15 Geochemical Tracers and Ocean Circulation

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15.1 Introduction

Tracers have always been an important adjunct to physical oceanography. The distribution of dissolved oxygen (and to some extent of the nutrients, nitrate, phosphate, and silica) played a very important role in defining the major water masses of the ocean [see Sverdrup, Johnson, and Fleming (1942) for a review of this subject]. Many attempts also have been made to harness the loss of dissolved oxygen from the water column as a measure of the rates of oceanic mixing processes (e.g., Riley, 1951; Wyrtki, 1962). These latter pursuits, however, have been of only marginal success because of our lack of knowledge of the consumption rate of O_2 within the sea.

The big breakthrough in geochemical tracing came after World War II with the discovery of the cosmic-ray-produced isotopes ^{14}C and ^{3}H. A further impetus to this field came with the realization in the mid 1950s that the ocean was receiving significant amounts of ^{90}Sr, ^{137}Cs, ^{3}H, ^{14}C, etc., from nuclear testing. Because the distributions of radioisotopes offered information not so highly dependent on assumptions regarding the rates at which biological processes proceed in the ocean, the emphasis in chemical oceanography moved quickly away from the traditional chemical tracers to the radiotracers. Only quite recently has interest in the chemically used compounds in the sea been renewed. Three reasons can be given for this renaissance:

(1) Radiocarbon is transported in particulate matter as well as in solution; hence the contributions of the two processes must be separated if the distribution of ^{14}C is to be used for water-transport modeling. This separation is based on the distribution of ΣCO_2 (concentration of total dissolved inorganic carbon), alkalinity, and dissolved O_2 in the ocean.
(2) The concentrations of nitrate and phosphate can be combined with that of dissolved oxygen to yield the quasi-conservative properties "PO" and "NO". As reviewed below, such properties are needed in modeling to unscramble the "mixtures" found in the deep sea.
(3) With the advent of (a) sediment trapping and other means for the direct measurement of the fluxes of particulate matter into the deep sea, (b) devices designed to measure the fluxes of materials from the sea floor, and (c) better means for the measurement of plant productivity, interest has been renewed in generating models capable of simultaneously explaining the distribution of the chemical species, the distribution of the radiospecies, and the flux measurements.

In this chapter I shall emphasize the development of radioisotope tracing, as I feel that it constitutes the major contribution of geochemistry to our understanding of ocean circulation over the past four decades (i.e., since the writing of *The Oceans*). I will mention the use of the classical chemical tracers only where they bear on the interpretation of the radioisotope data.

Over the last decade, the Geochemical Ocean Sections Study (GEOSECS) has determined the distribution of the radioisotope tracers on a global scale. Attempts to model the previously existing ^{14}C results (Bolin and Stommel, 1961; Arons and Stommel, 1967) made clear the inadequacy of this data set. Henry Stommel therefore brought together a number of geochemists interested in this problem, and encouraged them to think big, to work together, and to produce a global set of very accurate ^{14}C data.

Because of its massive scope and of the measurement accuracy achieved, the GEOSECS data set has become dominant in the field of marine geochemistry. While previously existing radioisotope data (for review see Burton, 1975) were of great importance in the development of thinking with regard to the interpretation of tracer results and in the separation of the natural and the bomb-test contributions to ^{14}C and ^{3}H, the new data set eclipses what we had in 1969 when this program began. Thus I shall refer frequently to these new results in the sections that follow.

At the time this chapter was written the GEOSECS field program had been completed. Maps showing the ship tracks and station positions are given in figure 15.1. The laboratory analyses for the Atlantic and Pacific phases of the program are complete. Those for the Indian Ocean are still in progress. The mammoth job of making scientific use of this data set has just begun. Many years will pass before the meat of this effort will appear in print.

15.2 Water-Transport Tracers

The efforts in the field of radioisotope tracing can be divided into two categories: those that are aimed at a better understanding of the dynamics of the ventilation of, and mixing within, the ocean's interior, and those that are aimed at a better understanding of the origin, movement, and fate of particulate matter within the sea. While many of the tracers we use are influenced by both processes, a division can be made into a group primarily distributed by water transport and into a group primarily distributed by particulate transport (table 15.1). I will simplify my task by discussing here only the water-transport tracers.

The water-transport tracers can be subdivided according to their mode of origin. ^{90}Sr, ^{137}Cs, ^{85}Kr, and the freons are entirely anthropogenic in origin and hence are "transient tracers." ^{39}Ar, ^{222}Rn, ^{228}Ra, and ^{32}Si are entirely natural in origin and hence are steady-state tracers. ^{14}C and ^{3}H are in part natural and in part anthropogenic in origin. In the case of ^{3}H the man-made component dominates. For ^{14}C the man-made component constitutes about 20% of the total in surface waters and is negligible in deep water.

^{3}He, the daughter product of ^{3}H, is also a tracer. It is produced within the sea by the decay of its parent; it also leaks into the deep sea from the mantle. These components produce an excess over atmospheric solubility within the sea. As will be shown below, the contributions of these sources can usually be separated.

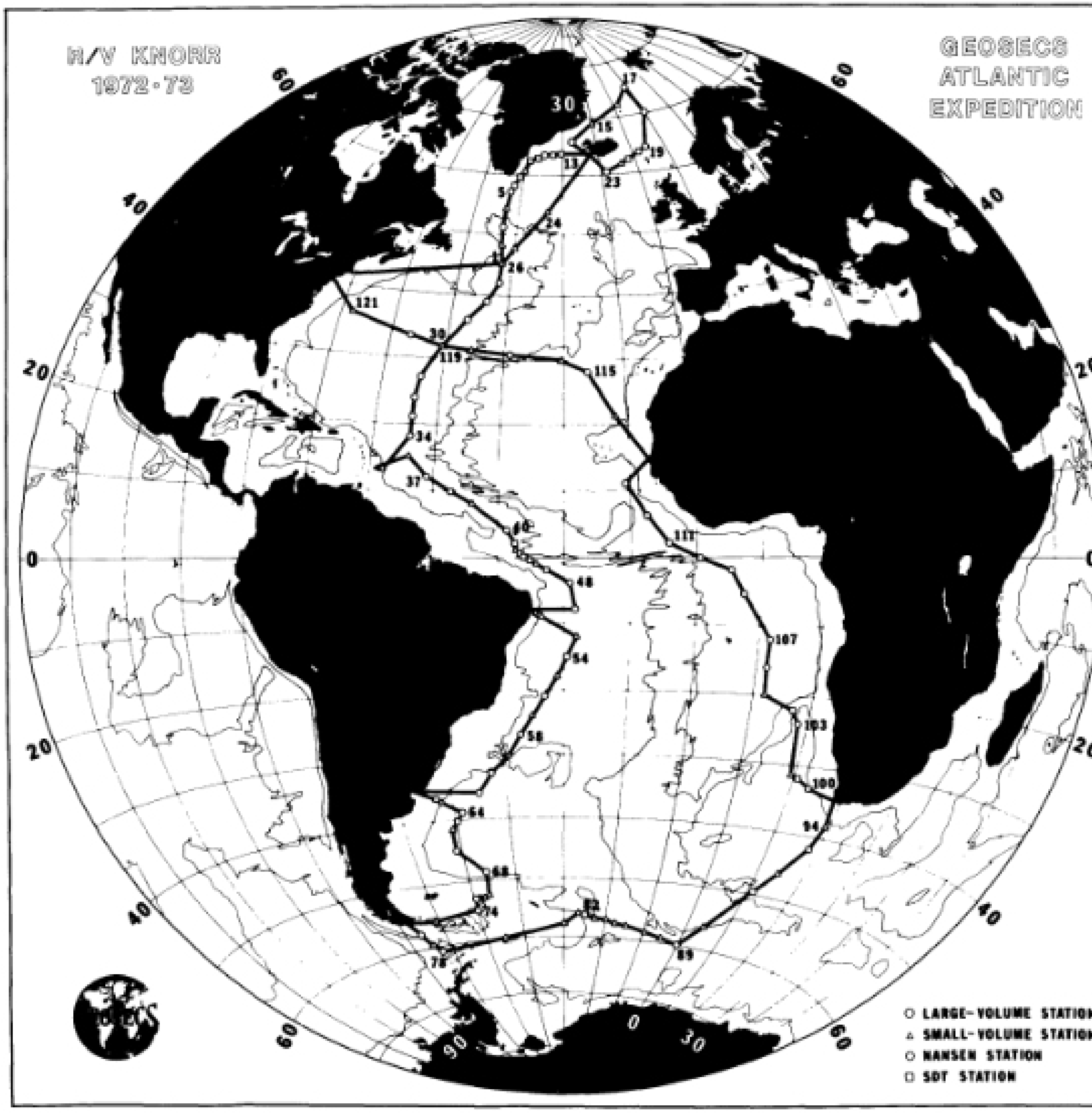
The applicability of any given isotope depends on its half-life (in the case of steady-state tracers), or its temporal-input function (in the case of the transient tracers). It also depends on the geographic distribution of the input function. The differences from tracer to tracer are sufficiently large that the information obtained from the distribution of one isotope is not redundant with that obtained from another tracer. In the sections that follow the geochemistry of each of these tracers is reviewed.

Natural radiocarbon: ^{14}C is produced in the atmosphere by the interaction of ^{14}N atoms and the neutrons produced by cosmic rays. The current production rate is estimated to be about 2.2 atoms $cm^{-2} s^{-1}$ (Lingenfelter and Ramaty, 1970). This production is balanced by the beta decay of radiocarbon atoms. In its 8200-year mean lifetime, the average ^{14}C atom can penetrate the active carbon reservoirs (atmosphere, terrestrial biosphere, ocean, ice, soils). Some ^{14}C atoms become

Table 15.1 Ocean Tracers Currently in Use[a]

Isotope	Half-life (years)	Origin: Cosmic rays	U+Th series	Weapons testing	Other anthro.
^{14}C	5730	✓		✓	
^{226}Ra	1600		✓		
^{32}Si	250	✓			
^{39}Ar	270	✓			
^{137}Cs	30.2			✓	
^{90}Sr	28.6			✓	
^{3}H	12.4	✓		✓	
^{3}He	—	✓	✓	✓	
^{85}Kr	10.7			✓	✓
^{228}Ra	5.8		✓		
^{7}Be	0.15	✓			
^{222}Rn	0.01		✓		
Freons	—				✓
^{239}Pu	24,400			✓	✓
^{240}Pu	6540			✓	✓
^{210}Pb	22.3		✓		
^{228}Th	1.9		✓		
^{210}Po	0.38		✓		
^{234}Th	0.07		✓		

a. In the column headed Isotopes, freons and all entries above it are water tracers; all entries below freons are particulate tracers.



(15.1A)

Figure 15.1 Maps showing the locations of the stations occupied during the GEOSECS program in the Atlantic (A), Pacific (B), and Indian (C) Oceans. Those properties measurable on 30-liter samples were determined at every station. Radiocarbon, which requires ~250 liters of water, was sampled only at the large-volume stations. The 4000-m contour is shown on each map.