Ocean Sci. Discuss., 7, 1533–1557, 2010
www.ocean-sci-discuss.net/7/1533/2010/
doi:10.5194/osd-7-1533-2010

Ocean Science Discussions

Tracers confirm downward mixing of Tyrrhenian Sea upper waters associated with the Eastern Mediterranean Transient

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Received: 12 August 2010 – Accepted: 15 August 2010 – Published: 24 August 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Observations of tritium and ^{3}He in the Tyrrhenian Sea, 1987–2009, confirm the enhanced convective mixing of intermediate waters into the deep waters that has been noted and associated with the Eastern Mediterranean Transient in previous studies. Our evidence for the mixing rests on increasing tracer concentrations in the Tyrrhenian deep waters, accompanied by decreases in the upper waters, which are supplied from the Eastern Mediterranean. The downward transfer is particularly evident between 1987 and 1997. Later on, information partly rests on increasing tritium-^{3}He ages; here we correct the observed ^{3}He for contributions released from the ocean floor. The Tyrrhenian tracer distributions are fully compatible with data upstream of the Sicily Strait and in the Western Mediterranean. The tracer data show that mixing reached to the bottom and confirm a cyclonic nature of the deep water circulation in the Tyrrhenian. They furthermore indicate that horizontal homogenization of the deep waters occurs on a time scale of several years. Various features point to a reduced impact of Western Mediterranean Deep Water (WMDW) in the Tyrrhenian during the enhanced-convection period. This is an important finding because it implies less upward mixing of WMDW, which has been named a major process to enable the WMDW to leave the Mediterranean via the Gibraltar Strait. On the other hand, the TDW outflow for several years represented a major influx of enhanced salinity and density waters into the deep-water range of the Western Mediterranean.

1 Introduction

A recent study observed the release of ^{3}He, the rare isotope of helium (He), from the submarine volcanoes of the Aeolian Arc in the southern Tyrrhenian Sea (Lupton et al., 2010). Such He is derived from the Earth's interior. It has a ^{3}He/^{4}He ratio an order of magnitude higher than that in the atmosphere (atmospheric ratio R_a=1.384 10^{-6}; Clarke et al., 1976). Thus ^{3}He is a unique indicator of volcanic input. While the effect,

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in accordance with the depths of release, was essentially confined to 300–700 m depth, it was found to be superimposed on a ^{3}He background that increased downwards with maximum concentrations below 1000 m (Lupton et al., 2010). That difference in depth together with the rather moderate volcanic ^{3}He signals led the authors to conclude that the deep signal was independent of the observed release, and instead was the result either of hydrothermal input elsewhere or of ingrowth from the decay of tritium. We here show that the latter source has indeed been dominant. We find that the deep-water ^{3}He maximum was generated by the enhanced convective activity in the Tyrrhenian intermediate and deep waters that was associated, as noted previously (e.g., Gasparini et al., 2005), with the Eastern Mediterranean Transient (EMT; Roether et al., 1996).

The available tritium and ^{3}He data, combined with suitable boundary conditions, give robust information on the mixing down into the Tyrrhenian deep waters, independent of previous work. Tritium is produced by cosmic radiation, but the dominant source over the past decades has been the atmospheric testing of nuclear weapons. As a consequence, its atmospheric concentrations strongly peaked in the 1960s and have since decreased by radioactive decay ($T_{1/2}$=12.32 years; Lucas and Unterweger, 2000) and by exchange primarily with the ocean waters. From concurrent data of tritium and tritiugenic ^{3}He a water age (subsurface travel period; see below) can be computed.

2 The Tyrrhenian Sea: the pre-EMT situation and EMT-induced changes

The classical situation has been described, among others, by Astraldi et al. (1996) and Millot (1999). Tyrrhenian Sea subsurface waters are composed of overflow at the Sicily Strait (~500 m sill) from the Eastern Mediterranean Sea (EMed) and of Western Mediterranean Deep Water (WMDW), which enters via the Sardinian Passage (~1900 m sill; Fig. 1) at greater depths. Together they form the Tyrrhenian Deep Water (TDW), which leaves through the passage against the flow of WMDW. The input from

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the Sicily Strait is topographically steered into the south of the sea. It is composed of Levantine Intermediate Water (LIW), which is formed in the northwestern Levantine Sea, and of waters adjoining the LIW from below. The latter waters, termed transitional Eastern Mediterranean Deep Water (tEMDW), are part of the extensive mixing regime between EMDW and LIW, with contributions of intermediate waters formed in the Aegean Sea. It is mostly the tEMDW that contributes to the TDW, while much of the LIW leaves the sea via the Sardinian Passage and the rather shallow Corsican Channel (~450 m sill) in the north. These outflows incorporate part of the volcanic ^{3}He mentioned above because the depth ranges overlap. Hopkins (1988) reported a ratio of WMDW to Sicily Strait overflow waters of 2:1 on average and estimated the Sicily Strait input as $7\,10^4\ m^3/s$ (0.07 Sverdrup; Sv). Millot (1999) notes cascading on the northern slope of Sicily in the southern Tyrrhenian as a dominating mixing process between the Sicily Strait overflow and the WMDW. The author considers that the implied lifting of the WMDW is a prerequisite for the WMDW to eventually take part in the Strait of Gibraltar outflow. He believes that therefore the "Tyrrhenian Sea is a key place for the working of the whole Western Mediterranean Sea", and that by its action the Western Mediterranean (hereafter WMed) deep waters have a faster turnover than those of the EMed. A further point of his is that the mixing should increase with the WMDW inflow rate. He notes that the cascading of the overflow waters reaches to about 2000 m, so that below that depth WMDW should be predominant. He characterizes the circulation within the Tyrrhenian as cyclonic at all depths (see his Fig. 3), which means that the WMDW inflow would be concentrated toward the Sicilian slope and TDW outflow toward Sardinia. The subsurface waters of the Mediterranean have been subject to slow increases in temperature and salinity (e.g., Bethoux et al., 1998); a summary for the WMed including the Tyrrhenian has been given by Fuda et al. (2002).

The recent changes have been studied, among others, by Astraldi et al. (2002) and Gasparini et al. (2005). The basic fact is that the EMT increased the density of the Sicily Strait overflow, with the salinity being highest during 1992–1993 and decreasing thereafter (Gasparini et al., 2005; Fig. 4). As their Figs. 7 and 10 show, the change

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began to be felt in the Sicily Strait and at the entrance into the Tyrrhenian in about 1992, and, according to Astraldi et al. (2002; Fig. 15), shortly thereafter also within the TDW. This precedes the changes in the EMed deep waters, which is natural since the intermediate waters were affected by the EMT earlier than the EMDW, for which the massive influx from the Aegean only began in mid-1992 (Roether et al., 2007; Fig. 9). Consequently, the density contrast between 500 and 2000 m in the Tyrrhenian was lowered (Gasparini et al., 2005; Fig. 16), enhancing downward mixing. On the basis of temperature and salinity balances, the authors deduced the Sicily Strait input rates at approximately 0.3 Sv on average between 1988 and 1994, a four-fold increase over the previous rate, and about half as high between 1996 and 2002 (their Fig. 15). One expects that the enhanced Sicily Strait input and increasing density of the TDW would modify, and presumably reduce, the WMDW impact. The property changes in the LIW have been identified as a factor in inducing changes in the WMDW that were recently observed (Schröder et al., 2006).

LIW is formed in the northwestern Levantine Sea (east of the island of Rhodes). This water mass starts with tritiugenic ^{3}He corresponding to a few years of ingrowth, and significant further ingrowth occurs during the several-year subsurface travel time up to the Sicily Strait (Roether et al., 1998a). Travel times can vary due to reversals of the upper circulation in the Ionian Sea, and it appears that in the years around 1987 these were comparatively long and became shorter in about 1997 (Gacic et al., 2010).

Tritium observations in the Tyrrhenian exist since 1972. Cortecci et al. (1974) reported for that year about 10 TU at the surface (1 TU means a ^{3}H/H ratio of 10^{-18}), 4–6 TU in LIW, and 2.7 TU in TDW, while the corresponding values in 1981 were 6.5 TU, 5.5 TU, and 2.7 TU (Andrie and Merlivat, 1988); the latter values refer to the Sardinian Passage but should be near to those in the Tyrrhenian proper. The surface water values are compatible with the reconstruction for the Ionian Sea surface waters by Roether et al. (1992), i.e., maximum tritium in 1965 of approximately 28 TU, 14 TU in 1972, and 7 TU in 1981. The data suggest that subsurface tritium in the Tyrrhenian went through a broad maximum in the 1970s and has decreased since. Tritium and He isotope

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observations were carried out in 1997 (Rhein et al., 1999); the authors show that at that time the ^{3}He in the Tyrrhenian deep waters exceeded that in the WMed.

3 Data and methods

Table 1 lists the cruises that provided tritium, He isotope and neon (Ne) data used in this paper. All data prior to 2007 were measured at Bremen using the procedure of Sültenfuß et al. (2009). We report helium isotope ratios as δ^3He (%), which is the percentage deviation of the ^{3}He/^{4}He ratio from the atmospheric ratio. Typical precisions are about ±0.2% for δ^3He, ±0.3% for He and Ne concentration, and ±3% or 0.01 TU (whichever is greater) for tritium. For the 1987 cruise, tritium measurements were partly done by gas counting following isotopic enrichment, with typical precisions of 5%/0.08 TU (cf. Roether et al., 1999). Data from the 2007 and 2009 cruises were measured in Newport, Oregon, using the procedure of Lupton (1990). Tritium was measured by mass spectrometer using the ^{3}He ingrowth method. Precisions are about ±0.2% for δ^3He and ±0.03 TU for tritium. The stations that we use below are shown in Fig. 1, which also outlines the bathymetry. Those in the Tyrrhenian are scattered throughout the basin, consequences are addressed below. Temperature and salinity uncertainties for METEOR 5/6 and POSEIDON 234 are about ±0.003 °C and ±0.004, but lower for MEDOCC07. Depths are given in decibars (1 dbar≈0.99 m) and density as potential density referenced to 2000 dbar (σ_2).

The POSEIDON cruise has four Tyrrhenian stations with data for the named tracers, i.e., the full set at Stas. 745 and 764, tritium only at 765, and the He/Ne set only at 766. That station is located near to the center of the deep part of the basin, while Sta. 764 has a rather more peripheral location. To enable evaluation of the former station, we use tritium data obtained by a correlation with the tracer CFC-12, setting $c_{\mathrm{tri}}(766)=c_{\mathrm{CFC-12}}(766)\ c_{\mathrm{tri}}(765)/c_{\mathrm{CFC-12}}(765)$, where the Sta. 765 ratios are interpolated to Sta. 766 depths.

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The tritium-^{3}He age can be derived as follows:

$$\tau = t_{1/e} \ln\left(1 + {}^3\mathrm{He}_{\mathrm{tri}}/\mathrm{tritium}\right) \tag{1}$$

where, $t_{1/e}$ = radioactive mean life of tritium (17.9 years), and both tritium and $^3He_{tri}$, the tritiugenic ^{3}He, are in TU (1 TU means a ^{3}H/H ratio of 10^{-18}; it is equivalent to 2.49×10^{-15} ccSTP^{3}He per g of water). Under Mediterranean conditions, a ^{3}He concentration in equilibrium with the atmosphere corresponds to 21 TU of decayed tritium. Since $^3He_{tri}$ is lost at the water surface, τ refers to uninterrupted subsurface travel. However, due to mixing effects, τ is biased toward components of relatively higher tritium and $^3He_{tri}$ concentrations. To determine $^3He_{tri}$, we apply the procedure of Roether et al. (1998b) with the correction of Roether et al. (2001; see also Well et al., 2001), which is based on measured He and Ne concentrations; for the AEOLIAN station of 2007, we used He and Ne concentrations estimated from the Bremen data of the other years. The procedure uses Ne observations to determine the atmosphere-derived portions of the He isotope concentrations. The remaining ^{4}He represents the portion released from the ocean floor (terrigenic He), while the ^{3}He is composed of both terrigenic and tritiugenic ^{3}He. The terrigenic ^{3}He is the product of the terrigenic He and its isotopic ratio R_t and can thus be corrected for provided that R_t is known.

Contrary to the high R_t values for He released from the Earth's interior, those for He derived from the Earth's crust are low, i.e., on the order of R_t/R_a=0.1. While the former component has localized sources, the latter is added at basin scale (Well et al., 2001). Terrigenic He in the Eastern Mediterranean has been shown to have a rather low ratio, R_t/R_a=0.42±0.1 (Roether et al., 1998b). Its prominent crustal contribution results from continental-type crust and excessive sediment load (Morelli, 1985). In the WMed similar conditions hold, and we therefore assume that a similarly low R_t is applicable. The Tyrrhenian waters are thus a mixture of low R_t waters. Although the aforementioned volcanic releases have a far higher R_t, this input is at shallow depths and is partly removed with the LIW outflow. Furthermore the Tyrrhenian has a comparatively short

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turnover time, which limits the contributions from within the sea. On this basis, we use rounded R_t/R_a values of 1 for the Tyrrhenian waters (assumed uncertainty ±0.5) and 0.5 outside.

The corresponding contributions of terrigenic ^{3}He to the total non-atmospheric ^{3}He amount to only about 15% within the Tyrrhenian and 7% outside. The uncertainties in measurement and in R_t convert to standard precisions of tritiugenic ^{3}He of about ±0.2 TU. The age uncertainties are about ±3 years, or up to ±6 years in the case of low tritium concentrations measured by gas counting (i.e., for part of the deep Tyrrhenian values of 1987).

4 Results and discussion

The present study was initiated by the δ^3He profiles of Fig. 2, which reveal drastic changes over the period 1987–2009. The upper-layer values decrease steadily in time while the deep-water values rise, with a cross-over point near 1000 m depth. The figure gives a vivid illustration of the downward transfer of upper waters related to the EMT-associated convection. As mentioned, such convection lasted from about 1988 to 2002 (Sect. 2), so that the 1997 profiles fall into the active period, while those of 1987, 2007 and 2009 met more quiet conditions. It is thus no surprise that the 1997 profiles show significant differences, while those of 2007 and 2009 are virtually identical; we infer that the single profile of 1987 should be rather characteristic for the Tyrrhenian at large.

The question of uniformity within the Tyrrhenian in 1997 and of water exchange with the WMDW is addressed in Fig. 3, which presents density (σ_2) versus salinity for Tyrrhenian and WMed stations from the 1997 cruise (all in color), together with relationships for the 1987 and 2007 Tyrrhenian stations (black). Sta. 738 represents the WMed waters that potentially enter the Tyrrhenian, while Sta. 742, at the slope in the far southwest of Sardinia (Fig. 1), represents the mixture, moving northward, of regular WMDW and TDW outflow from the Tyrrhenian close to the entrance of the latter. As expected, the 1987 profile has distinctly lower densities than the 1997 set. The fact

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that its near-bottom salinity is even lower than at the 1997 WMed station reflects the differing characteristics of WMDW in earlier years (e.g., Bethoux et al., 1998). The 1997 Tyrrhenian stations vary systematically between 764 (red; highest densities and highest salinities on isopycnals) and 745 (blue). Following the notion of cyclonic circulation (Sect. 2), Sta. 764 represents the shortest path from the cascading region north of Sicily, and Sta. 745 the relatively longest. The longer path explains the lower salinity and density at Sta. 745, which reflect contributions of older waters carrying past characteristics in the sea (cf. the 1987 Sta. 786). Of the other 1997 stations, Sta. 765 (cyan) is more similar to 764, while 766 (green) is more similar to 745 down to about 1500 m. Farther down, Stas. 766 and, more so, 767 (magenta) exhibit changes in slope, pointing toward the WMed Sta. 738 properties at depths near to the Sardinian Channel sill depth. This feature indicates stronger WMDW contributions in the south of the sea, complying with the cyclonic flow pattern. The 2007 profile matches the σ_2-S range of the 1997 Tyrrhenian stations below about 1100 m, while at shallower depths it deviates toward higher salinity. Near the bottom the 2007 profile has higher salinity and is on the low side of the 1997 densities, indicating that WMDW influx in the years in-between must have been rather limited.

As for the prominence of WMDW in the deepest Tyrrhenian waters noted by Millot (1999), the 1987 Sta. 786 indeed has a near-homogeneous bottom layer reaching up to 2500 m depth. However, similar features in the 1997 Tyrrhenian profiles are restricted to below 3000 m depth. This is a further indication that in 1997 the WMDW had less prominence than prior to the period of enhanced convection.

The property values in the boundary flow west of Sardinia (Sta. 742) contrast strongly with those farther west (Stas. 736 and 738). Assuming that the addition of TDW occurs primarily along isopycnals, the higher salinities indicate TDW contributions of 60% or more on average, approaching 100% near 1200 m depth. Prior to the EMT-induced changes, the boundary flow certainly had lower salinity, a consequence of the comparatively lower salinity of the WMDW and its larger contribution to the TDW (Sect. 2); the effect is evident in the distinct shift of the σ_2-salinity relationship of the 1987 station in

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Fig. 3 relative those of 1997. Considering the enhanced influx of Sicily Strait overflow under EMT influence (1988–1994 average 0.3 Sv; Sect. 2), the WMDW contribution to the TDW, and WMDW entrainment upon passing the Sardinian Passage, the boundary flow along Sardinia definitely exceeded 0.5 Sv over several years. It follows that this flow represented a distinct input of high-salinity waters directly into the deep-water depth range, which to our knowledge has escaped the attention in previous studies (e.g., Schröder et al., 2006).

Figure 4 compares tracer profiles of the 1997 Stas. 766, 764, 745, and 736. At Sta. 766 (dotted), tritium is higher than at Stas. 764 (full lines) and 745 (dashed) above 700 m and below 1800 m, but intermediate at depths in between. Tritiugenic ^{3}He is likewise intermediate at mid depths, but at 1800 m the three stations almost coincide. The Sta. 766 tritium-^{3}He ages exceed those at Sta. 764 down to 2000 m, while at greater depths they are markedly lower. Sta. 736 (dash-dotted) in the WMed has the lowest tritium of the set at mid-depth (~800–1500 m), but the highest below 1800 m, while its ^{3}He is the lowest from ~800 m all the way to the bottom. Above we pointed out that Sta. 764 has the shortest path from the cascading region, which is consistent with its comparatively lower ^{3}He and lower ages down to about 1800 m. But at greater depths older waters are present, which is manifested in lower tritium and higher ^{3}He and ages. In that same depth range, Sta. 766 has comparatively constant property values. At Sta. 742 at the southwestern slope of Sardinia one finds tritium and ^{3}He values (not shown) rather similar to those at Sta. 736, in particular similarly low ^{3}He below 800 m. Considering the high Tyrrhenian contributions according to Fig. 3, the low ^{3}He indicates that the Tyrrhenian contributions at Sta. 742 observed in 1997 represent waters from earlier in the enhanced convection period or, partly, even before it, when tritium, and thus also ^{3}He, were still lower. The property differences in Figs. 3 and 4 indicate that horizontal homogenization in the Tyrrhenian deep waters by recirculation and mixing occurs on a time scale of several years.

For its rather central position in the basin, we take Sta. 766 to represent the Tyrrhenian deep basin in 1997. However, Figs. 3 and 4 provide no information east of 12° E,

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i.e., halfway across the basin (Fig. 1). For the part farther east, we envisage that along the eastern slope of the basin there is a band of "young waters" approximately represented by Sta. 764. Outside of that band, one should, according to the cyclonic pattern, find waters with rather long advection times which might still have had lower tritium than at our Tyrrhenian stations.

The temporal evolution of the tracer profiles for the Tyrrhenian is shown in Fig. 5. The tritium and ^{3}He profiles fully support the downward water transfer noted in Fig. 2. The cross-over depth between the 1987 and 1997 profiles is near 900 m, and below 1500 m tritium became uniformly higher by two-fold down to the bottom. The ages hardly change down to 1500 m and are lower farther down. After 1997, tritium decreased by decay, raising the ^{3}He values, which lead to an apparent ~10-year increase in age up to 2007, i.e., just about the difference in calendar time.

Before discussing Fig. 5 in more detail, we address the connection to the Sicily Strait overflow. Figure 6 compares the Tyrrhenian tracer profiles of 1987 with concurrent ones at the Malta Escarpment immediately upstream of the strait. Considering uplift of the waters upon entrance into the strait (Astraldi et al., 2001), the relevant depth range at the escarpment feeding the Tyrrhenian should be approximately 350–550 m. It follows that tritiugenic ^{3}He hardly increased on the way, tritium decreased, and the ages increased from about 12 to 15 years at the Sicily overflow depths. These changes are clearly attributable to tritium decay and ^{3}He ingrowth during the transit, accompanied by dilution. The consistency between the tracer profiles provides independent evidence of the ^{3}He in the Tyrrhenian arising predominantly from tritium decay.

In the upper-water column of the Tyrrhenian Sea, tritiugenic ^{3}He and tritium continually decreased in time (Fig. 5), but this is only partly due to convective mixing in the Tyrrhenian. A further cause is a decrease in the supply from the Sicily Strait. At the Malta Escarpment (Fig. 7) in the relevant depth range (350–550 m, see above), the tritium (^{3}He) values were 3.5 TU (3.2 TU) in 1987 and 1.3 TU (2.1 TU) in 2001. In detail one notes inversions between 1995 and 1999 in ^{3}He and between 1999 and 2001 in tritium. The 1999 profile displays the highest $^3He_{tri}$/tritium ratio in the set. Possible

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causes are the aforementioned inversions in the Ionian circulation (Sect. 2) or effects from the differing station positions. The 2007 upper water tritium and $^3He_{tri}$ values in the Tyrrhenian Sea (Fig. 5) were about 0.8 and 2.1 TU. Considering the decreasing tritium values in the overflow and decay after 2001, the 2001 Malta Escarpment and 2007 Tyrrhenian tracer values are fairly compatible.

Returning to Fig. 5, we note that in 1987 tritium was virtually constant below 1500 m down to 3500 m, and was again constant but a factor of two higher in 1997. The uniformity of tritium in 1987 is indicative of relatively fast vertical mixing, unless the potential WMDW contributions produced, accidentally, fitting tritium concentrations. Also for 1997, tritium might have been added at depth by intruding WMDW, but salinity increased so much during this period (Fig. 3) that such contributions must have been quite small. Between 1997 and 2007 one finds tritium in the 1200 to 2600 m depth range dropping by a factor of 2, in agreement with 10 years of decay within the data errors. However, within this depth range, there is corresponding ^3He ingrowth only below 2000 m, while at shallower depths the increase is at most half as great. At these depths there is clearly involvement of waters by which the tritium and/or the ^3He concentrations were modified. One mechanism should be the ongoing convective mixing from above (Sect. 2), which, according to Figs. 5 and 7, should have increased tritium and reduced ^3He. But such a contribution means that the part remaining since 1997 must have had lower tritium than observed in 2007. Since a reduction faster than predicted by decay is unphysical, it follows that either the convective contribution was small or there was a further compensating contribution. Compensation could arise by admixture of Tyrrhenian deep waters from east of 12° E, where, as mentioned above, waters could have been "older", i.e., had both lower tritium and ^3He. Below 2000 m, in contrast, the situation is indicative of a closed system, i.e. of essentially stagnant resident waters. A WMDW contribution can of course not be excluded, but would, according to Fig. 4, work in the same direction as the vertical mixing so that also here compensation would be needed. But matching concentrations in these contributions appear improbable, so that, even though the detection sensitivity is limited due to few tracer values in that

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depth range, we conclude that below 2000 m there was indeed stagnancy during this period. Note that the similarity of the 2007 and 2009 deep-water δ^3He values (Fig. 2) arises from the fact that by 2007 tritium had become so low (~0.4 TU) that decay up to 2009 represented a rather insignificant δ^3He increase (0.15%).

5 Conclusions

Tritium and ^{3}He data in the Tyrrhenian Sea, in the EMed immediately upstream of the Sicily Strait, and in the WMed, 1987–2009, give independent evidence of the convective mixing of the waters overflowing the Sicily Strait into the Tyrrhenian Sea deep waters, supporting previous studies (e.g., Astraldi et al., 2002; Gasparini et al., 2005). The data reflect the downward cascading of the inflowing waters from the Sicily Strait in the southern Tyrrhenian Sea, which, according to Millot (1999), should reach down to about 2000 m depth. In 1987 there was a thick bottom layer, depth 2500–3500 m, which showed near-constant temperature and salinity, while in 1997 such a layer did not reach above 3000 m depth. We interpret the increased depth of the top of the bottom layer, together with other evidence (see above), as indicating a reduced impact of WMDW on the Tyrrhenian deep waters during the period of enhanced convection. It follows that less WMDW was involved in the cascading within the sea compared to outside this period. According to Millot (1999) this means a reduced upward displacement of WMDW, reducing its capability to leave the WMed via Gibraltar Strait. The tracer concentrations, on the other hand, were virtually constant below 1200 to 1500 m in both cases. This finding points to a relatively fast mixing mechanism beyond the depth of the cascading. For 1997 we note substantial horizontal differences in deep-water tracer concentrations, which support the cyclonic nature of the circulation (Millot, 1999) and indicate a several-year time scale for horizontal exchange within the sea. We furthermore find that the TDW outflow must, for several years, have served as major source of waters of enhanced salinity and density in the deep-water depth range of the WMed.

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Our study furthermore confirms that the deep ^{3}He maximum observed by Lupton et al. (2010) was indeed almost entirely produced by tritium decay. The conditions for ingrowth of tritiugenic ^{3}He are favorable, since the waters overflowing in the Sicily Strait have long subsurface travel times from their formation regions, and once the waters have been transferred into the Tyrrhenian deep waters, further ingrowth can freely occur. The separation of tritiugenic ^{3}He followed a procedure described elsewhere (Roether et al., 1998b; 2001), which makes use of concurrent He and Ne concentration data. Under the special conditions of the Mediterranean Sea there is, fortunately, much less interference by ^{3}He released from the ocean floor than elsewhere in the ocean (Roether et al., 1998b; Well et al., 2001). Furthermore, the volcanic ^{3}He observed by Lupton et al. (2010) is released at rather shallow depths, so that much of it is removed with the LIW outflow from the Tyrrhenian Sea.

Acknowledgements. The METEOR cruises and part of the tracer measurements at Bremen were funded by the Deutsche Forschungsgemeinschaft, Bonn-Bad Godesberg, Germany. Further support was received by various grants of the European Union, Brussels, Belgium. We are grateful for the assistance of the masters and crew of the various cruises and for the efforts of numerous helpers at sea and in our laboratories, without whom the present study would not have been possible. We thank Monika Rhein, Bremen, principle investigator of the POSEIDON 234 cruise, for providing data, and Katrin Schröder and Gian Pietro Gasparini, Pozzuolo di Lerici, for the CTD data from their 2007 Geostar station. Leigh Evans and Ron Greene carried out the tracer measurements in Newport, and that work was supported by the NOAA Vents Program. We thank Mario Sprovieri and Angelo Bonanno for sampling on the Etymed expedition, and Sharon Walker for assistance with the CTD data. This is PMEL publication No. 3592.

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Table 1. The cruises providing data.

Cruise	Dates	Tracer data[a]	Reference
METEOR 5/6,	Aug–Sept 1987	++	Roether et al., 2007
METEOR 31/1	Jan–Feb 1995	++	"
POSEIDON 234	Oct–Nov 1997	++	Rhein et al., 1999
METEOR 44/4	Apr–May 1999	++	Roether et al., 2007
METEOR 51/2	Oct–Nov 2001	++	"
AEOLIAN '07	Nov 2007	+	Lupton et al., 2010
ETYMED	June–2009	δ^3He only	"

[a] ++: tritium, δ^3He, He- and Ne-concentrations, T, S; + tritium and δ^3He only.

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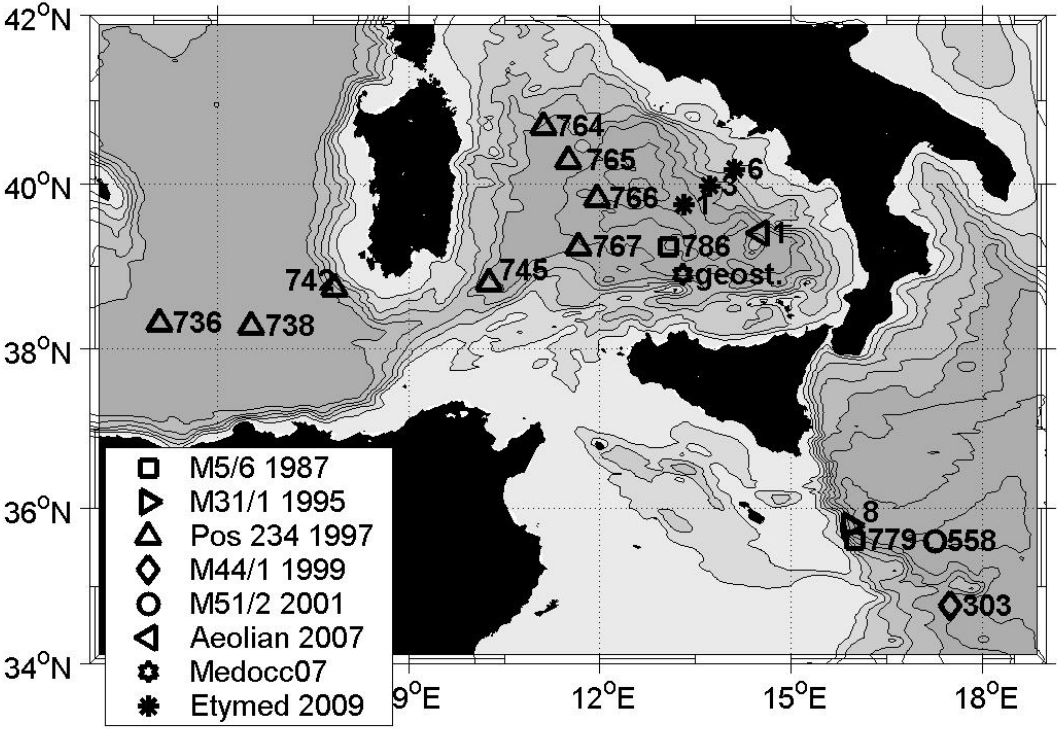

Fig. 1. Map of stations used in the present work. Station numbers are given next to the markings. Depth isolines are 500 m apart. Malta Escarpment = steep slope near 1995 Sta. 8; Sardinian Passage = deep connection between Tyrrhenian and WMed south of Sardinia.

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Tracers confirm downward mixing of Tyrrhenian Sea

W. Roether and J. E. Lupton

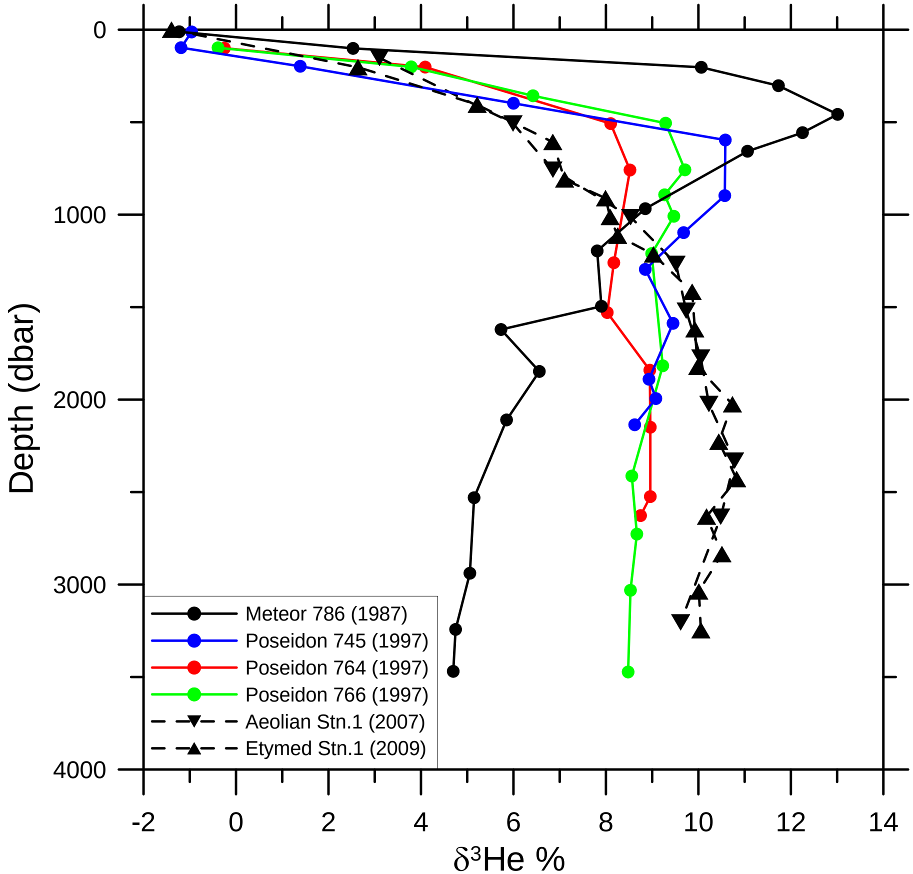

Fig. 2. δ^3He versus depth in 1987 (METEOR cruise 5/6), 1997 (POSEIDON cruise 234) and 2007/2009 (AEOLIAN 07 and ETYMED). For cruises see Table 1 and for station positions see Fig. 1. δ^3He is defined as the relative deviation (%) from the atmospheric $^3He/^4He$ ratio. Due to different solubility of the two isotopes, δ^3He has surface values near −1.6%.

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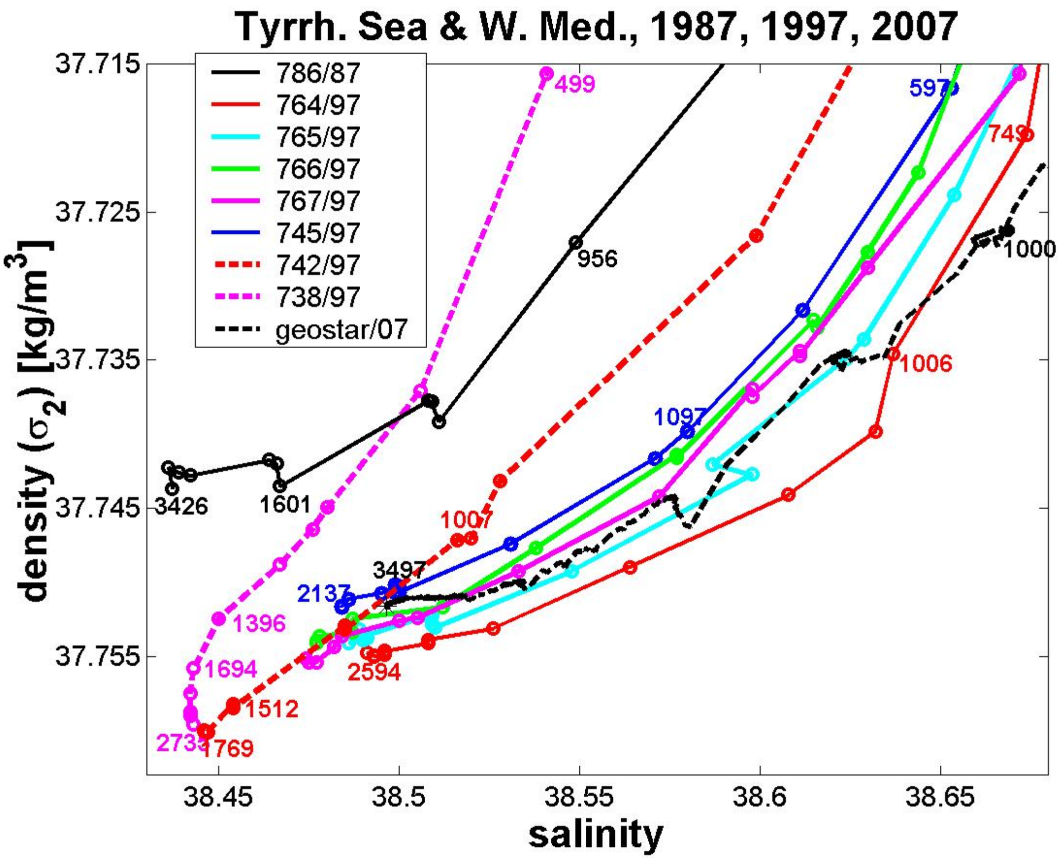

Fig. 3. Density (σ_2 = potential density referenced to 2000 dbar) versus salinity for Tyrrhenian stations, 1987–2007 and for WMed stations of 1997 (bottle data; the 1997 profiles are in color). For cruises and station positions see Table 1 and Fig. 1, depth markings are in dbar. For the 2007 tracer station a nearby CTD profile is shown, which displays staircase structures.

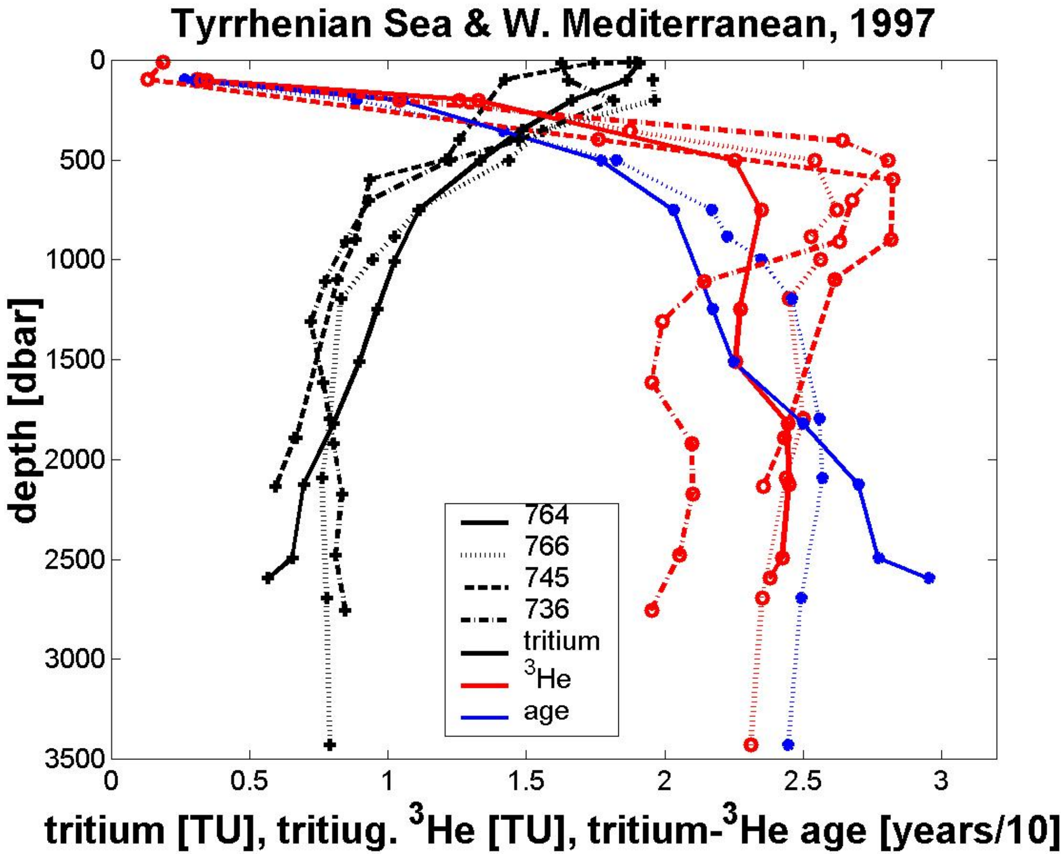

Fig. 4. Profiles of tritium and tritiugenic ^{3}He (both in TU) and tritium-^{3}He ages in the Tyrrhenian Sea and the WMed, POSEIDON 234, 1997. Note that age scale is compressed 10-fold (1 unit = 10 years). For station positions see Fig. 1. Sta. 736 replaces 738 shown in Fig. 3 which does not have tracer data, while T and S are nearly the same. Tritium data for station 766 converted from Sta. 765 data using a correlation with the tracer CFC-12 (Sect. 3).

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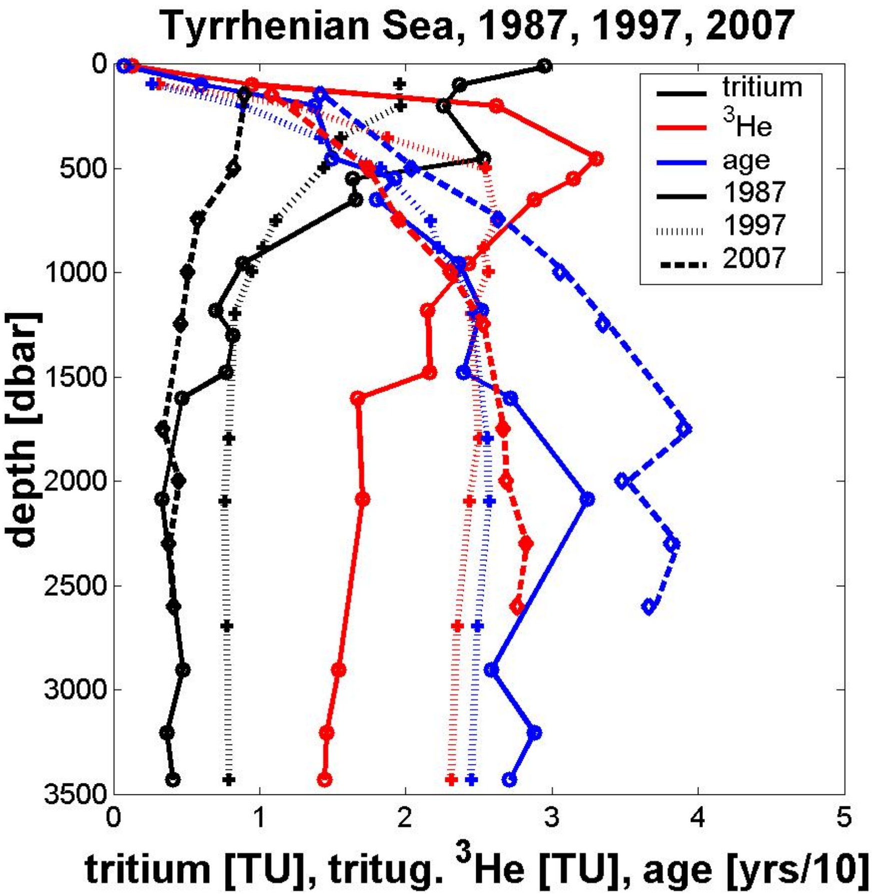

Fig. 5. Tritium, tritiugenic ^{3}He [TU] and tritium-^{3}He age [years/10] in the Tyrrhenian Sea in 1987 (M 5/6, Sta. 786, full lines), 1997 (POSEIDON 234, Sta. 766, dotted) and 2007 (AEOLIAN 07, V07B-01, dashed). For station positions see Fig. 1. The scatter in the 1987 tritium profile and in the age profiles reflects the data uncertainties (Sect. 3).

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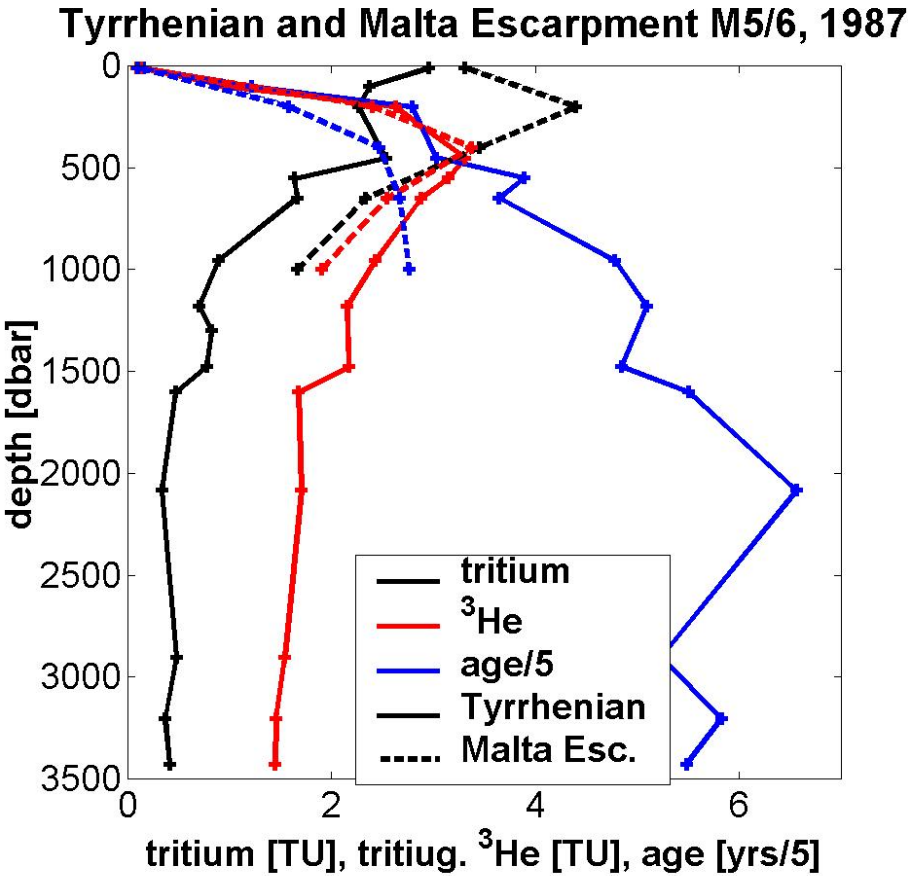

Fig. 6. Profiles of tritium, tritiugenic ^{3}He [TU] and tritium-^{3}He-ages [years/5], METEOR 5/6, 1987, in the Tyrrhenian Sea (Sta. 786) and at the Malta Escarpment upstream of the Sicily Strait (Sta. 779). For Sta. 779 only the upper 1000 m are shown, for station positions see Fig. 1.

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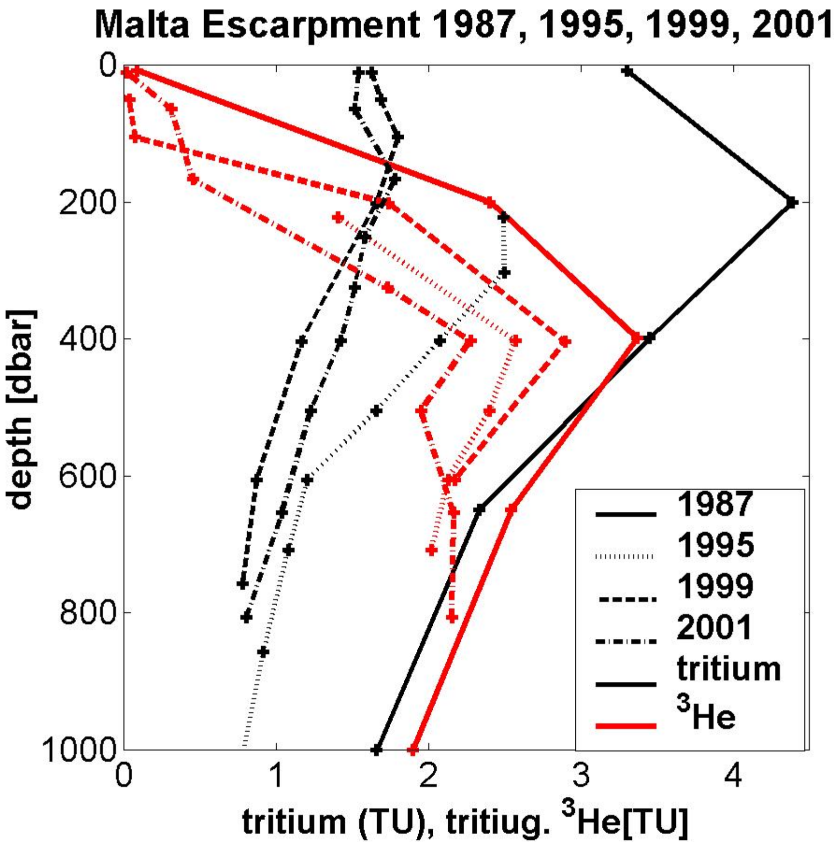

Fig. 7. Profiles of tritium and tritiugenic ^{3}He off the Malta Escarpment in 1987 (METEOR 5/6, Sta. 779), 1995 (METEOR 31/1, Sta. 8), 1999 (METEOR 44/4, Sta. 303) and 2001 (METEOR 51/2, Sta. 558). For station positions see Fig. 1. The locations of the 1999 and 2001 stations are somewhat farther away from the escarpment. Note temporal inversions in the general trend of decreasing tracer concentrations.

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