean water which settled to different horizons (after mixing with Black Sea waters).

If a consequence of entrainment is the establishment of the oxygen "null zone", then earlier studies suggesting an overlap at the pycnocline where oxygen and sulfide co-exist (the so-called "S layer", e.g. FASHCHUK and AYZATULLIN, 1986), may be in error. The overlap may result as a sampling artifact due to atmospheric contamination as suggested by GRASSHOFF (1975) and CODISPOTI *et al.* (1991).

We feel that earlier studies support our view that entrainment and lateral mixing of oxic waters into anoxic depths is not a new or unique process. If it were, in the absence of continuing entrainment, the depth of the oxygen and sulfide boundaries should move closer together, while the Chernobyl Cs tracers will remain at depth and continue to be mixed both vertically and laterally by advective and diffusive processes. Following ^{134}Cs/^{137}Cs ratios and the oxygen and sulfide boundaries over time would therefore be quite useful in furthering our understanding of the regularity and extent of mixing at these intermediate depths.

SUMMARY AND CONCLUSIONS

The data presented above for the Cs isotopes suggest that the waters between 50 and 150 m in the interior of the Black Sea can be rapidly ventilated by surface waters via an entrainment process and lateral isopycnal transport. This process is thought to occur in the Bosporus region along the SW margin and is supported by the observation of sub-surface ^{134}Cs/^{137}Cs peaks in this region in 1986 and 1987. This is consistent with the growing body of R.V. *Knorr* hydrographic and tracer data sets. Being a conservative tracer of recent surface water origin, Chernobyl Cs is ideally suited to study this entrainment process.

Multiple interleaving layers of water masses with differing histories must therefore be considered in the interpretation of any vertical profile. The chemocline, rather than a site of one-dimensional transport, as currently used in most models, is a region of strong lateral ventilation. For example, the separation between the depth of oxygen zero and sulfide onset (Murray *et al.*, 1989; Codispoti *et al.*, 1991) is likely a reflection of lateral processes. Both waters and suspended particulates would be affected by this process. This is seen in particulate data, where peaks in Mn, Fe and ^{234}Th are found in anoxic waters at margin sites and are absent or much reduced in the basin interior. It would appear that these suspended sediments originate from the oxic margin shelf and are transported laterally across the basin. Subsequent reduction and settling losses diminish this margin signal at interior sites. A final point is that budgets and models for deep Black Sea ventilation may need to increase the entrainment fluxes if this feature is as strong and regular as the 1986–1988 Cs data suggest (such as the entrainment flow, W_1, in Boudreau and Leblond's (1989) evolutionary model for water and salt in the Black Sea).

Future analysis of the Cs tracer data in conjunction with other tracers measured on the R.V. *Knorr* cruise (such as freons, tritium, ^{14}C, etc.) may allow for more quantitative modeling to be attempted which includes this entrainment process in Black Sea ventilation models. It would also be very useful if more complete long-term tracer and hydrographic monitoring in follow-up studies could establish the true driving forces which determine the extent and timing of this process. The dynamics of overflow processes and entrainment are likely to be very complex, and snapshots of vertical distributions at single points in space and time are not likely to be sufficient for gaining a more complete understanding of ventilation processes in this basin. Recent reductions in riverine inputs to the Black Sea (Al'tman, 1982; Tolmazin, 1985) may also severely change the intensity and dynamics of intermediate and deep water ventilation in the near future.

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