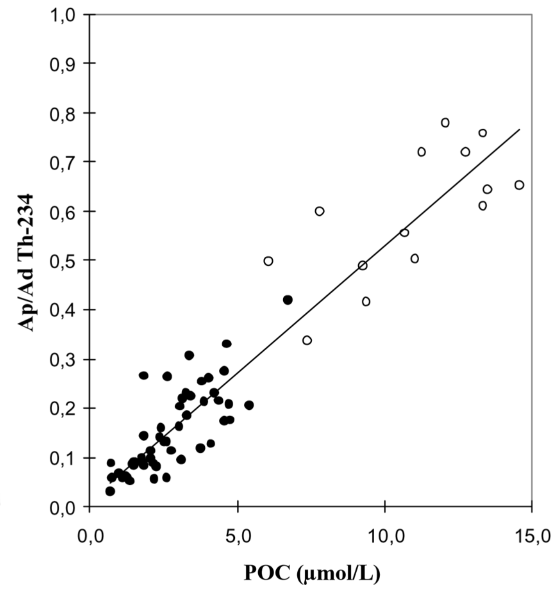

Fig. 8. Particulate ^{234}Th (A_p, normalised to the dissolved activity A_d) as a function of POC in suspended material collected near the Polar Front at 20-60m depth (open circles) and below 80m (closed circles), an example of the kind of data used to determine the POC/^{234}Th ratio on particles suspended at the depth where the export is to be determined. Summer expedition, ANT XIII/2 (Rutgers van der Loeff et al. 2002)

tained from a high-resolution transect of total ^{234}Th in surface water alone as shown by the examples given above (Figs. 6,7). Another example is given by a transect from the SE Pacific (Fig. 9), where a strong export could be demonstrated near the ice edge, probably related to iron inputs (de Baar et al. 1999).

We conclude that the under-way analysis of total ^{234}Th in surface waters, collected at high resolution from the ship's seawater supply, is a powerful tool to describe the geographical distribution of export production. Such a monitoring, supported by occasional measurements of activity-depth profiles and/or of the mixed layer depth, and linked with a satellite-based (SeaWiFS) monitoring of the distribution of chlorophyll (calibrated with shipboard observations, e.g. Bathmann et al. 1997), would provide a tool to estimate export production on a basin-wide scale.

The Fate of Exported Particles: Shallow Mineralization in the Weddell Sea

In an area of the Weddell Sea with extremely low suspended particle load (61-67°S, Fig. 7) we found for the first time a situation with export from the surface mixed layer that was balanced by a release at only 150-350m depth (Fig. 10) implying a very shallow mineralization. This situation is extraordinary, as it is associated with a net uptake of CO_2, which is in part exported to greater depths through the formation of AABW, whereas no record of this export is retained in the underlying sediments (Usbeck et al. 2002; Hoppema et al. 1997).

This shallow mineralization is also reflected in the distribution of dissolved nutrients (Whitworth and Nowlin 1987), as shown in detail by inverse modelling of available hydrographic and nutrient data sets from the literature (Usbeck 1999; Usbeck et al. 2002; Schlitzer 2000, 2002). It is also found in the distribution of oxygen and CO_2 (Hoppema et al. 1997), and in the distribution of another particle-reactive nuclide: ^{210}Pb (Farley and Turekian 1990). The mineralization depth recorded with ^{234}Th is somewhat shallower than expected from the distribution of these other tracers. This is probably related to the short half-life of ^{234}Th, which implies that the ^{234}Th release at 150-350m is asso-

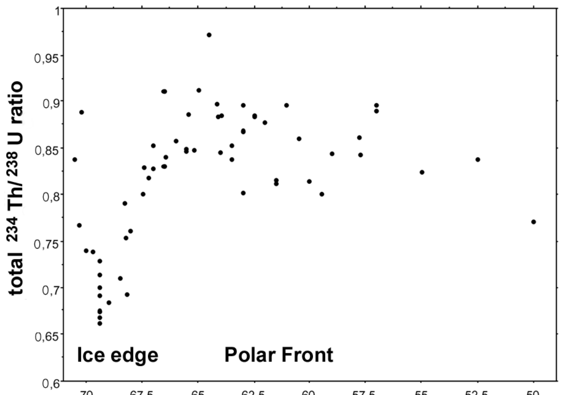

Fig. 9. April 1995: Total $^{234}Th/^{238}U$ ratios on a transect across the ACC in the SE Pacific (90°W, *Polarstern* Expedition ANT XII/4, redrawn from de Baar et al. 1999)

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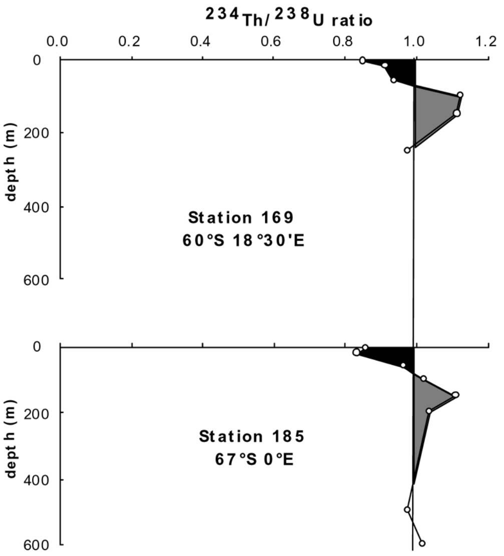

Fig. 10. Depth profiles of total ^{234}Th/^{238}U ratios, showing remineralization maxima and negligible net export production below 350m in the central Weddell Sea (ANT XVI/3, redrawn from Usbeck et al. 2002)

ciated with the decomposition of the most labile fractions, whereas the distribution of the other tracers is determined by the cumulative decomposition of a wider range of fractions.

^{234}Th in the Nepheloid Layer

Near the seafloor a situation exists that is very similar to that in the surface ocean. In the benthic nepheloid layer (BNL), ^{234}Th is adsorbed on resuspended particles. The resuspension-sedimentation cycle causes a depletion of total (dissolved + particulate) ^{234}Th in a layer that is on the order of 100m thick. This depletion can be used to quantify the particle exchange between sediment and bottom water (Bacon and Rutgers van der Loeff 1989; Rutgers van der Loeff and Boudreau 1997). We have measured the distribution of ^{234}Th in bottom waters on three transects across the Antarctic Circumpolar Current (ACC) in the southeast Atlantic (approx. 0° and 40°E, ANT XI/4) and in the southeast Pacific (90°W, ANT XII/4) (Fig. 11). The distribution of particulate ^{234}Th can be considered as a measure of particle load. Whereas in surface waters particulate ^{234}Th is well correlated with algal biomass and chlorophyll, in deep waters it depicts the intensity of the nepheloid layer. Relative to the low particle loads in the far south (central Weddell Sea), we observe enhanced particle loads associated with the major fronts in the ACC, probably as a result of high bottom water currents and of rugged topography.

In the entire area we observed only minimal depletion of ^{234}Th with respect to ^{238}U in the bottom water. This implies that the residence time of particles in the nepheloid layer is generally longer than a few weeks, the time scale that can be measured with this tracer. One station in the central Enderby basin with high suspended load in the bottom water formed a conspicuous exception with a depletion of 13% (Fig. 12). Apparently, a strong resuspension and partial sedimentation of the opal rich sediments had occurred here.

An essential parameter of the budget of ^{234}Th in the BNL is the activity of ^{234}Th on the resuspended material. The interaction between resuspension and bioturbation can be described in a model that can be calibrated with ^{234}Th measurements. With this model (Rutgers van der Loeff and Boudreau 1997), turnover rates of other exchange processes at the sediment-water interface can be gauged with the ^{234}Th tracer.

Water Mass Tracers: ^{228}Ra, ^{227}Ac

Radium and Actinium are relatively mobile elements with isotopes that are produced in the uranium decay series from highly insoluble parents. Consequently, they are very well suited to trace water masses after their contact with sediment surfaces. In the remote oceans like the Southern Ocean it is of particular importance to have a tool to trace the advection of water masses with a potential input of terrigenous micronutrients. In the framework of investigations on the sources of iron in the South Atlantic we have studied the distribution of the isotopes ^{228}Ra and ^{227}Ac.

^{228}Ra: Tracer for Shelf Waters

^{228}Ra is produced by decay of ^{232}Th, which is ubiquitous in all sediments. ^{228}Ra is therefore released by all sediments, both in the deep-sea and near-

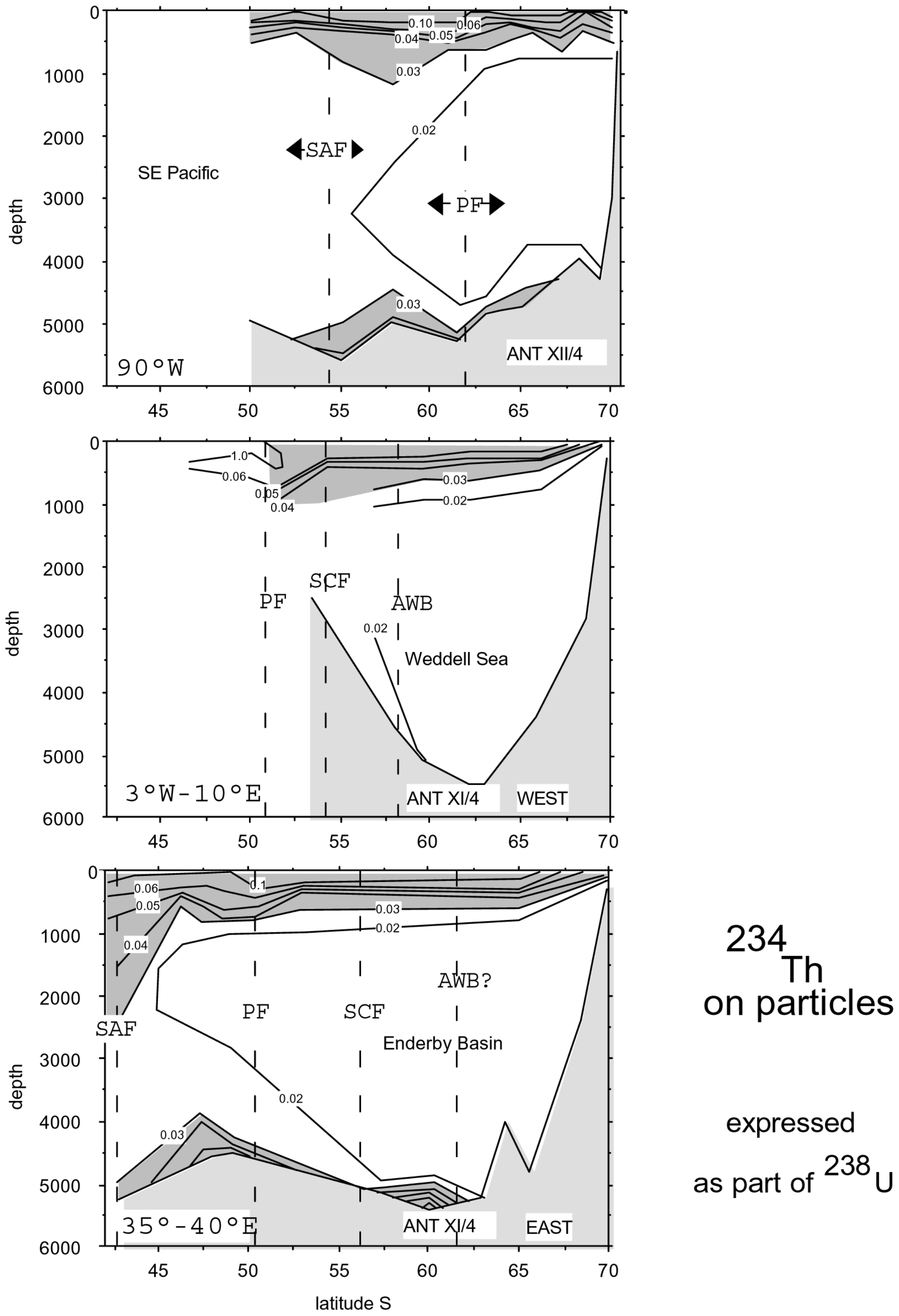

Fig. 11. Transects of particulate ^{234}Th on N-S sections across the ACC in the SE Pacific, the SE Atlantic and the SW Indian Ocean. South of the ACC, suspended loads in the bottom water are generally low.

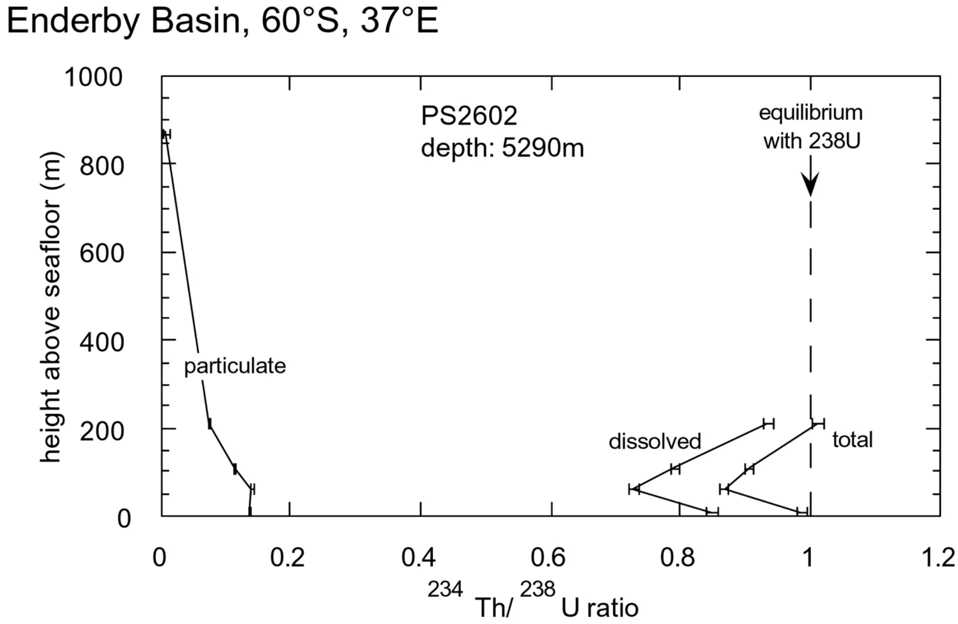

Fig. 12. An example of an exceptionally well-developed nepheloid layer in the center of the Enderby Basin. The 13% depletion of total ^{234}Th (2.8 dpm cm^{-2}) implies an intensive exchange with surface sediments with an average residence time of about 12 days.

shore. The extended residence time of coastal water masses in shallow shelf seas allows the tracer to build up here far higher activities than are reached in near-bottom waters in the deep-sea. ^{228}Ra is therefore especially well suited as a tracer of shelf waters. After the fundamental work of the GEOSECS expedition had established global distribution patterns of many radionuclide tracers including ^{228}Ra (Li et al. 1980), the first transect across the ACC towards the Antarctic continent (Rutgers van der Loeff 1994) confirmed the expected enrichment of ^{228}Ra on the Antarctic shelf. In the framework of the search for pathways of iron to the surface waters of the High Nutrient Low Chlorophyll (HNLC) Southern Ocean we have recently completed a detailed survey of ^{228}Ra in the Atlantic sector of the Southern Ocean (Hanfland 2002). Gamma spectroscopy of radium fractions collected from surface waters on MnO_2 adsorbers revealed the strong ^{228}Ra sources both near South Africa (in the Agulhas Current, carrying signals obtained on the east-African coast), near the Antarctic continent (both near Neumayer station and near the Antarctic Peninsula) and near the south American continent. In the Argentinean Basin, enhanced ^{228}Ra activities were also found far offshore, indicating the far-reaching continental influence in the south Atlantic Gyre, in support of the studies of Li et al. (1980).

In the ACC proper, Hanfland (2002) mapped the distribution of ^{228}Ra in the surface water with the far more sensitive ^{228}Th ingrowth technique (after Li et al. 1980). The idea was, that if shelf-influenced water masses intrude into the frontal jets of the ACC, this ought to be visible in enhanced ^{228}Ra levels. Radioactive decay of this 5.8-y half-life tracer cannot be significant during the transit across the Atlantic sector of the ACC, which can be estimated to be on the order of several months. But on several high-resolution sections across the ACC at 0° to 20°E Hanfland observed mostly very low ^{228}Ra activities, discounting the role of this transport route for terrigenous material. As it can be expected that uptake and scavenging cause iron to be removed more rapidly than radium, Hanfland concluded that the shelf of South America, of the

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Peninsula or of the south Sandwich Islands is not an important source for iron to alleviate the iron stress of plankton communities in the SE Atlantic (De Baar et al. 1995).

^{227}Ac: Tracer for Deep Upwelling

The application of this tracer is very similar to the previous tracer but with two major differences:

- the half-life of ^{227}Ac (21.8 y) is much longer (^{228}Ra 5.8 y). The tracer is therefore suitable for transport processes on a timescale of decades rather than years.
- the activity of the parent nuclide of ^{227}Ac (^{231}Pa) in sediments is dependent on water depth. As a consequence, deep-sea sediments are a far more important source for ^{227}Ac than shallow sediments.

Geibert (2001; Geibert et al. 2002) compared the release rate of ^{228}Ra and ^{227}Ac from marine sediments into the overlying water. This release rate depends not only on the activity of the mother nuclide in surface sediments, but also on the fraction of the daughter reaching the pore water, the adsorption equilibrium in the sediment pore water, and the bioturbation rate. Based on a model of Cochran and Krishnaswami (1980) for ^{228}Ra and an application of this model to ^{227}Ac by Nozaki et al. (1990) he shows that the ^{227}Ac/^{228}Ra release rate ratio is indeed highly distinctive, changing from 0.026 for shelf sediments to 1.4 for the deep-sea. Consequently, ^{227}Ac can be considered as a specific tracer for contact with deep-sea sediments.

The first ^{227}Ac profiles from the Southern Ocean (Geibert 2001) show indeed this bottom source of ^{227}Ac, and can in principle be used to quantify mixing rates in the deep-sea. Similar studies have been performed based on the distribution of ^{228}Ra, but can now be extended to the longer time scale of ^{227}Ac. It is remarkable that these profiles show significant excess ^{227}Ac activities (i.e. in excess over the amount supported by ^{231}Pa in the water column) in surface waters south of the Polar Front. This implies that ^{227}Ac can be used here as a tracer for upwelling of water masses from the deep-sea. Upwelling rates in the Weddell Sea as based on these ^{227}Ac data (approx. 55 ma^{-1}) are in line with earlier estimates based on heat budgets. The tracer appears to have a large potential for studies of upwelling and diapycnal mixing rates in the ocean. The tracer may thus be used to monitor temporal changes in upwelling rates. If in the past two decades deep water production in the Weddell Sea had been smaller than usual, as has been hypothesised by Broecker et al. (1998), this would require a corresponding change in upwelling rate. If the circulation returned to normal, this might be detected as an increase in the ^{227}Ac levels in surface waters.

Concluding Remarks

Natural radionuclides help us to study the transport of particles and water masses in the southern Atlantic Ocean.

Water masses that flow over continental shelf regions obtain a strong ^{228}Ra signal. Mostly very low ^{228}Ra activities in the frontal jets of the ACC show that such water masses cannot be responsible for the local fertilization in the central ACC with terrigenous trace substances like iron.

Upwelling of deep water south of the Polar Front can be followed with ^{227}Ac, a promising new tracer for water masses that have been in contact with deep-sea sediments.

Scavenging of particle-reactive isotopes helps us to calibrate particle fluxes. Export production, as measured with ^{234}Th, is absent in winter, shows large pulses in spring and continues with moderate rates during summer and autumn, with highest rates associated with the fronts of the ACC. South of the ACC, in the Weddell Gyre, we find a significant export production from the euphotic zone, but a highly efficient shallow remineralization in the depth zone of 150-350m, leaving only extremely low particle fluxes below 350m.

The low particle flux south of the ACC causes inefficient scavenging of ^{230}Th, observed in low ^{230}Th inventories and an accumulation of ^{230}Th in the water column. ^{230}Th is thus exported with AABW to the ACC where the surplus is removed by scavenging.

In the ACC, strong currents down to the seafloor are responsible for resuspension of particles in the bottom waters, as observed by increases in turbidity and in particulate ^{234}Th. This causes a large-scale redistribution of sediments, with accumulation rates that can exceed the local rain rates by an order of magnitude. ^{230}Th is very suitable to correct for these focusing and winnowing effects, provided that the boundary scavenging of ^{230}Th in the water column is taken into account.

Boundary scavenging is much more pronounced for ^{231}Pa than for ^{230}Th, making the Southern Ocean a sink for ^{231}Pa produced further north in the Atlantic. The demonstration that this process continued during the last glacial (Yu et al. 1996) tells us that NADW transport continued during the LGM but not at what intensity. The lack of fractionation between Th and Pa in the opal-dominated Southern Ocean south of the Polar Front causes the $^{231}Pa_{xs}/^{230}Th_{xs}$ ratio here to have very limited value as proxy for (paleo)productivity.

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