

Impact of the Mediterranean Outflow Water on particle dynamics in intermediate waters of the North-East Atlantic, as revealed by ^{234}Th and ^{228}Th

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Abstract

Over the last decade ^{234}Th has become increasingly used to study particle transport in the ocean on a timescale of weeks. The application of ^{234}Th is mainly focused on the determination of particle and associated carbon fluxes from oceanic surface water. However, ^{234}Th is also suitable for investigating particle dynamic from the upper ocean down to interface sediments, as illustrated by the present work which reports unexpected behavior of ^{234}Th in intermediate waters associated with the Mediterranean Outflow Water (MOW). Concentration profiles of dissolved ^{238}U and ^{228}Ra , and dissolved and particulate ^{234}Th and ^{228}Th were measured in the Mediterranean Outflow Water (MOW) near the Gibraltar Straits and at two sites ($36^{\circ}30'\text{N} - 15^{\circ}35'\text{W}$, *Nicole*; $36^{\circ}27'\text{N} - 10^{\circ}35'\text{W}$, *Yseult*) which had hydrographic characteristics of Meddies, i.e. MOW that propagates as eddies in the North-Eastern Atlantic at intermediate depths.

There are marked differences in the distribution of thorium between MOW and the surrounding Atlantic waters. At the youngest Meddy *Nicole* salinity maximum at 1,000 meters depth, $^{234}\text{Th}(\text{total})$: ^{238}U and $^{228}\text{Th}(\text{total})$: ^{228}Ra activity ratios are significantly lower than radioactive

equilibrium, indicating an unusual deficit of short half-life thorium nuclides. This implies an export of thorium, presumably on particles, from intermediate Meddy *Nicole* waters. This process is supported by an increase of particulate thorium fluxes measured in sediment traps deployed for two weeks above and within Meddy *Nicole*. In contrast, offshore Meddy *Yseult* has more typical profiles of both thorium nuclides that are nearly in equilibrium with their parents. These results indicate that at intermediate depths, the presence of MOW affects the exchange of reactive elements between particles and dissolved forms and enhances the downward flux of particles from intermediate waters in the North-East Atlantic.

Keywords: thorium, residence time, particulate flux, water column, Meddy, Mediterranean water

Regional index term: Northeast Atlantic (0-20°W, 34-36°N)

1. Introduction

The different isotopes of the natural radioactive Uranium and Thorium decay series are powerful tools for calculating the intensity of chemical scavenging within aquatic ecosystems (Cochran, 1992, and references herein). In particular, the radiogenic isotopes of thorium, supplied to the ocean by decay of dissolved parents, have been used for determining the removal rate of settling particles, and particulate residence times (Bhat et al., 1969; Broecker et al., 1973; Coale and Bruland, 1985). ^{234}Th , with its short half-life of 24.1 days, is an appropriate tracer for studying these processes on a timescales of weeks (Buesseler et al., 1992; Benitez-Nelson et al., 2001; Cochran et al, same issue), whereas the longer lived thorium isotopes, ^{228}Th (1.9 years) and ^{230}Th (75,200 y) are more suitable for following processes occurring on timescales of months to years (Bacon and Anderson, 1982; Luo et al., 1995; Yu et al., 2001). In the open ocean, particle reactive ^{234}Th is often depleted relative to its parents, thus enabling the quantification of export production (e.g. ^{234}Th removed on settling particles) from surface waters to depth (Buesseler, 1998). ^{234}Th typically reaches secular equilibrium below 200 m. As a result, sampling of ^{234}Th usually only occurs in the upper layers of the ocean where deficits are expected. However several studies have reported ^{234}Th excess

concentrations below the mixed layer, which result from particle break-up and remineralization (Savoie et al., 2004), or ^{234}Th depletions in deep nepheloid layers, ascribed to particle exchange between bottom waters and surface sediments (Bacon and Rutgers van der Loeff, 1989; Turnewish and Springer, 2001; Rutgers van der Loeff et al., 2002). This work presents evidence of unexpected behavior of ^{234}Th in intermediate waters of the North-East Atlantic.

Due to the Mediterranean Outflow Water (MOW) off Gibraltar, the North-East Atlantic Ocean is characterized by a warm and saline water mass at a depth of about 800 to 1,200 meters (Thorpe, 1972). This Mediterranean water is comprised of chemical and biological properties, which contrast with those of surrounding Atlantic waters (Savenkoff et al., 1993). In addition MOW carries suspended particulate matter, which differs in load and characteristics from those of Atlantic waters (Biscaye and Eitrem, 1977; Ambar et al., 2002). These particles, which are deposited along the Iberian slope as MOW propagates into the Atlantic, have been used to reconstruct hydrological exchanges at the Gibraltar strait over the past 18,000 years (Grousset et al., 1988). In addition the MOW can propagate as large anticyclonic subsurface eddies, called Meddies, which may subsist as individual entities for as long as 2 to 3 years without completely mixing with Atlantic waters (Armi et al., 1988; Rossby, 1988). These Meddies, which exhibit a positive salinity anomaly of about 0.25, have a typical diameter of 40 - 100 km and dwell at depths ranging from about 700 to 1,500 m. In recent years Meddies have been found to be relatively common in the Canary Basin (Armi and Zenk, 1984; Stammer et al., 1991; Rios et al., 1992; Fig. 1)

Because Meddies originate in the Mediterranean and are relatively abundant, they could play a role in the transport of trace elements into the Northeast Atlantic, as well as heat and salt (Marshall, 1988). But little is known about the impact of Meddies on metal scavenging and vertical particle flux in the water column. As Meddies are mesoscale features with lifetimes on the order of months to years, ^{234}Th : ^{238}U and ^{228}Th : ^{228}Ra appear to be the most appropriate radioisotope pairs to study these particle interactions. The objectives of this work were to determine: (1) how these radionuclides are partitioned between dissolved and particulate forms, (2) how this partitioning is affected by the presence of MOW in the water column, (3) the vertical fluxes of radionuclides

carried by sinking particles, and (4) how the sinking flux changes as Meddies age using water column measurements and sediment traps.

2. Methods

Samples were collected from different sites in the N.W. Mediterranean Sea and N.E. Atlantic following the MOW flow path during two cruises of the JGOFS-France MEDATLANTE program on the R/V *Jean Charcot*: (1) MEDATLANTE I (from December, 26, 1988 to January, 28, 1989) and (2) MEDATLANTE II (from August, 8 to Septembre 8, 1989) (Fig. 1). To identify Meddies, which are anomalous in their temperature (T) and salinity (S) characteristics compared to the surrounding water masses (typically $> 11.9^{\circ}\text{C}$ and 36.2), repeated CTD profiles were conducted. These profiles led to the selection of two sites for which T and S indicated the presence of Meddies: (1) *Nicole* (MEDATLANTE I) and (2) *Yseult* (MEDATLANTE II). These two sites were investigated in detail by water column profiles between surface and 3100 m and by sediment traps.

The low levels of ^{228}Ra and ^{228}Th usually measured in seawater require either large sample volumes or more sensitive measurement methods (Orr, 1988). During the MEDATLANTE cruises, we used two techniques: (1) in situ filtration of large volumes (300 to 800 l) onto MnO_2 -coated cartridges, and (2) $\text{Fe}(\text{OH})_3$ coprecipitation on reduced volumes (55-60 l) The preparation and radiochemical treatment of cartridges are described in Schmidt and Reyss (1996).

On the reduced volume samples, separation of dissolved ^{234}Th from its ^{238}U parent was carried out on board ship within 24 hours after seawater collection in order to reduce ^{238}U ingrowth. A ^{229}Th yield tracer and 150 mg Fe (as FeCl_3) were added to the dissolved sample after acidification to pH 2. After spike equilibration and $\text{Fe}(\text{OH})_3$ precipitation, ^{234}Th was separated from ^{238}U using standard anionic exchange procedures (Schmidt et Reyss, 2000; Rutgers van der Loeff et al, this issue). Samples were first α counted to enable the determination of ^{228}Th and ^{229}Th (chemical yield), followed by a γ counting for ^{234}Th . Particulate thorium activities were directly measured on filters by γ counting.

Two very low-background, high-efficiency well type germanium detectors (Ge volume of 215 and 430 cm³, low-noise Al-(4% Si) alloy) were used; both detectors are in the Laboratoire Souterrain de Modane (LSM CNRS / CEA, French Alps) shielded from cosmic radiations by 1,700 m of rock and from ambient radioactivity by 20 cm of archaeological lead and 10 cm of electrolytic copper (Reyss et al., 1995). The three standards used for the calibration of the γ detector are (1) a marine sediment enriched with 1000 ppm of U and Th U.S. standards from National Bureau of Standards, (2) a matrix of a Ba solution enriched with ²²⁶Ra standard (Harwell) and (3) a known amount of ²³⁸U deposited on an aluminum disk and cross checked by α -counting using a grid chamber of a known efficiencies. Counting efficiencies and backgrounds for ²³⁴Th, ²²⁸Th, ²²⁶Ra and ²²⁸Ra are detailed in Reyss et al. (1995) and Schmidt and Reyss (1996, 2000).

Radium was co-precipitated with BaSO₄ from the cartridge solution or seawater and radium activities were measured by γ -counting (Schmidt and Reyss, 1996). Uranium was co-precipitated with Fe(OH)₃, in the presence of a known amount of ²³²U spike from 2 liters of seawater and subsequently purified by ion-exchange (Schmidt and Reyss, 1991). Uranium activities were determined by α -counting.

At both sites, two automated sediment traps (TECHNICAP, PPS3, 0.125 m² opening) were moored at depths of 700 and 1,000 m during MEDATLANTE I at the Meddy *Nicole* site from January, 6 to 26 1989 (20 days) and during MEDATLANTE II at the Meddy *Nicole* site from August, 20 to September 05, 1989 (15 days). Each trap collected a single sample for the duration of the deployment. Preliminary treatment of trapped particles (sub-sampling, freeze-drying, weighing, etc.) was done at the IAEA Laboratory of Monaco as described in Miquel et al. (1994). Radionuclide activities were determined by non-destructive low-background high-efficiency γ spectrometry. ²³⁴Th and ²²⁸Th activities were corrected for decay to the midpoint of sample collection. Specific activities (dpm g⁻¹) measured in the sediment trap samples were multiplied by the mass fluxes (mg m⁻² d⁻¹) to yield the radionuclide fluxes (dpm m⁻² d⁻¹). All errors were determined from counting statistics.

3. Results and discussion

3.1. Impact of the Meddies on the vertical distribution of ^{228}Ra

The first Meddy, named *Nicole*, was sampled at 36°27'N - 10°35'W during MEDATLANTE I in the vicinity of Meddies formation area, off the Gibraltar Straits. This site is characterized by a warm, salty, surface mixed layer (Figure 2). Below 100 m depth, both temperature and salinity decrease rapidly with minimum values around 500 m depth. Below 500 m, salinity increases to 36.46 at 1200 m, highlighting the presence of Meddy *Nicole*. Below 1500 m, T and S are typical of the deep Atlantic. Repeated 0-2000 CTD profiles showed that *Nicole* is a large lens, about 100 km in diameter and 800 m thick from 700 to 1500 m.

The second Meddy, *Yseult*, was sampled at 36°30'N - 15°35'W during MEDATLANTE II. In the upper 500 m, T and S profiles present the same general shape to those of *Nicole*. Both T and S increase to reach maximum values at a depth of around 1100 m, corresponding to the center of the lens (Figure 2). However *Yseult* had a weaker salinity signal than *Nicole* and appeared to be about half *Nicole*'s size. This is likely due to the fact that *Yseult* was found far from the source area. Hence dilution by Atlantic waters was more pronounced. Dilution processes have been hypothesized to limit the mean life of Meddies (Armi et al., 1989).

The presence of Meddies *Nicole* and *Yseult* is reflected in the vertical ^{228}Ra profiles (Table 1, Figures 3/4). Under the thermocline, ^{228}Ra decreases rapidly to reach activities less than 5×10^{-3} dpm L^{-1} at 500-600 m and below 1500 m, as often reported for deep waters (Moore et al., 1986). However, ^{228}Ra shows enhanced values in the intermediate Meddies waters: up to 9×10^{-3} dpm L^{-1} at 1200 m for *Nicole*, and 7×10^{-3} dpm L^{-1} at 1100 m for *Yseult*. Both Meddies show higher ^{228}Ra activities when compared to surrounding Atlantic waters ($< 5 \times 10^{-3}$ dpm L^{-1}). This results from the recent contact of the MOW with the Spanish continental shelf. The maximum ^{228}Ra activity of *Yseult* is lower than in *Nicole* due to (1) progressive dilution of Meddy by Atlantic waters, which contain lower levels of ^{228}Ra , and (2) radioactive decay during the longer advection time from the

shelf source. This decay, used as an internal tracer of water mass motion, leads to a transit time of Meddy *Yseult* of less than 1 year since its formation (Schmidt and Reys, 1996).

3.2. Thorium activities within the Mediterranean Outflow Water

3.2.1. Gibraltar strait. To define Meddy core water, we sampled the MOW just before and after the Gibraltar Strait (Fig. 1, Table 1) at 36°41N-1°12W (F: at 1000 m) and 35°53N-6°35W (I: at 450 m, 50 m above bottom). At Station F within the Mediterranean Sea, both ^{234}Th and ^{228}Th are in radioactive equilibrium with their respective parents, ^{238}U and ^{228}Ra . Thorium activities are mainly in the dissolved phase, as usually observed in deep waters. After the Gibraltar strait, at Station I in the Atlantic Ocean, although both ^{234}Th and ^{228}Th are still in equilibrium with their parent, there is a noticeable increase in particulate Th content, with $^{234}\text{Th}^p$ increasing by a factor of 4. This may be due to an increase of MOW particle load when the Mediterranean water flows as an undercurrent jet in contact with the seafloor through the Straits of Gibraltar (Thorpe, 1972).

3.2.2. Meddy Nicole. The Meddy *Nicole* was found westward of the Gibraltar Strait (Fig 1). Figure 3 shows radionuclide profiles between 500 and 1700 m depth at the *Nicole* site. In Atlantic waters, at 500, 800 and 1700 m, both thorium isotopes are close to equilibrium with their respective parents. These results are in agreement with those usually reported in deep waters (Bacon and Anderson, 1982). However, within Meddy *Nicole* core water, scavenging of Th is observed. At 1000 m, ^{234}Th and ^{228}Th show measurable depletions relative to ^{238}U and ^{228}Ra , of 12 % and 51 % respectively. This is unexpected at such deep depths. ^{228}Th activities are consistently lower than equilibrium values at all depths corresponding to Meddy *Nicole* (800, 1000 and 1200 m). These results may indicate that recent particle export had occurred.

Particle scavenging is confirmed by sediment trap data which recorded a sedimentation rate of 309 mg (dry weight) $\text{m}^{-2} \text{d}^{-1}$ and an associated particulate ^{234}Th flux of 860 dpm $\text{m}^{-2} \text{d}^{-1}$ at 1,000 m (Table 2). These values are rather high, in the mean range reported by Buesseler (1991) for ^{234}Th fluxes from the upper 50 - 300 m. Mass fluxes also have an unexpected increase, by a factor of 3, between 700 and 1,000 m. Meddies are mostly comprised of MOW, which flows from the Gibraltar

Strait to the west of 8°W in contact with sediments around the northern side of the Gulf of Cadiz. Previous observations have reported a cloud of sediment originated from the Mediterranean water itself within the Gulf of Cadiz (Thorpe, 1972). Therefore such an increase in settling particles may be specifically due to the advection of MOW, which was recently in contact with the seafloor.

Thorium specific activities in the two traps have values similar to those observed for trapped particles (Shaw et al., 1998). The particulate ^{228}Th flux at 700 m, $1.7 \text{ dpm m}^{-2} \text{ d}^{-1}$, is similar to those reported in deep Sargasso Sea by Bacon et al (1985). In contrast, at 1,000 m, this flux is much higher and reaches $4.2 \text{ dpm m}^{-2} \text{ d}^{-1}$. An increase in particulate ^{228}Th flux can explain the deficit of ^{228}Th relative to ^{228}Ra . However, in this case, another factor needs to be included as well. A few months prior to sampling, MOW was newly enriched with radium in the vicinity of Gibraltar Straits when it was in direct contact with sediments (Schmidt and Reys, 1996). Therefore it is not surprising that ^{228}Th , with its half-life of 1.9 years, may not have reached complete ingrowth (secular equilibrium) within Meddy *Nicole*.

3.2.3. *Meddy Yseult*. At site *Yseult*, contrary to salinity or radium profiles, there is no evidence of the presence of a Meddy at intermediate depths in the total ^{234}Th distribution (Fig. 4). In surface waters total ^{234}Th has only a weak deficit, 13%, presumably due to biological activity, as is often observed in summer. Below 100 m depth, ^{234}Th is in close equilibrium with ^{238}U . Only particulate ^{234}Th has a small increase at 1100 m depth, from an average of 1 and 5%, to 10% within the Meddy *Yseult* core (Table 1). Similar to ^{234}Th , total ^{228}Th has a marked deficiency in surface waters, 57%, but is in equilibrium in deep Atlantic waters. In contrast to ^{234}Th , however, total ^{228}Th is always less than ^{228}Ra activities within Meddy *Yseult*, at 850 and 1100 m. The equilibrium of ^{234}Th with ^{238}U indicates that no scavenging event had occurred within the past 35 days (mean life of ^{234}Th). Thus, such processes cannot account for $^{228}\text{Th} / ^{228}\text{Ra}$ disequilibrium. Rather, it implies that the time elapsed since ^{228}Ra supply (e.g. contact of MOW with sediment) was too short to allow complete ingrowth of ^{228}Th relative to ^{228}Ra at 1100 m.

The absence of a significant thorium export is supported by trap data. The particulate flux at 1,000 m is considerably smaller, $21 \text{ mg m}^{-2} \text{ d}^{-1}$, when compared to 1000 m in Meddy *Nicole* in

January ($309 \text{ mg m}^{-2} \text{ d}^{-1}$) and not statistically different from that observed at 700 m (Table 2). At 1,000 m, specific Th activities are similar to those previously measured a few months earlier. At 700 m, however, specific activities of ^{234}Th and ^{228}Th are considerably higher, by about a factor of 2. One explanation could be the occurrence of very fine and probably detrital particles, with higher specific surface adsorption.

3.3. Influence of MOW onto particle exchange

The distribution of the short-lived thorium isotopes is clearly affected by the presence of the MOW, and in particular by Meddies. The purpose of our discussion now is to define the influence of MOW on particle exchange.

3.3.1. *Deep water scavenging.* For deep waters, Bacon and Anderson (1982) proposed the following equation for determining rate coefficients of thorium uptake by the particulate matter:

$$k_1 C_d^X = (\lambda^X + k_{-1}) C_p^X \quad (1)$$

with k_1 and k_{-1} adsorption and desorption rate coefficients, C_d^X and C_p^X activities of dissolved and particulate thorium (X: ^{234}Th or ^{228}Th). Only samples corresponding to Atlantic and MOW, with no evidence of thorium deficit, were used for this calculation (Table 3). The assumption is that the residence time of suspended particles is long enough to allow equilibrium between scavenging (loss) and remineralization (gain) processes of thorium.

Adsorption rate coefficients of Atlantic waters vary between 0.12 to 1.30 year^{-1} (Table 3), and is in the upper range of values reported for the deep Pacific (Bacon and Anderson, 1982) or in the Nansen Basin, Arctic Ocean (Cochran et al, 1995). But for MOW, there is a marked discrepancy: k_1 reaches up to 3.4 y^{-1} . This indicates an unusually large increase of thorium scavenging onto particles, in comparison with surrounding waters. Unfortunately there was no estimate of particle load during this program. Nevertheless Bacon and Anderson (1982) have shown a strong positive correlation between adsorption rate and total suspended matter concentration. Therefore the striking increase of adsorption rates in MOW after the Gibraltar Strait suggests an increase in total

suspended matter, which is ascribed to particle resuspension when MOW crossed the Gibraltar Strait. Indeed the high-salinity MOW layer is tagged by a relatively high abundance of particles (Ambar et al, 2002). Desorption rates vary from 0.3 to 7.4 yr⁻¹, with the highest value observed for MOW. In Atlantic waters, k₋₁ of 0.3-4.3 lies within the range of values reported previously (Bacon and Anderson, 1982; Cochran et al., 1995).

3.3.2. *Thorium scavenging in the Meddies.* Within Meddy *Nicole*, at 800, 1,000 and 1,200 m, ²²⁸Th, and to a lesser extent ²³⁴Th, are depleted relative to their parents. Here, this scavenging is treated in a manner similar to that used for surface waters. ²³⁴Th activities are the result of a balance between its continuous production from ²³⁸U, its decay, removal onto rapidly sinking particles, and advection/diffusion (Coale et Bruland, 1985; Savoye et al., 2005). The temporal change in total ²³⁴Th is expressed by the classical equation:

$$\partial A_{Th} / \partial t = \lambda A_U - \lambda A_{Th} - P + V \quad (2)$$

where A_U is the ²³⁸U activity, A_{Th} is the total ²³⁴Th activity measured, P is the net removal flux of ²³⁴Th^p, and V is the sum of the advective/diffusive fluxes. Assuming steady state and negligible physical processes, P can be determined from the deficit of A_{Th} relative to A_U:

$$P = \lambda (A_U - A_{Th}) \quad (3)$$

The treatment of ²²⁸Th data is more awkward. Indeed the recent input of radium in MOW and the evidence of large deficiency of ²²⁸Th implies non steady state processes have occurred. To test the assumption that the deficit of ²²⁸Th relative to its parent ²²⁸Ra is due not only to export via settling particles but to incomplete ingrowth, we estimate a removal flux of ²²⁸Th, P²²⁸, by assuming that the ratio of thorium fluxes (P) is equal to the ratio of particulate thorium:

$$\frac{P^{228}}{P^{234}} = \frac{C_d^{234}}{C_p^{234}} \quad (4)$$

At 1,000 m in Meddy *Nicole*, P²³⁴ is 9.5 dpm m⁻³ d⁻¹ (Table 3) which leads to an estimate for P²²⁸ of 3.2x10⁻³ dpm m⁻³ d⁻¹. If particle removal was the only factor controlling ²²⁸Th activities, we would expected a total ²²⁸Th of about 4.5x10⁻³ dpm l⁻¹ based on the ²²⁸Ra activity measured at 1000 m. The

difference between the calculated and the measured total ^{228}Th , 3.8×10^{-3} dpm l^{-1} , indicates an incomplete ingrowth of ^{228}Th since the recent ^{228}Ra enrichment. This hypothesis is further supported by the fact that the total $^{228}\text{Th}/^{228}\text{Ra}$ activity ratio increases, as the MOW propagates westward, from 49% within Meddy *Nicole* to 79% % within Meddy *Yseult*. Assuming that the same mechanisms produced both Meddies, this difference in $^{228}\text{Th}/^{228}\text{Ra}$ activity can be used as an indirect dating method, according to equation (5), which calculates the evolution of $^{228}\text{Th}/^{228}\text{Ra}$ activity ratio with time (Reyss *et al.*, 1996):

$$\frac{C_{Th}}{C_{Ra}} = \frac{\lambda_{Th}}{\lambda_{Th} - \lambda_{Ra}} * \left[1 - e^{+(\lambda_{Ra} - \lambda_{Th}) * t} \right] \quad (5)$$

where C_{Ra} and λ_{Ra} are the activity and decay constant for ^{228}Ra and t is the time elapsed after the incorporation of Ra. The main assumptions of this equation are rapid incorporation of radium and a closed system. There is no more diffusive supply of radium because the two Meddies are no longer in contact with the continental shelf. However, the radium activity of Meddy *Yseult* is slightly lowered by dilution with surrounding Atlantic waters. Moreover, the system is not closed due to the probable loss of ^{228}Th via settling particles. Taking into account these limits, it is only possible to convert the ingrowth of ^{228}Th as a rough and minimal estimate of the transit time of MOW. Using equation (5), and an increase of ^{228}Th of 1.75×10^{-3} dpm l^{-1} between *Nicole* and *Yseult*, leads to a minimum transit time of 9 months, in agreement with previous estimates of less than 1 y (Savenkoff *et al.*, 1993; Schmidt and Reyss, 1996).

Due to incomplete ingrowth of ^{228}Th , particle residence times were calculated using only ^{234}Th . Residence times of particulate thorium are given by the ratio of $^{234}\text{Th}^P$ inventories within a specific layer to particulate ^{234}Th flux (P^{234}). T_p is about 44 days in surface waters of Meddy *Yseult* (Table 3), which is in the range of values (1 – 126 days) reported for the subtropical and tropical Atlantic Ocean (Charette *et al.*, 1999) and the Northwestern Iberian margin (Hall *et al.*, 2000). Within the deeper waters of Meddy *Nicole*, T_p is much higher, up to 200 days (Table 3), equivalent to those reported for surface waters of the oligotrophic central gyre of the Pacific Ocean (Bruland and Coale,

1986). Bacon and Anderson (1982) demonstrated that particles in the deep ocean have an average residence time in the water column of about 5 - 10 years. Within Meddy *Nicole*, particle residence times are much shorter.

4. Conclusions

Short lived thorium isotopes within Meddy *Nicole* reveal unusually high particle fluxes and an associated short residence time of particles at 1,000 meter depth. This anomaly is explained by the presence of MOW, and is likely related to the high amount of suspended particles swept along when the MOW was in contact with the shelf in the Gulf of Cadiz. These results highlight how the presence of the MOW in the North-East Atlantic affects not only salt and temperature budgets, but also the exchange between dissolved and particulate material and hence the vertical local particulate flux at intermediate depths.

Although ^{234}Th has become mainly used as a tracer for studying particle transport and carbon export from oceanic surface waters, there is a renewed interest in intermediate and deep waters and their role in particle export and oceanic carbon sequestration. The present work clearly illustrates how ^{234}Th may be used in the water column to examine how recycling or local features (hydrology, nepheloid layers) may affect particle dynamic and sinking flux. Several studies have reported ^{234}Th measurements in intermediate and deep layers (Bacon and Rutgers van der Loeff, 1989; Turnewish and Springer, 2001; Benitez-Nelson et al. 2001; Frigani, et al., 2002; Rutgers van der Loeff et al., 2002; Savoye et al., 2004). However, a multi-tracer approach, i.e. ^{234}Th used in combination with longer half-life radionuclides, is more powerful for studying particle scavenging throughout the water column as it supplies further information about particle sources, formation, and sinking over a range of timescales. The original work of Bacon and Anderson (1982) clearly illustrates the interest and power of combining several thorium isotopes (^{234}Th , ^{228}Th , ^{230}Th) to estimate particle residence time in open ocean water column. More recently Smoak et al. (2004) used a suite of radionuclides to understand particle scavenging throughout the water column of the Cariaco Basin over seasonal (^{234}Th) and annual (^{228}Th) to decadal timescales (^{210}Pb). Considering the interest of this multi-

approach, an effort is now required for improving our ability to model these data sets from both water column measurements and sediment traps (Savoie et al., 2005).

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Figure caption

Figure 1. Location of Meddies *Nicole* and *Yseult* in the North-east Atlantic Ocean. The arrows indicate the dispersion of the Mediterranean Outflow Water off the Gibraltar Straits. Sites I and F were sampled in the MOW. The shaded area shows where Meddies have been often reported. The grey line underlines the 200 m depth.

Figure 2. Vertical profiles of salinity and temperature (°C) at sites *Nicole* (solid line) and *Yseult* (dotted line).

Figure 3. Vertical profiles of thorium at site *Nicole*: A) particulate ^{234}Th (solid squares), ^{234}Th dissolved (open squares) and total ^{234}Th (open circles), ^{238}U (solid circles). B) particulate ^{228}Th (solid squares), dissolved ^{228}Th (open squares) and total ^{228}Th (open circles), ^{228}Ra (solid circles).

Figure 4. Vertical profiles of radionuclides at site *Yseult*: same symbols as defined for Figure 3.

Figure 1

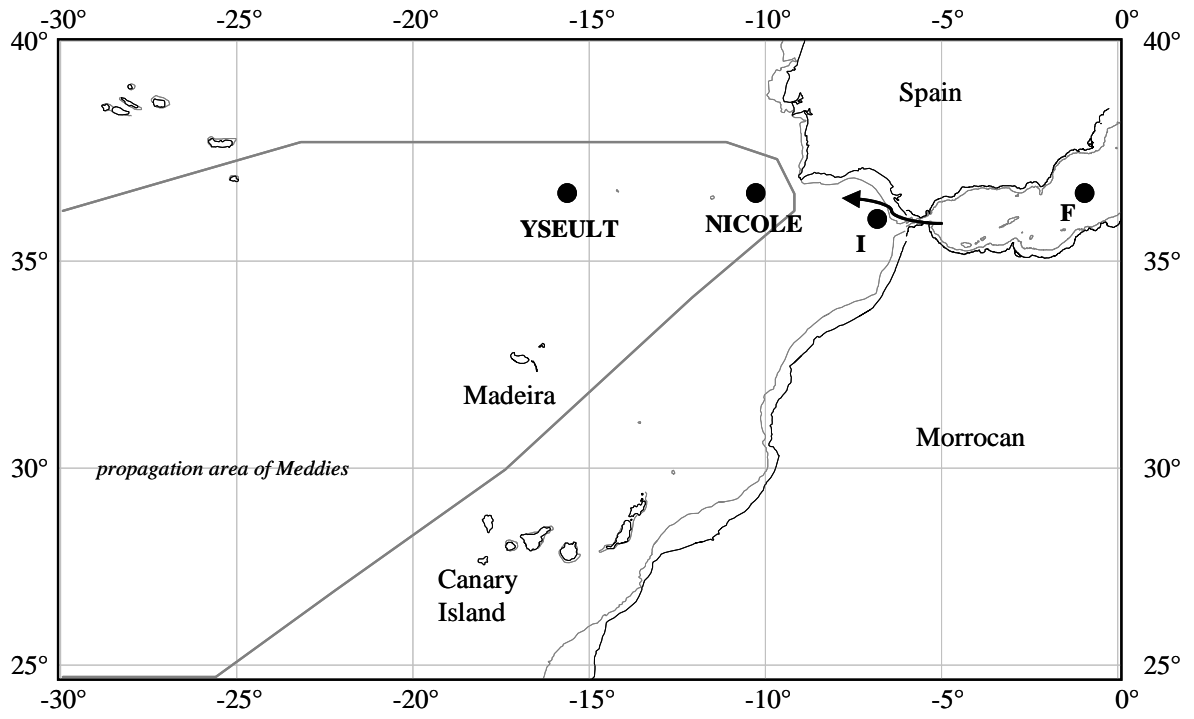


Figure 2

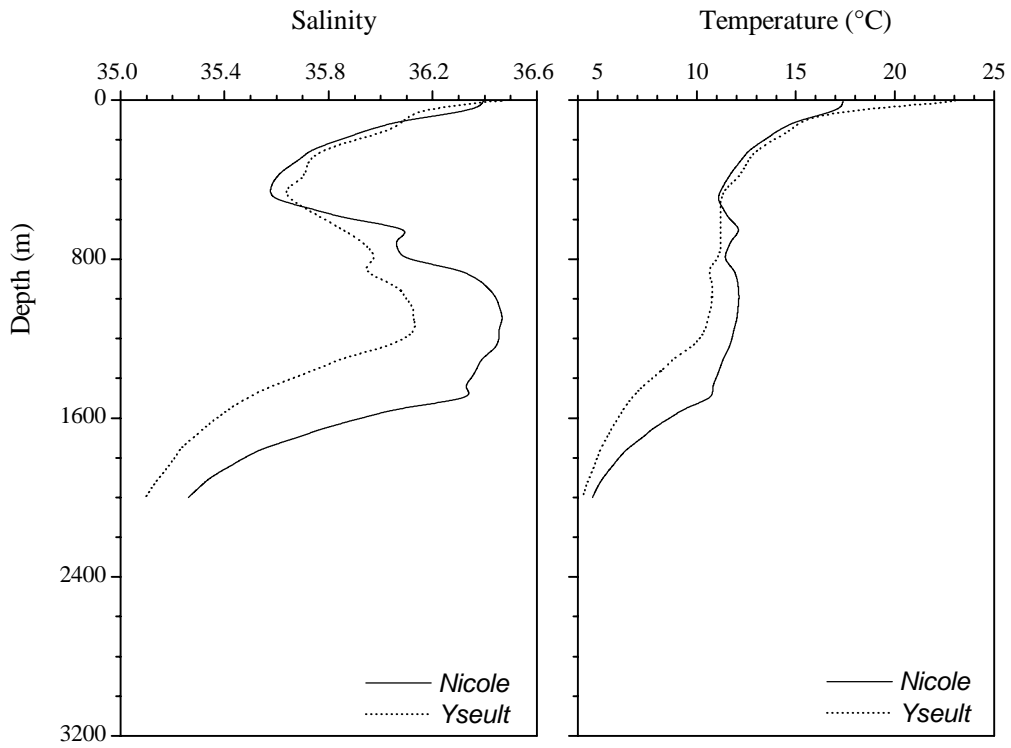


Figure 3

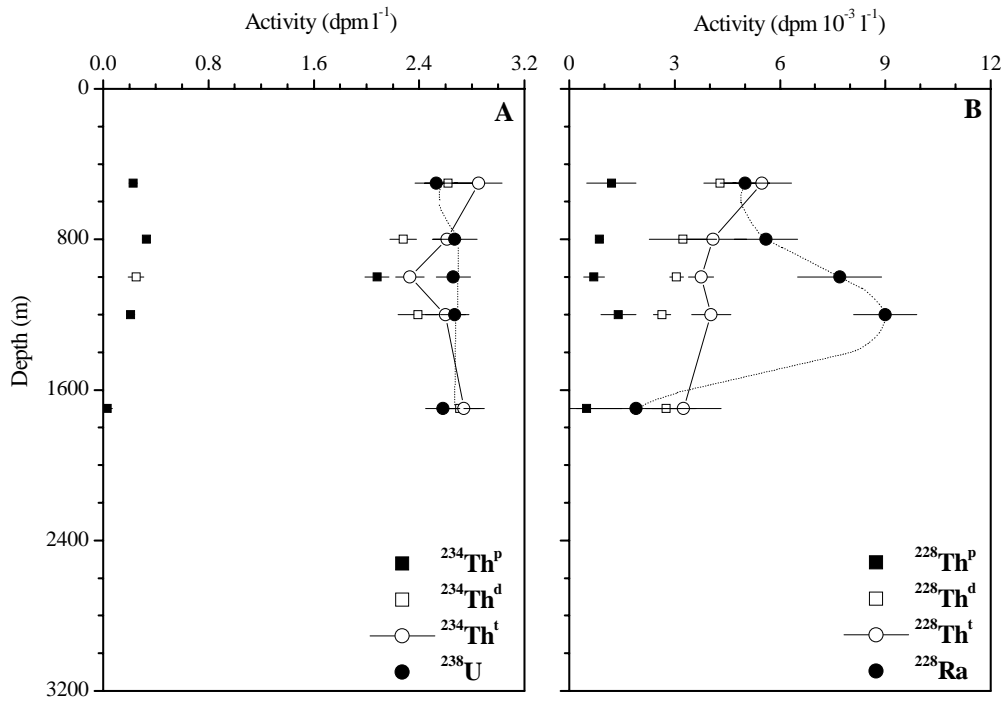


Figure 4

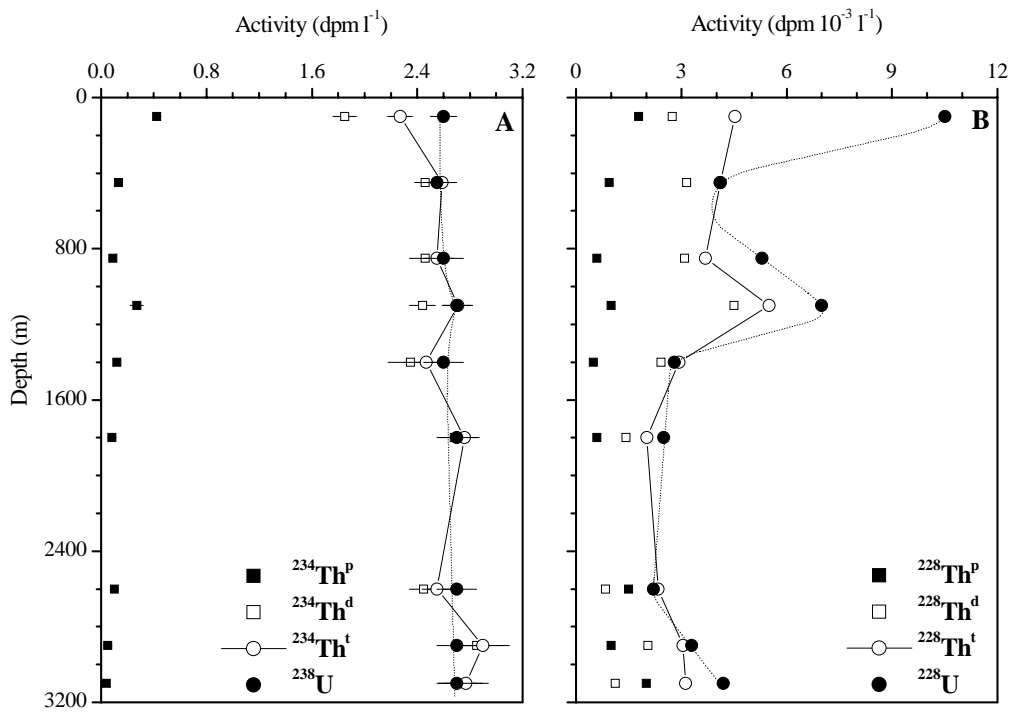


Table 1

Salinity and radionuclide data: dissolved ^{238}U and ^{228}Ra , and dissolved, particulate and total ^{234}Th and ^{228}Th

Site/ Depth	Salinity	$^{234}\text{Th}^{\text{p}}$ dpm l ⁻¹	$^{234}\text{Th}^{\text{d}}$ dpm l ⁻¹	$^{234}\text{Th}^{\text{t}}$ dpm l ⁻¹	^{238}U dpm l ⁻¹	$^{228}\text{Th}^{\text{p}}$ dpm 10 ⁻³ l ⁻¹	$^{228}\text{Th}^{\text{d}}$ dpm 10 ⁻³ l ⁻¹	$^{228}\text{Th}^{\text{t}}$ dpm 10 ⁻³ l ⁻¹	^{228}Ra dpm 10 ⁻³ l ⁻¹
<i>MOW</i>									
F - 1000 m	38.43	0.10±0.01	3.08±0.13	3.18±0.14	2.82±0.10	1.2±0.2	3.6±0.2	4.8±0.3	4.9±0.4
I - 450 m	35.98	0.42±0.02	2.21±0.09	2.63±0.09	2.78±0.15	2.1±0.5	4.8±0.5	6.9±0.7	6.7±0.7
<i>Nicole</i>									
500 m	35.58	0.23±0.02	2.62±0.18	2.85±0.18	2.53±0.16	1.2±0.7	4.3±0.5	5.5±0.8	5.0±0.7
600 m	35.88								4.5±0.8
800 m	36.08	0.33±0.03	2.28±0.10	2.61±0.10	2.67±0.17	0.9±0.1	3.2±1.0	4.1±1.0	5.6±0.9
1000 m	36.45	0.25±0.06	2.08±0.09	2.33±0.11	2.66±0.13	0.7±0.3	3.1±0.2	3.8±0.4	7.7±1.2
1200 m	36.46	0.21±0.01	2.39±0.15	2.60±0.15	2.67±0.11	1.4±0.5	2.6±0.2	4.0±0.6	9.0±0.9
1700 m	35.68	0.03±0.03	2.71±0.15	2.74±0.15	2.58±0.13	0.5±1.0	2.8±0.4	3.3±1.1	1.9±1.7
<i>Yseult</i>									
10 m	36.48								8.8 1.5
100 m	36.09	0.42±0.03	1.85±0.09	2.27±0.09	2.60±0.10	1.8±0.6	2.7±0.1	4.5±0.6	10.5±1.7
450 m	35.62	0.13±0.03	2.46±0.08	2.59±0.09	2.55±0.15	1.0±3.3	3.2±0.6	4.1±3.4	4.1±1.3
850 m	35.92	0.09±0.03	2.46±0.12	2.55±0.12	2.60±0.15	0.6±3.1	3.1±0.6	3.7±3.2	5.3±1.8
1100 m	36.12	0.27±0.05	2.44±0.10	2.71±0.11	2.70±0.11	1.0±4.8	4.5±0.9	5.5±4.9	7.0±1.0
1400 m	35.66	0.12±0.03	2.35±0.17	2.47±0.17	2.60±0.15	0.5±	2.4±0.5	2.9±0.5	2.8±2.4
1800 m	35.21	0.08±0.02	2.68±0.11	2.76±0.11	2.70±0.15	0.6±3.0	1.4±0.3	2.0±3.0	2.5±2.9
2600 m		0.10±0.02	2.45±0.11	2.55±0.11		1.5±1.5	0.8±0.4	2.3±1.6	2.2±2.5
2900 m		0.05±0.02	2.85±0.20	2.90±0.20		1.0±0.5	2.1±0.4	3.1±0.6	3.3±1.9
3100 m		0.04±0.03	2.73±0.17	2.77±0.17		2.0±4.0	1.1±0.4	3.1±4.0	4.2±1.6

Table 2

Mass flux, radionuclide specific activity and flux in sediment traps.

	Mass flux	^{234}Th	^{234}Th	^{228}Th	^{228}Th
	$\text{mg m}^{-2} \text{d}^{-1}$	dpm g^{-1}	$\text{dpm m}^{-2} \text{d}^{-1}$	dpm g^{-1}	$\text{dpm m}^{-2} \text{d}^{-1}$
Nicole (deployment duration = 20 d.)					
700 m	103	4308 ± 72	444 ± 7	16.1 ± 0.6	1.66 ± 0.06
1,000 m	309	2783 ± 32	860 ± 10	13.6 ± 0.3	4.20 ± 0.09
Yseult (deployment duration = 15 d.)					
700 m	31	10440 ± 1466	324 ± 45	31.1 ± 1.2	0.96 ± 0.04
1,000 m	21	3871 ± 496	81 ± 10	17.5 ± 0.8	0.37 ± 0.02

Table 3. Adsorption (k_1), desorption (k_{-1}) rate coefficients, particulate fluxes (P) and residence times (T_p) based on Th isotope data, as explained in the text.

Site/ Depth	k_1 yr ⁻¹	k_{-1} yr ⁻¹	P dpm m ⁻³ d ⁻¹	T_p days
<i>MOW</i>				
F - 1000 m	0.36	0.73		
I - 450 m	3.40	7.37		
<i>Nicole</i>				
500 m	1.30	4.28		
800 m			1.7	191
1000 m			9.5	219
1200 m			2.0	104
1700 m	0.12	0.29		
<i>Yseult</i>				
100 m			9.5	44
450 m	0.65	1.79		
850 m	0.46	1.99		
1400 m	0.69	2.98		
1800 m	0.33	0.40		
2600 m	0.42			
2900 m	0.18			