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ABSTRACT

The complexity of ocean transport processes has meant that the limits for the dumping of low-activity radioactive wastes have had to be based on very simplified models of the oceans. This report discusses the models used to determine dumping limits and contrasts them with the known ocean circulation patterns. The deep circulations of the Indian and Pacific Oceans are reviewed to provide a basis for estimating the possible destinations and likely transit times for dissolved material released at the ocean floor.

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INDIAN OCEAN; PACIFIC OCEAN; LOW-LEVEL RADIOACTIVE WASTES; MARINE DISPOSAL; RADIOACTIVE WASTE DISPOSAL; SIMULATION; OCEAN CIRCULATION (PROPOSED); RADIONUCLIDE MIGRATION

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1. INTRODUCTION

The ocean dumping of low-level radioactive waste is being seriously considered by several countries. Since the oceans are an international resource, the impact of such dumping must be carefully assessed to determine the effect on the oceans and the surrounding nations.

The transport and dispersal of matter in the ocean is a complex process, involving physical water movement, attachment to sinking particulates, biological transport and, ultimately, incorporation into the sediments. Radioactive waste dumped onto the ocean floor releases radioactivity into the bottom waters of the oceans, whereas the fallout from nuclear weapons and the effluent from nuclear establishments introduce radioactivity into the surface waters.

This report considers the quantity of man-made radioactivity already introduced into the oceans and compares it with the natural activity. The water circulation in the Indian and Pacific Oceans is discussed to provide a basis from which to estimate water movement from possible dumping sites. Several natural and introduced radioactive tracers are then used to illustrate possible effects of sedimentation and chemical processes on the transport of specific elements. Finally, the models that have been used to assess dumping programs and to define the limits to the dumping rates are evaluated.

2. RADIOACTIVITY IN THE OCEAN

Although more than 60 radionuclides occur naturally, only a few are significant in the ocean. Some radionuclides have half-lives which are comparable with the age of the solar system and were present when the earth was formed. Potassium-40 (half-life = 1.3×10^9 y) occurs at a concentration in seawater of 0.33 μCi m^{-3} (1.2×10^4 Bq m^{-3}); this accounts for over 90 per cent of the natural radioactivity in seawater [Burton 1975; Joseph et al. 1971]. Another important primordial radionuclide is rubidium-87 (half-life = 4.7×10^{10} y) which has a specific activity of 2.9 nCi m^{-3} (110 Bq m^{-3}).

Uranium has a reasonably uniform distribution in the ocean with a concentration of about 3.3 mg m^{-3} which corresponds to an activity of 2.2 nCi m^{-3} (81 Bq m^{-3}) for uranium-238 and -234 [Burton 1975]. The uranium decays to thorium-230 which is efficiently removed to the sediment leaving a very low

concentration in seawater. The next daughter, radium-226, is not as strongly attached to the sediment and leaches out through the interstitial water. The concentration of radium and its daughters is only about 10 per cent of that corresponding to the equilibrium of the uranium present. The activity of dissolved α-emitters is about 2.6 nCi m^{-3} (96 Bq m^{-3}) giving a total α activity of about 3 GCi (10^{20}Bq) dissolved in the World's oceans.

Some short-lived radionuclides are produced by the interaction of cosmic rays with the atmosphere. Generally, their natural concentration in the ocean is low, e.g. the average specific activity of carbon-14 is 120 pCi m^{-3} (0.04 Bq m^{-3}), but they are useful as tracers for ocean circulation [Burton 1975]. The total activity of the natural radionuclides dissolved in the ocean is about 460 GCi (1.7×10^{22} Bq) which is much greater than the total man-made activity now in the ocean.

The 350 atmospheric nuclear explosions before 1963 produced about 21 MCi (7.8×10^{17} Bq) of strontium-90, 34 MCi (1.2×10^{18} Bq) of caesium-137 and larger quantities of shorter-lived radionuclides. About half of the activity from atmospheric explosions is injected into the stratosphere from whence it is widely distributed over the Earth's surface and much of it is deposited in the oceans [Joseph et al. 1971].

The dumping of low-level radioactive wastes into the oceans has been carried out by the United States of America (USA) and European countries [Joseph et al. 1971]. Between 1946 and 1967, the USA disposed of about 80 kCi (3×10^{15} Bq) of activity in 34 000 containers into the Atlantic Ocean and 15 kCi (5×10^{14} Bq) of activity in 52 000 containers into the Pacific Ocean. There have been no US dumping operations since 1967. The United Kingdom (UK) dumped about 3.7 kCi (1.4×10^{14} Bq) of alpha and 45 kCi (1.7×10^{15} Bq) of beta activity into the Atlantic Ocean between 1950 and 1966. The European countries have continued dumping operations (Table 1) under the auspices of the Nuclear Energy Agency (NEA) of the Organisation for Economic Cooperation and Development (OECD). In 1976, the NEA operation dumped 6700 tonnes of low-level wastes from Belgium, the Netherlands, Switzerland and the UK. The material was solidified in either concrete or bitumen and packaged in 200 L drums. The packaging was designed to ensure that the wastes were contained at least until the drums were resting on the ocean floor. The dumping site used by the OECD since 1971 is an area 130 km in diameter, located 900 km southwest of Lands End, Cornwall, England, at 46°15' north, 17°25' west, in water 4500 m deep [Oliver 1975].

The activity added to the oceans by OECD dumping operations is less than the activity of potassium-40 that has been added naturally over the same period. The mean residence time of potassium in the ocean is estimated to be 7×10^6 y [Brewer 1975] which implies that 60 kCi y^{-1} (2.2×10^{15} Bq y^{-1}) of potassium-40 would be required to maintain the total ocean inventory of 450 GCi (1.7×10^{22} Bq). The radioactive half-lives of virtually all of the dumped radionuclides are much less than the radioactive half-life or the ocean residence time of potassium-40.

TABLE 1
DETAILS OF THE NUCLEAR ENERGY AGENCY SEA DISPOSAL OPERATIONS

Year	Gross Weight (t)	Approximate Activity (Ci)	
		alpha	beta-gamma (incl. ^3H)
1967	10 840	250	7 600
1969	9 180	500	22 000
1971	3 970	630	11 200
1972	4 130	680	21 600
1973	4 350	740	12 000
1974	2 270	420	100 000*
Total	34 740	3 220	174 400

1 Ci = 3.7×10^{10} Bq.

*This activity is almost exclusively due to tritium.

Dyer [1976] used submersible vessels to survey the disused US radioactive waste dump sites at 2800 m in the Atlantic and 900 and 1700 m in the Pacific. Some contamination of the surface sediments by plutonium-238, -239 and -240 and caesium-137 was detected. Many of the drums had failed because of the lack of pressure-equalising devices which have been used in more recent dumping operations. The mild steel containers, which had been immersed for 13 to 23 years, showed considerable evidence of surface corrosion, but none of the drums had been breached solely as a result of external corrosive forces. Further studies of the dump site in the Pacific west of San Francisco showed

that the quantities of plutonium-239 and -240 and caesium-137 in the sediment and water columns were not significantly different from the amounts elsewhere in the open sea [Noshkin 1978]. Furthermore, the body burdens of plutonium-239 and -240 in fish and invertebrates collected in the area were similar to the body burdens of species collected elsewhere.

As well as the dumping of low-level radioactive materials onto the floor of the abyssal ocean, a comparable amount of low-level activity has been discharged directly into the surface waters from nuclear installations and nuclear-propelled shipping. The main discharges have come from fuel reprocessing plants such as Windscale (UK), La Hague (France) and Trombay (India). The Windscale plant, for example, discharged an average of 64.5 kCi y^{-1} (2.4×10^{15} Bq y^{-1}) of beta activity into the Irish Sea between 1957 and 1967 [Joseph et al. 1971]. The discharged alpha activity has been increasing over the years, and in 1974 the waste water discharged from Windscale contained 20 kg of dissolved plutonium isotopes having a total activity of 1.2 kCi (4.4×10^{13} Bq) [Hetherington et al. 1975]. Liquid effluent from power reactors usually contains less than 100 Ci y^{-1} (3.7×10^{12} Bq y^{-1}) of activity (excluding tritium) and, in many cases, the release is less than 1 Ci y^{-1} (3.7×10^{10} Bq y^{-1}).

2.1 The London Convention

An intergovernmental conference on the dumping of all types of wastes into the oceans was held at London in 1972. The members of the conference adopted the 'Convention on the Prevention of Marine Pollution by the Dumping of Wastes and Other Matter', often referred to as the London Convention [IAEA 1974], which came into force on 30 August 1975.

The convention sets out the conditions for dumping operations and the factors to be considered in the issue of permits by national authorities, and includes lists of substances for which dumping is prohibited or which require special care. Specifically, the dumping of high-level radioactive matter is prohibited in Annex I, with the definition of high-level activity being left to the International Atomic Energy Agency (IAEA), with the direction that the definition is to be made on public health, biological or other grounds. Other radioactive matter not included in the definition of high-level activity is listed in Annex II among substances that are permitted to be dumped, but that require special care. Annex II, item 6, states that in the issue of permits for the dumping of this matter (i.e. low-level radioactive material), the

contracting parties should take full account of the recommendations of the competent international body in this field which, at present, is the IAEA.

In December 1974, the IAEA issued the 'Provisional Definition and Recommendations Concerning Radioactive Wastes and other Radioactive Matter Referred to in Annexes I and II to the Convention' [IAEA 1975]. High-level radioactive matter, unsuitable for dumping at sea, was defined as matter with activities exceeding

(a) 10 Ci t^{-1} (3.7×10^{8} Bq kg^{-1}) of α-activity,

(b) 10^{3} Ci t^{-1} (3.7×10^{10} Bq kg^{-1}) of β/γ wastes (excluding tritium), but with a limit of 10^{2} Ci t^{-1} (3.7×10^{9} Bq kg^{-1}) for strontium-90 plus caesium-137, or

(c) 10^{6} Ci t^{-1} (3.7×10^{13} Bq kg^{-1}) of tritium.

These limits were based on a maximum dumping rate of 100 000 tonnes per year at a given site. The recommendations included a requirement for a detailed environmental assessment of dumping, requirements for selecting a dumping site, requirements for packages and recommended procedures during the dumping operation.

The limits and recommendations were reviewed by a series of consultant and advisory group meetings [IAEA 1978a,b]. A more suitable oceanographic model for the dispersal of radionuclides in the ocean was adopted and the effect of radionuclides on the food chains was considered in greater depth. The definition of the high-level waste that is unsuitable for dumping at sea was redefined to include any matter with an activity per tonne exceeding:

(a) 1 Ci t^{-1} (3.7×10^{7} Bq kg^{-1}) for α-emitters but limited to 0.1 Ci t^{-1} (3.7×10^{6} Bq kg^{-1}) for ^{226}Ra and supported ^{210}Po,

(b) 10^{2} Ci t^{-1} (3.7×10^{9} Bq kg^{-1}) for β/γ-emitters with half-lives of at least 0.5 years (excluding tritium), and

(c) 10^{6} Ci t^{-1} (3.7×10^{13} Bq kg^{-1}) for tritium and β/γ-emitters with half-lives less than 0.5 years,

where the activity concentrations are averaged over a gross mass not exceeding

1000 tonnes.

This definition of high activity waste is based on the need to limit the activity released into an ocean basin and assumes that the dumping rate will not exceed 100 000 t y^{-1} at a single dumping site. The calculated upper limits to activity release rates from all sources (other than natural sources) are:

(a) 10^5 Ci y^{-1} (3.7×10^{15} Bq y^{-1}) for α-emitters but limited to 10^4 Ci y^{-1} (3.7×10^{14} Bq y^{-1}) for ^{226}Ra and supported ^{210}Po,

(b) 10^7 Ci y^{-1} (3.7×10^{17} Bq y^{-1}) for β/γ-emitters with half-lives of at least 0.5 years (excluding tritium), and

(c) 10^{11} Ci y^{-1} (3.7×10^{21} Bq y^{-1}) for tritium and β/γ-emitters with half-lives less than 0.5 years,

at a single dumping site and for α-emitters when released into a basin of not less than 10^{17} m^3.

2.2 Future Dumping Plans

The European countries, particularly the UK, will probably continue the dumping program at present carried out under the auspices of the NEA. Possibly there will be some changes in the coordinating organisation, but there are advantages in countries combining under international organisations. Firstly, there is an overall control of the dumping operations and secondly, the responsibility is taken away from the local authorities.

With the increasing reluctance of many governments to dispose of low-level radioactive material by shallow land burial, there is likely to be increasing interest in ocean disposal. Under the terms of the London Convention, the dumping of low-level radioactivity into the ocean is accepted in principle.

Japan has a large nuclear program and is looking very closely at ocean disposal for its low-level waste [Machida et al. 1976; Ohmachi 1978]. In 1969 Japan began feasibility studies and selected four sites on the abyssal plains of the Pacific Ocean between 800 and 1900 km south-east of Japan for detailed study. Investigations have since been carried out at each site into the ocean

currents, the bottom topography, the background radioactivity, the bottom boundary layer, the marine life and the effect on the fishing industry. In parallel with the oceanographic work, research and development is being carried out into the packaging of the waste. The leachability of cement packages is being measured under simulated sea floor conditions, and dumping tests are being carried out using inactive drums monitored by deep-sea television cameras.

The USA does not have any plans to dump low-level radioactive waste into the ocean, although it has taken an active interest in the drafting of the regulations to control any dumping operations. However, the USA has an active program to consider all possible methods for the disposal of high-level waste and one of the options is disposal beneath the ocean floor [ERDA 1976; Anderson 1979]. In seabed disposal, the high-level waste would be contained in high integrity containers which would be positioned in the geological formations beneath the ocean floor. The water column itself would be considered primarily as a means to isolate the waste from human intervention and provide some protection against inadvertent releases of small amounts of activity. The sediments are being closely investigated to see if they provide an adequate barrier to the transport of radionuclides. Seabed geological disposal does have some advantages over land-based disposal; interstitial water movement in the ocean sediments is slower than ground water movement on land, and there is a continuous deposition of sediment onto the ocean floor in contrast to the continual erosion on land. Nevertheless, the greater cost of seabed disposal and international and political considerations suggest that, for the USA at least, land-based geological disposal will be adopted before seabed disposal.

3. DEEP WATER CIRCULATION

It is important to relate the oceanographic models used for defining the limits for radioactive waste disposal to the properties of the real oceans. The models are very simple and use a few empirical parameters to replace the many complex processes occurring in the ocean. Before discussing the models, the deep circulation of the Indian and Pacific Oceans will be reviewed to show the complexity and extent of the circulation patterns. Any human exposure to leached material is likely to occur at a location remote from the original dumping site. Only by considering the real circulation patterns can we hope to predict the travel paths and destinations of material released from dumped

waste.

3.1 The Indian Ocean

The Indian Ocean extends from the Asian land mass in the north to Antarctica in the south. The boundary between the Atlantic and the Indian Oceans is taken to be at 20°E. The boundary between the Pacific and Indian Oceans is taken to follow a line from the Malay Peninsula, through Java, Timor and Tasmania and thence along longitude 147°E to Antarctica. The area of the Indian Ocean, including adjacent seas, is 7.5×10^7 km^2 and the volume is 3×10^8 km^3.

The surface circulation of the Indian Ocean consists of three distinct systems [Figure 1; after Wyrtki 1973]:

- A tropical gyre driven by the monsoonal winds and which reverses between the seasons. The Somali current flows southward in February and northward in August.

- A subtropical gyre of water with low nutrient concentrations. This gyre has a strong western boundary current (the Agulhas current) and a very weak and sometimes non-existent eastern boundary current off Western Australia.

- The eastward circumpolar current.

The deep water in the Indian Ocean originates in the South Atlantic Ocean and flows into the Indian Ocean with the circumpolar current. The deep water in the South Atlantic is a combination of water from three sources [Callahan 1972; Reid et al. 1977]:

- Circumpolar water from the Pacific Ocean.

- Very cold and less saline bottom water formed in the Weddell Sea, a semi-enclosed Antarctic sea.

- Very saline North Atlantic deep water.

The Weddell Sea bottom water is the densest water and forms the lowest layer. The North Atlantic deep water has a density within the range of

densities of the circumpolar water and so it divides the circumpolar water into two layers [Reid et al. 1977]. The core of the North Atlantic deep water enters the Indian Ocean at a depth of between 2500 and 3200 m. It spreads north into the Indian Ocean although its spreading seems to be diffusive rather than caused by a real flow [Wyrtki 1973]. The salinity maximum associated with the core of the North Atlantic water can be identified to the north of Madagascar and east to the Tasman Sea.

3.1.1 Bottom water

The bottom water flows east and north into the Indian Ocean and the flow can be inferred from the properties at 4000 m depth in the major basins (Table 2). As the water flows along its path, the potential temperature increases because of mixing with the overlying water and geothermal heating from below, the salinity increases because of mixing with the overlying water, and the silicate concentration increases because of the contact with the skeletal material in the sediments. The bottom water follows two routes (Figure 2); one starts at the African-Antarctic Basin and flows in the Arabian Basin and the other starts at the South Indian Basin and flows to the Northwest Australian Basin with some flow to the Central Indian Basin [Kolla et al. 1976].

TABLE 2
POTENTIAL TEMPERATURES AND SALINITY AT 4000 m
DEPTH IN THE MAJOR INDIAN OCEAN BASINS
[After Wyrtki 1971]

Basin	Sill (m)	Potential Temperature (°C)	Salinity (g kg^{-1})	Silicate (mol m^{-3})
African-Antarctic		-0.4	34.665 ± 0.015	0.100 ± 0.026
East Crozet		0.45	34.712 ± 0.013	0.100
Madagascar	3950	0.85	34.725 ± 0.010	0.122 ± 0.014
Somali	4100	1.11 ± 0.05	34.725 ± 0.009	0.126 ± 0.019
Arabian	3800	1.32 ± 0.03	34.737 ± 0.014	0.146 ± 0.012
South Indian		-0.25	34.683 ± 0.016	0.107 ± 0.027
South Australian		0.7	34.732 ± 0.016	0.080
Northwest Australian		0.87 ± 0.04	34.721 ± 0.012	0.120
Central Indian	3750	1.05 ± 0.03	34.734 ± 0.034	0.130

NOTE: Where the properties are sufficiently uniform, the mean value and the standard deviation of all the measurements in the basin are given. Where a wide range of values occurs in a given basin, an estimate of the mean is shown. The sill depth into the basin is derived from the temperature profile.

The bottom water in the African-Antarctic Basin following the western route flows through the Crozet Basin into the Madagascar Basin [Kolla et al. 1976]. The water descending into the Madagascar Basin moves southwest along the western flank of the ridge, conserving potential vorticity, before moving north along the western side of the basin [Warren 1974]. Warren carried out hydrographical sections along latitudes 12°S and 23°S between Madagascar and the Central Indian Ridge and observed a deep western boundary current in the Madagascar Basin which has a volume transport of 4 to 5 x 10^6 m^3 s^{-1} below 3000 m. There was no suggestion in the sections of any return flow in the basin, so most of the current must flow into the Somali Basin. Finally, some bottom water from the Somali Basin flows into the Arabian Basin over a sill of depth 3800 to 4000 m. Bottom photographs, current measurements and low turbidity values show that the flow in the two northern basins is much less vigorous than in the southern basins [Kolla et al. 1976].

The bottom water from the African-Antarctic Basin also forms part of the circumpolar current and flows along the northern edge of the South Indian Basin [Kolla et al. 1976]. The actual flow path over the Kerguelen Plateau between the African-Antarctic Basin and the South Indian Basin is uncertain. Kennett and Watkins [1975] suggested that most of the bottom water in the South Indian Basin originates from the Ross Sea at latitude 80°S and flows westward close to the Antarctic continent. Gordon [1972] looked at the potential temperature, oxygen and salinity in the South Indian Basin and concluded that most of the bottom water was similar to Weddell Sea water but different from Ross Sea shelf water.

The second route for bottom water flowing northwards in the Indian Ocean starts at the South Indian Basin. At latitude 120 to 125°E, a portion of the deep flow moves north into the South Australian Basin. The bottom water in the South Australian Basin is very active, resulting in unconformities in sedimentary sections and manganese nodule formation [Kennett and Watkins 1975]. Part of the South Australian Basin bottom water flows north into the West Australian Basin. The bottom flow in the West Australian Basin appears to be weak, although there is a lack of data to confirm this [Kolla et al. 1976]. Warren [1977] demonstrated the existence of a western boundary current in the West Australian Basin from the slope of the isotherms at latitude 18°S. The flow is concentrated within about 30 km of the Ninety East Ridge with a maximum flowrate of about 6 cm s^{-1} and a volume transport of 4 to 7 x 10^6 m^3 s^{-1}.

The source of the deep water in the Central Indian Basin is very uncertain. The bottom waters of the Central Indian Basin have the highest temperatures of any of the deep Indian Ocean basins at the same latitude (Table 2), suggesting that the inflow of bottom water is less than for other basins. Most likely, the water enters the Central Indian Basin from the South Indian Basin or the West Australian Basin.

3.1.2 Southward flow at intermediate depths

Upwelling of bottom water and vertical mixing are likely to take place in the North Indian Ocean where the vertical stability of the deep water is low [Reid and Lynn 1971]. The outflows from the Red Sea and the Persian Gulf into the Northwest Indian Ocean are very saline and form a very stable layer at 300 to 800 m depth. Vertical mixing with the deep water forms a thick layer of high salinity water, called the North Indian intermediate water, which extends to more than 1200 m depth [Wyrtki 1973]. The isolation and stagnation of this water, combined with its high biological activity, produces very low oxygen concentrations of less than 1 mL L^{-1} in the layer between 200 and 1200 m everywhere north of latitude 3°S. The layer of low oxygen concentration is connected with a deep oxygen minimum which is present over the whole ocean. Near the equator the minimum lies at 800 m depth, but it deepens to about 1200 m near latitude 40°S and rises to about 400 m at latitude 50°S near the polar front. The oxygen content of the minimum increases slowly southward and reaches 4 mL L^{-1} at 40°S [Wyrtki 1973].

The oxygen minimum water is probably moving south and the increase in oxygen is caused by mixing with waters flowing above and below, which have higher oxygen concentrations. However, there is no direct evidence of southward flow. The distribution of properties in the core of the oxygen minimum water [Wyrtki 1973] could equally well be explained by large scale mixing processes. There is a suggestion of a preferential flow south in the Western Indian Ocean [Callahan 1972] and possibly southward transport occurs with the Agulhas current which extends to 2000 m depth [Wyrtki 1973].

A deep, anti-cyclonic (anti-clockwise in the southern hemisphere) gyre exists in the South Australian Basin, whereas a cyclonic gyre exists in the South Indian Basin [Callahan 1972; Gordon 1972; Eittreim et al. 1972]. Callahan [1972] suggested that water flows from the Tasman Sea into the South Australian Basin. Such a flow is likely to recirculate the oxygen minimum water from the tropical Indian Ocean. Gordon [1972] also analysed the

distributions of temperature, salinity and oxygen, but, conversely, suggested that water flows from the South Australian Basin to the Tasman Basin. There is agreement that a deep, westward flow exists close to the south coast of Australia.

3.2 The Pacific Ocean

The Pacific Ocean is a vast body of water having an area of 1.8×10^8 km^2 (including adjacent seas) and a volume of 7×10^8 km^3. The mean surface currents of the Pacific Ocean are shown in Figure 3. The equatorial surface currents are generally shallow, extending perhaps to a depth of 300 to 500 m, whereas the western boundary currents can extend to a depth of 2000 m [Gordon 1975]. The jet-like equatorial undercurrent which flows towards the east, has a maximum velocity at a depth of only 100 m and does not extend much below 200 m. The main features of the surface circulation are the north and south sub-tropical, anti-cyclonic gyres (i.e. clockwise in the northern hemisphere and anti-clockwise in the southern hemisphere). The gyres are intensified in the west, producing the Kuroshio current in the northern hemisphere and the east Australian current in the southern hemisphere. The circumpolar current forms one boundary of the southern gyre. At high latitudes in the North and South Pacific there are cyclonic gyres which are weak in summer, but probably stronger in winter [Reid 1973a].

The low salinity North Pacific and Antarctic intermediate waters flow towards the equator at depths of 500 to 1000 m [Reid 1965; Johnstone 1973]. At these intermediate depths, the circulation is similar to the surface circulation, except that the gyres are slightly displaced in the polar region.

3.2.1 Bottom water

Although the surface temperatures in the North Pacific Ocean approach freezing in winter, the salinity is low and the density is always less than the deep water [Reid 1973a; Mantyla 1975]. This means that deep mixing to depths below about 2000 m is not possible under normal winter conditions. Ice formation in semi-enclosed seas can increase the salinity but the quantities of bottom water produced are too small to be recognisable in the ocean. The deep and bottom waters in the North Pacific Ocean must have flowed across the equator from the circumpolar current in the south. The bathymetry of the Pacific Ocean (Figure 4) shows that the only route for bottom water to reach the deep basins of the North Pacific is through the narrow Tokelau (Samoan)

Passage at latitude 10°S, longitude 170°W. The Tasman Sea is closed by a sill to the north at a depth of 3000 m and the Southeast Pacific Ocean is limited by the East Pacific Ridge with a sill depth of 3500 m [Lonsdale 1976].

The bottom water flows into the Pacific Ocean from the South Indian Basin across the Southeast Indian Ridge into the Tasman Basin at longitude approximately 145 to 155°E [Gordon 1972]. The bottom water of the Tasman Basin south of latitude 45°S is similar to the water in the South Indian Basin, but colder and fresher than the water of the South Australian Basin. The flow of water between the Tasman and South Australian Basins is uncertain; Callahan [1972] and Gordon [1972] inferred opposite flow directions from their respective data.

A tongue of circumpolar bottom water extends into the Tasman Sea, possibly deflected northwards by the Macquarie Ridge [Callahan 1972]. Reid and Arthur [1975] in their study of the geopotential anomaly in the Pacific found evidence for a deep anti-cyclonic gyre in the Tasman Basin. In contrast, Gordon [1972] suggested a clockwise gyre in the Tasman Basin. The bottom flow in the Tasman Basin is uncertain [Harries 1976] but there must be a net flow towards the north as the bottom water warms from a potential temperature of 0.62°C at latitude 43°S to 0.80°C at latitude 28°S [Warren 1973]. No simple circulation pattern could explain all of the water properties observed by Warren. The flow of the bottom water in the Tasman Sea is probably coupled to the flow of the lower layers of the circumpolar current which flows through the southern part of the Tasman Basin. Any variations in the transport or location of the flow of the circumpolar current might cause variations in the flow of the Tasman Basin bottom water.

The water of the circumpolar current is relatively uniform in the Pacific sector and the distinction between deep and bottom water in the circumpolar current disappears. Hence all of the water in the lower layers of the circumpolar current will be referred to as bottom water. Within this bottom water there will still be some gradation of properties and, in places, the core of the North Atlantic deep water can be identified as a weak salinity maximum.

The flow of bottom water into the main Pacific basins can be inferred from the distribution of bottom potential temperatures (Figure 5). Circumpolar bottom water flows into the Southwest Pacific Basin and travels north along the Kermadec Trench at the western boundary of the basin [Callahan

1972]. The maximum geostrophic velocity in the trench is almost 20 cm s^{-1} at 5000 m and the total transport to the north below a depth of 2000 m is about 15 x 10^6 m^3 s^{-1} [Warren 1973]. The current flows along the western boundary of the Samoan Basin at a depth greater than 4000 m and northwards through the Tokelau (Samoan) Passage. Once through the passage, the water cascades into the deeper water of the Central Pacific Basin [Reid and Lonsdale 1974] and the flow divides into two branches [Mantyla 1975; Reed 1969]. The larger flow is to the Northwest Pacific with a smaller flow towards the east and both branches converge in the Northeast Pacific Basin to the north of Hawaii. Here the bottom potential temperature is greater than 1.1°C and the water has a low oxygen and high silicate concentration [Mantyla 1975].

Gordon and Gerard [1970] estimated that bottom water would take 750 years to travel from latitude 10°S to the centre of the Northeast Pacific Basin, on the basis of the temperature increase and the oxygen decrease. A residence time of 500 to 750 years is obtained by dividing Warren's transport value of 15 x 10^6 m^3 s^{-1} into the volume of the Pacific Ocean north of latitude 28°S. These residence times are consistent with earlier estimates of 500 to 1000 years for the residence time of water in the deep Pacific Ocean [Pritchard et al. 1971].

3.2.2 Flow at intermediate depths

The water in the Northeast Pacific Basin below a depth of 3500 m has a low vertical stability and hence will be subject to vertical mixing. The mixed water forms the North Pacific deep water which flows to the south over the bottom water. The interface between the North Pacific deep water and the northward flowing bottom water can be identified as a discontinuity in the vertical temperature profile from latitude 60°S to 20°N [Chung 1975]. The depth of the interface varies from about 3000 m at latitude 40°S to 4000 m at latitude 20°N.

The southward flowing North Pacific deep water has relatively low dissolved oxygen and high silicate concentrations. It is not as topographically controlled as the bottom water and the flow pattern is difficult to discern. In the northern hemisphere, the North Pacific deep water flows in the same direction as the overlying North Pacific intermediate water and the flow is likely to be concentrated into a western boundary current [Stommel 1958]. After crossing the equator, the North Pacific deep water appears to flow through the Tokelau (Samoan) Passage and travel along

the western side of the Samoan Basin at a depth between 2000 and 3500 m, immediately above the northwards flowing bottom water [Reid and Lonsdale 1974; Reid and Arthur 1975].

The SCORPIO sections across the Pacific at latitudes 28°S and 43°S showed a broad oxygen minimum and a phosphate maximum in the vertical distributions at about 2000 m over most of the South Pacific. Reid [1973b] interpreted these sections as indicative of North Pacific deep water flowing southeast of the Tonga and Kermadec Ridges at depths of 1500 to 2500 m. Away from the deep, western boundary current in the Kermadec Trench, the vertical profile of the oxygen minimum could equally be explained by the one-dimensional vertical and diffusion model of Wyrtki [1972] with local oxygen consumption [Warren 1973, 1976]. The surface circulation, which extends downwards in a weakened form to depths as great as 3000 m [Reid and Arthur 1975], will also affect the transport of oxygen-minimum water. At increasing depths, the subtropical anti-cyclonic gyres retreat towards the poles.

Some oxygen-minimum water appears to continue south along the east coast of New Zealand, until it joins the circumpolar current [Callahan 1972]. A larger volume of low-oxygen water flows as a broad current off South America and joins the circumpolar current to the west of the Drake Passage. Only a small fraction of the oxygen-minimum water is likely to flow through the Tasman Sea because of the presence of several ridges at a depth of less than 2000 m and a relatively narrow channel with a depth of about 3000 m.

The flow of the oxygen-minimum water has been inferred from the water properties because the flow rate is too small to measure by current meters or geostrophic flow analysis, with the possible exception of flow in the Tokelau (Samoan) Passage. Most of the water properties are also consistent with horizontal and vertical eddy-diffusion of properties without the southward flow. The oxygen minimum would then be produced <u>in situ</u> by biological activity. The observed increase in the oxygen concentration of the oxygen minimum towards the south shows that there is significant vertical mixing with the oxygen-rich waters above and below the oxygen minimum even in the presence of a southward flow. The concept of a southward flow of oxygen-minimum water that balances the northward abyssal flow is attractive, but the available data, although suggestive of this, are insufficient to prove its existence.

3.3 Transport and Destination of Pollutants Mixed with Bottom Water

The circulation patterns in the major oceans are interconnected. Bottom water from the Atlantic Ocean flows south, joins the circumpolar current, and then flows north into both the Indian and Pacific Oceans. Any pollutant leached from waste dumps in the Atlantic and which is not sorbed onto the sediments will be transported into the Indian and Pacific Oceans by the movement of the Atlantic bottom water. Pollutants leached from waste dumps in the Indian or Pacific oceans will be transported to the north before joining the sluggish southward flow of oxygen-minimum water.

Superimposed on the mean flows are mesoscale features which cause horizontal eddy-diffusion of the water properties. Away from the abyssal western boundary currents, eddy-diffusion is probably the most important transport process of pollutants dissolved in the deep and bottom waters. The strength of the mesoscale eddy field in the Atlantic has been observed to decrease with the distance from the Gulf Stream [Schmitz 1976] and a similar decrease with distance from the western boundary current is likely to occur in the Pacific and Indian Oceans.

The bottom water slowly upwells to depths of order 2000 m or mixes with overlying water. Estimates of vertical advection based on the northward flow of the deep currents and the area of the ocean give results in the range of 4 to 7 m y^{-1} [Harries 1976]. At these rates, it would take the water about 500 years to upwell from 5000 m to 2000 m. This is a mean upwelling time for the whole ocean but there could be locations where it is even faster. Armi [1978] has suggested that vertical mixing mainly occurs within a 50 m boundary layer at the edge of the ocean basins and around topographic features. The mixed water from the boundary layer is then advected and mixed on constant-density surfaces into the centre of the ocean basins.

The arrival time of water molecules reaching 2000 m will be broadly distributed about the mean upwelling time. The vertical mixing rate is given by the vertical eddy-diffusivity which depends on the local stability and averages to about 10^{-4} m^2 s^{-1} below the thermocline [Okubo 1971]. The eddy-diffusivity is an ocean average including both the boundary layer and the mid-ocean areas. A calculation combining an eddy diffusivity of 10^{-4} m^2 s^{-1} with an upwelling velocity at 6 m y^{-1} shows that 10 per cent of the water would reach 2000 m within 240 years, and 90 per cent within 1050 years, with a median upwelling time of 500 years. Even at 2000 m, the water is still too

dense to reach the surface, but it is close to the density of Antarctic surface waters.

The velocities of deep and bottom currents are uncertain. Measured velocities tend to be less than 0.05 m s^{-1} but, in most locations, the direction of the current varies. Measurements of long-term bottom currents in the North Pacific give vector-averaged currents of 0.01 m s^{-1} [Anderson et al. 1975]. A current of 0.01 m s^{-1} would transport water a distance of 300 km in a year if the direction was constant. Stronger currents are found close to the western boundaries of ocean basins. The horizontal currents are probably sufficient to ensure that water in the mid-basin areas exchanges with water in the mixing boundary layers on a time-scale which is short compared to the upwelling time.

Pollutants dissolved in the bottom water will be subject to sorption on sedimenting particulates passing through the bottom water. Pollutants not sorbed will be mixed and transported towards the surface with the bottom water. Some of the upwelling water will reach the surface near Antarctica, but it will have been carried towards the east by the circumpolar current which extends towards the ocean floor. A small fraction of Antarctic surface water returns as newly formed bottom water, and a larger fraction forms Antarctic intermediate water which flows north at depths of about 800 m. Eventually some of the intermediate water mixes with warmer surface water in equatorial and subequatorial regions. The time-scales for intermediate and surface water circulations and exchange are short compared with the time-scale for the bottom water to reach the surface layers in Antarctic waters.

4. RADIOACTIVE TRACERS

Several radionuclides already present in the ocean provide an estimate of the time-scales for the deep ocean circulation. In general, the vertical distributions of these radionuclides are consistent with advection models that use vertical upwelling of about 5 m y^{-1} and vertical eddy-diffusivities of about 10^{-4} m^2 s^{-1}, or with box models that use deep-water residence times of the order of 1000 years for the Pacific [Pritchard et al. 1971]. Most tracers are transported downwards more rapidly than ocean water because they become associated with sinking particulate matter. Transport from the deep ocean back to the surface layers occurs principally by dissolved materials carried

by the upwelling deep water, although biological transport cannot be ruled out.

Several important radioactive tracers will be discussed below to demonstrate the complexity of oceanic transport and its dependence on chemical, biological and physical processes.

4.1 Naturally Occurring Radionuclides

4.1.1 Carbon-14

Carbon-14 ($t_{\frac{1}{2}}$ = 5730 years) is produced in the atmosphere by the interaction of cosmic-ray neutrons on nitrogen. The usefulness of carbon-14 as a tracer for ocean circulation depends on the relative constancy of its production. The production rate depends on solar activity and varies as much as 16 per cent during a solar cycle; even the average production rate varies by as much as 6 per cent over a time-scale of 200 to 1000 years. Recently, human activities have caused changes to the production rate by the introduction of fossil-fuel carbon, which is almost free of carbon-14, and by atmospheric weapons testing, which has added about 3 per cent to the total carbon-14 inventory [Burton 1975]. These changes have affected the carbon-14 concentration of surface waters, but have not yet affected the deep water.

More than 90 per cent of the World's total exchangeable carbon is in the ocean. About 97 per cent of ocean carbon occurs as inorganic carbon consisting of dissolved carbon dioxide, carbonate ions and bicarbonate ions. Photosynthesis in the surface layers converts some of the inorganic carbon to organic compounds. The organic carbon is divided into two components: dissolved organic carbon (DOC), which is transported by water movement, and particulate organic carbon (POC). Particulate organic carbon is defined somewhat arbitrarily as particles, living or non-living, that are larger than 0.5 to 1.0 μm; usually it consists of about 90 per cent detritus and 10 per cent living phytoplankton. Although the POC comprises only about 0.1 per cent of the carbon in the oceans, it is an important component of the carbon cycle because much of the POC sinks to the deep ocean where it may be reconverted to DOC. Some of the DOC is oxidised to inorganic carbon by the bacteria and larger organisms at all depths in the oceans.

The specific activity of carbon-14 is related to the 'age' of the water, which is the time required for the carbon-14 to decay to the observed level.

The age of a given sample of water depends on its mixing history and the quantities of older and younger water from which it was formed. Even the surface layers are deficient in carbon-14 in comparison with the specific activity of carbon-14 in atmospheric carbon.

Analysis of the carbon-14 data of deep water shows that the age increases from the North Atlantic to the Indian Ocean, with the oldest water in the North Pacific. The North Pacific water below 3000 m is about 1100 years older than the North Atlantic water below 3000 m [Bien et al. 1965; Kuo and Veronis 1970]. The DOC is considerably older than the inorganic carbon, e.g. at 2000 m in the North Pacific, the 'age' of DOC is 3400 years compared with 1480 to 2194 years for inorganic carbon coming from the same area [Williams et al. 1969]. The DOC may follow a different path than the inorganic carbon with a fraction of the DOC being re-cycled. Much of the DOC must be resistant to biochemical oxidation or bacterial utilisation.

In fact, the complex transport cycle of carbon can only be analysed by constructing simplified models and calculating the material balances. Broecker and Li [1970] used a three-box model to evaluate the exchange between a warm surface water mass, a North Atlantic deep-water mass and a Pacific and Indian deep-water mass. The mean residence time for water molecules was 1360 years for the Pacific-Indian and 400 years for the North Atlantic deep water. Some water was exchanged between these two deep-water masses and the mean residence time for water molecules in deep water was 1500 years.

Keeling and Bolin [1968] used a three-reservoir model of the North and South Pacific Ocean to analyse the data for eight different tracers: salinity, oxygen, inorganic phosphorus, organic and inorganic carbon, carbonate alkalinity, insoluble carbonate and radiocarbon. They obtained a residence time for deep water in the Pacific of 1100 years, which was in agreement with the average carbon-14 age relative to that of surface water. Ten per cent of the inorganic carbon in deep water arrived by the gravitational settling of organic carbon.

4.1.2 Radium-226

Thorium-230 ($t_{\frac{1}{2}}$ = 77 000 years) has a residence time in the ocean of less than 200 years because it is efficiently transferred to the sediments. The thorium-230 decays to radium-226 ($t_{\frac{1}{2}}$ = 1600 years) which, since it is not as strongly attached to the sediment, is released from the interstitial waters

into the ocean. The concentration of radium-226 in the deep and bottom Atlantic waters is about double the concentration in the surface water, whereas the concentration in the deep and bottom Pacific waters is about four times the surface concentration [Broecker et al. 1967; Chung and Craig 1973; Burton 1975]. The surface concentration is reasonably uniform over all the oceans.

The difference in radium-226 concentrations in the surface and deep waters is too great to explain using the deep circulation patterns with the residence times derived from carbon-14 data. The difference could be due to particulate transport of radium from the surface to the depths. The greater concentration in the deep Pacific Ocean is caused by the longer residence time of water.

4.1.3 Radon-222

In the water immediately above the deep sea sediment, the concentration of radon-222 ($t_{\frac{1}{2}}$ = 3.8 days) is greater than the amount expected from the *in situ* decay of dissolved radium-226. The excess is maintained by the release of radon-222 from the interstitial waters of the sediment. The vertical distribution of the excess radon provides information about the boundary layer within about 200 m of the bottom [Burton 1975].

One hundred and nineteen radon profiles were measured from the GEOSECS program [Sarmiento et al. 1976]. Only thirteen profiles showed a reasonably exponential decrease from the bottom which could be analysed assuming a simple diffusion process. The resulting vertical eddy-diffusivities were in the range 5 to 440 $cm^2\ s^{-1}$. About 80 of the profiles showed bottom mixed layers and some had intermediate radon maxima indicating complex mixing processes that are probably dependent on the local topography.

4.2 Introduced Radionuclides

4.2.1 Weapons fallout

Studies of radioactive materials added to the ocean from weapons fallout have demonstrated the need to consider the physical and chemical form in which the radionuclides are introduced. Some radionuclides (e.g. ^{60}Co, ^{65}Zn) freshly introduced in fallout have been taken up by marine organisms more readily by orders of magnitude than the corresponding stable elements

already present [Jenkins 1969]. In time, the radionuclides will be found in the same chemical forms as the stable elements, but very little work has been done on the time-scale on which equilibrium will be approached.

Much work has been carried out to measure the concentration of strontium-90 ($t_{½}$ = 30 years) in the ocean. Stable strontium in the ocean shows a conservative behaviour, i.e. the concentration is proportional to the salinity. This makes strontium-90 an ideal tracer for ocean circulation. The results obtained by different workers for depths less than 700 m are in good general agreement. However, there has been disagreement about the concentrations of strontium-90 and caesium-137 in deep waters [Volchok et al. 1971]. However, more recent results [Bowen et al. 1974; Kupferman et al. 1979] indicate that the difficulties were related to the magnitude and variations of the analytical 'blank', and that the amount of strontium-90 and caesium-137 below 1000 m in the North Atlantic is consistent with the expected rate of formation of North Atlantic deep water.

The fate of long-lived radionuclides is removal and deposition to the ocean floor. Fallout plutonium penetrates to deep water at a faster rate than either fallout strontium-90 or caesium-137. Noshkin and Bowman [1972] measured the amounts of plutonium-239, strontium-90 and caesium-137 at various depths in the sediments of the Atlantic Ocean. The sediment data and the water column data were consistent with a model which postulates that 30 per cent of the plutonium sinks at 400 m y^{-1}, 40 per cent sinks at 140 m y^{-1} and 30 per cent sinks at 70 m y^{-1}.

4.2.2 Waste from nuclear installations

The Windscale nuclear fuel reprocessing plant in the United Kingdom has had a policy of discharging low-level radioactive waste into the Irish Sea. The dispersion of the radionuclides has been monitored in a series of surveys.

Caesium-137 from Windscale has been detected leaving the Irish Sea and flowing north of Scotland into the North Sea. The transit time of the caesium can be estimated by comparing the concentration of the shorter-lived caesium-134 to the longer-lived caesium-137. Caesium appears to spend one to two years in the Irish Sea and then move rapidly, in perhaps two months, into the North Sea [Jefferies et al. 1973, Livingston and Bowen 1977]. Around 30 per cent of Windscale radio-caesium output passes through the Clyde sea area, but less than 0.3 per cent remains in the sediments [Baxter et al. 1979]. The

soluble portion of plutonium appears to follow the same route as caesium, but about half of it is lost to sedimentation during the transport to the North Sea [Livingstone and Bowen 1977]. Actinides released from the French reprocessing plant at La Hague have been detected in the southern North Sea [Murray et al. 1979].

5. OCEAN SEDIMENTS

The ultimate destination for nearly all chemical species in the oceans is to be incorporated into the sediment. This section describes the sediments of the Indian and Pacific Oceans and discusses the difficulties of predicting the rates at which radionuclides could be removed to the sediments.

The total suspended sediment carried to the oceans by the World's rivers is estimated to be about 1.8×10^{13} kg y^{-1} [Holeman 1968]. The bulk of the suspended sediment is carried by Asian rivers into the Pacific and Indian Oceans. Most of the suspended matter carried by rivers is deposited in the ocean basins near the river mouth. The cone of unconsolidated sediment from the Ganges extends for about 2000 km and has a thickness exceeding 2 km [Figure 7; after Ewing et al. 1969]. The volume of sediment in the Ganges and Indus cones is about 40 per cent of the total sediments of the Indian Ocean.

Away from the continental shelves, the remains of planktonic organisms are a major component of the sediment. About 54 per cent of the floor of the Indian Ocean is covered by calcareous sediment [Figure 8; after Venkatarathnam and Hayes 1974]. The deposition rate of the calcareous sediment is about 1 cm per 1000 years. Calcareous sediments occupy the more shallow areas which are not dominated by terrigenous or siliceous skeletal remains. The solubility of calcium carbonate increases at higher pressures and lower temperatures and, below a depth of about 4500 m, the rate of solution of calcium carbonate exceeds the rate of deposition. Hence, calcareous sediments are not found on the bottom of the deeper ocean basins.

In the colder Antarctic water, diatoms occur in great numbers and this results in a belt of siliceous ooze between latitudes 45°S and 60°S. Another belt of siliceous ooze is formed in tropical water by the remains of radiolaria. The siliceous deposits are less soluble than calcium carbonate and hence can occur at the bottom of deep ocean basins.

In the deepest basins, away from any source of terrigenous sediment and beneath unproductive surface water, a fine grained sediment is found which is called red or brown clay. These clays are basically the inorganic residue after all soluble materials have been removed, and contain shark's teeth, meteorite dust and manganese nodules. The build-up of the clay is very slow - only 1 or 2 mm per 1000 years with a greater build-up in the depressions than on the hills. This ultimately produces the abyssal plains on the oldest parts of the ocean floor.

The Pacific Ocean differs from the Indian Ocean in having a much greater area of red clay and a comparative lack of terrigenous sediment [Figure 9; after Horn et al. 1974]. A barrier of secondary basins, island arcs and trenches around the Pacific prevents most of the suspended sediment from the major rivers reaching the main ocean basins. Only the Columbia River discharges directly into a deep basin.

The sorption capacity of the sediments is expressed by the distribution coefficient which is defined as the ratio of the amount of bound element or chemical species in a unit volume of dry sediment to the amount of the element or chemical species in a unit volume of sea-water in contact with the sediment. An equilibrium is established between the concentration sorbed and the concentration dissolved in the water. The distribution coefficients vary between elements, but are fairly insensitive to the sediment type. For radionuclides, the distribution coefficient for low concentrations varies from about 100 for strontium-90 to 10^5 for cerium-144 [Duursma and Gross 1971]. At high concentrations the distribution coefficient will be less.

The upper 2 to 20 mm of the sediment is well oxygenated, but below this oxygen depletion occurs leading to reducing conditions. The distribution coefficient for some elements (e.g. Ru, Fe, Pm, Mn, Nb, Ce) is lower under reducing conditions. These elements will tend to dissolve in the reducing zone and move into the overlying oxygenated zone [Duursma and Gross 1971]. Other elements (e.g. Sr, Zn, Co) have a higher distribution coefficient in reducing sediment and these will be transported towards the deeper layers.

The distribution coefficient indicates the sorptive capacity under ideal conditions. The sorption process is reversible and, if conditions change, the sorbed material can be released back into the water column. The fine top layer of the sediment can also be resuspended even by moderate bottom currents [Baker and Feely 1978]. Sorption into deeper sediment, either by diffusion or

by the overlaying of further sediment probably gives a permanent removal of the sorbed material.

An estimate of the removal rate to the sediments can be obtained from the data on the residence time of the elements. The residence time is defined as

$$T = A/(dA/dT) \quad (1)$$

where A is the total amount of the element dissolved in the ocean and dA/dT is the amount introduced or removed per unit time. It is usually calculated from measurements of the concentrations in rivers discharging into the ocean. The residence times for different elements lie in the range of 100 years to 10^8 years (Table 3), but the errors can be large because of uncertainties in the input and removal rates. Elements which are removed mainly by evaporation or wind driven spray have residence times of order 10^8 years. For aluminium (100 years), iron (200 years), thorium (200 years), lead (400 years), and lanthanum (600 years), the residence time is much shorter than the circulation time for the deep ocean water. The short residence time of aluminium and iron is mainly due to the particulate cycles and the residence time of the dissolved fractions would be considerably greater [Yokoyama et al. 1978]. The radionuclides from waste disposal sites would be released at the ocean floor and are likely to have a faster removal rate than predicted by the residence times. For most radionuclides the residence times are longer than the radionuclide half-lives, and for these removal to the sediments can be ignored without greatly affecting the derived limits for dumping radioactive waste.

6. OCEANOGRAPHIC MODELS DEFINING DUMPING LIMITS

The London Convention (see Section 2.1) approved of the dumping of low-level radioactive waste into the ocean under certain conditions and limitations. Several simplified models of the oceans have been proposed for defining the dumping limits.

6.1 Uniform Mixing Model

The simplest model of dispersion in the oceans assumes that uniform mixing occurs throughout the ocean or, perhaps, within individual basins [Shepherd 1976]. The model is reasonable for time-scales greater than several thousand years. If the dumping continues at a constant rate, the

TABLE 3
RESIDENCE TIMES OF ELEMENTS IN THE OCEAN
[After Brewer 1975]

Element	Mean Conc. (mg m^{-3})	Residence Time (y)	Element	Mean Conc. (mg m^{-3})	Residence Time (y)
Li	180	2.3×10^6	Zn	4.9	2×10^4
B	4440	1.3×10^7	Ga	0.03	1×10^4
F	1300	5.2×10^5	As	3.7	5×10^4
Na	1.08×10^7	6.8×10^7	Se	0.2	2×10^4
Mg	1.29×10^6	1.2×10^7	Br	6.7×10^4	1×10^8
Al	2	100	Rb	120	4×10^6
Si	2×10^6	1.8×10^4	Sr	8×10^4	4×10^6
P	60	1.8×10^5	Mo	10	2×10^5
Cl	1.88×10^7	1×10^8	Ag	0.04	4×10^4
K	3.8×10^5	7×10^6	Sb	0.24	7000
Ca	4.12×10^5	1×10^6	I	60	4×10^5
Sc	0.0006	4×10^4	Cs	0.4	6×10^5
Ti	1	1.3×10^4	Ba	2	4×10^4
V	2.5	8×10^4	La	0.003	600
Cr	0.3	6000	W	0.1	1.2×10^5
Mn	0.2	1×10^4	Au	0.004	2×10^5
Fe	2	200	Hg	0.03	8×10^4
Co	0.05	3×10^4	Pb	0.03	400
Ni	1.7	9×10^4	Th	0.01	200
Cu	0.5	2×10^4	U	3.2	3×10^6

concentration builds up until the rate of addition equals the rate of removal by radioactive decay and sedimentation.

Consider a radionuclide with a radioactive decay rate, λ_d, which is dumped into a well mixed ocean of volume V. The rate of removal, R, is

$$R = (\lambda_d+\lambda_s)V\ S_\infty \qquad (2)$$

where λ_s is the removal rate due to sedimentation and S_∞ is the equilibrium concentration per unit volume. When equilibrium is reached, the removal rate is equal to the dumping rate, hence

$$S_\infty = \frac{D}{(\lambda_d+\lambda_s)V} \qquad (3)$$

The concentration in surface waters will always be less than this estimate of S_∞ if the pollutant is being released at the ocean floor. For radionuclides with half-lives less than 100 years, much of the activity will decay during the time taken for material to reach the surface, and the surface concentration will be very much less than S_∞.

6.2 Diffusion Models

At times less than a few thousand years, or for radionuclides with half-lives less than a few hundred years, it is necessary to estimate the distribution of radionuclides as they build up in the ocean. The simplest method is to assume a simple Fickian diffusion process with constant eddy-diffusivities.

Many of the diffusion models used to assess radioactive waste dumping have ignored vertical advection and attempted to correct for the omission by using large values of vertical eddy-diffusivity. The spread of material in these models is proportional to the square root of elapsed time and differs from advection where the transport is directly proportional to time. Over a long enough time, even a very slow advection will overwhelm diffusion. Hence the simple diffusion models are only applicable over time-scales short enough for the vertical advection to be less than the diffusive transport predicted from the assumed eddy-diffusivity.

Radionuclides released at the seabed will disperse both horizontally and vertically; the greater the horizontal spread, the lower is the concentration of the radionuclides transported to the surface. Hence a low value of horizontal eddy-diffusivity is usually assumed to ensure that the estimated surface concentration is conservative, i.e. it will be greater than the actual surface concentration. Deep horizontal advection can be ignored because it leads to a change in the location of the maximum surface concentration without necessarily changing the magnitude of the maximum, provided that the material does not move to a region of rapid upwelling.

In 1965, a diffusion model was used by the OECD group of experts to assess the hazards of the OECD/NEA dumping operation [OECD/NEA 1968]. Although the diffusion model was introduced and eddy-diffusivities were defined, the estimated surface concentrations were not derived from the diffusion calculations. Instead, it was assumed that the delay for radionuclides to reach the surface would be 20 years after the containers reached the seabed. The surface concentration was determined by assuming that activity would be mixed in a surface layer, 1000 km^2 by 300 m deep, which would be replaced by uncontaminated water every year. The use of an infinite reservoir of uncontaminated water is satisfactory for short-lived radionuclides but clearly inadequate for long-lived radionuclides.

Webb and Morley [1973] re-assessed the OECD/NEA operation using a three-layer model of the ocean, with eddy-diffusion in the deep ocean and reduced diffusion through a thermocline layer. Their model provided a somewhat more realistic buildup of the radionuclides in the surface layers. They still, however, used an infinite source of uncontaminated surface water on a time-scale of one year. Webb and Morley [1973] used the derived surface concentrations to estimate the exposures to people eating marine foods. The Webb and Morley model was used for the provisional IAEA recommendations issued in 1974 [Section 2.1]. These recommendations have now been superseded. The model has been criticised [e.g. Miyake and Saruhashi 1976] because of the neglect of potentially important processes, uncertainties about the generality of the model, and the use of an ocean which is infinite horizontally.

Webb and Grimwood [1976] revised the Webb and Morley model by adding a long-term model to determine the effect of the finite size of the ocean on the concentration of long-lived radionuclides. The long-term model was a six-box model of the world oceans with material being transferred between adjacent boxes and lost by radioactive decay and by incorporation into the sediments.

Removal by sediments was determined from the experimental distribution coefficient (Section 5), using a sedimentation rate of 1 mm per 100 years. The new long-term model was considered to be valid at times greater than 1000 years, but the short-term model was limited to the first 100 years. In a second report, Grimwood and Webb [1976] used the model to assess the impact of dumping all the waste generated by the world nuclear power program to the year 2000. In spite of many uncertainties, they attempted to follow the transport of radionuclides from the waste containers to the impact on man.

Sugiura et al. [1976] developed a simple diffusion model for the North Pacific. They used eddy-diffusivities of 0.01 $m^2 s^{-1}$ in the vertical direction and 10^4 $m^2 s^{-1}$ in the horizontal to determine the maximum surface concentrations produced by the continuous release of radionuclides at the ocean bottom. Several safety factors were introduced to relate the limiting concentrations to the ICRP maximum permissible daily intakes and very low disposal limits were derived, e.g. 10 Ci t^{-1} (3.7×10^8 Bq kg^{-1}) for β/γ-emitters, 1 Ci t^{-1} (3.7×10^7 Bq kg^{-1}) for strontium-90 and caesium-137 and 10^4 Ci t^{-1} (3.7×10^{11} Bq kg^{-1}) for tritium. These limits are two or three orders of magnitude less than the IAEA recommendations (Section 2.1).

Aoyama et al. [1977] evaluated the proposed Japanese ocean dumping program for low activity wastes on the basis of a two-layer model of the ocean. They considered two radionuclides: caesium-137 and cobalt-60. Caesium-137 was chosen as being representative of the radionuclides that would be in ionic form in cement and which would diffuse through the interstitial water. Cobalt-60 is representative of radionuclides firmly adsorbed by the cement hydrates and only released as the cement surface dissolves. Experimentally determined equations were used to describe the leach rates from the concrete. The diffusion equation was solved for a horizontal eddy-diffusivity of 0.1 $m^2 s^{-1}$ and vertical eddy-diffusivities of 2, 20, 100 and 200 $cm^2 s^{-1}$.

6.3 Advection Models

Advection of dissolved or suspended material by ocean currents was ignored in all the diffusion models of the previous section. The complex World ocean numerical models, which are being developed to study the fundamentals of ocean circulation, are not suitable for estimating the advections of pollution because they contain too many unknown variables.

Shepherd [1976] proposed a simple model which included horizontal advection and non-Fickian diffusion. He modelled the ocean as a rectangular channel, the length of which matched the main current path in the ocean basin. The depth of the channel was equal to the average depth of the ocean and the width was chosen to give the correct volume. The fluid had a uniform horizontal velocity equal to typically observed surface currents and fluid reaching one end of the channel was recirculated to the other end. The recycle time was only 50 years which is much shorter than the circulation time of the deep ocean. A source of contamination was located on the bottom of the channel and the released material was carried horizontally by the bulk fluid movement and dispersed horizontally and vertically by diffusion. The eddy-diffusivities were taken to be 1 or 10 $cm^2\ s^{-1}$ in the vertical direction. The release of contamination was assumed to be continuous and the final steady-state concentrations were calculated.

The short recycle time makes the horizontal variations in concentrations small; this means that the results are substantially the same whether the Fickian diffusion equation or the more realistic Okubo-Pritchard diffusion equation is used. The calculated surface concentrations are substantially less than the well-mixed average for short-lived radionuclides. For radionuclides with half-lives greater than a few thousand years, the calculated concentrations are very close to those calculated by the uniform mixing model (Section 6.1). Even the bottom concentrations of radionuclides with half-lives greater than 30 years do not exceed the uniform mixing average concentration by more than a factor of 10. The results from Shepherd's advection model showed that the uniform mixing model was reasonably though not excessively conservative under most conditions and an explicit safety factor of 10 could be used to allow for the local higher concentrations on the ocean floor.

6.4 IAEA Oceanographic Model

The problem of developing an oceanographic model suitable for defining the limits and restrictions for ocean dumping of radioactive waste was considered at a series of IAEA advisory group and consultant meetings [IAEA 1978a,b]. No single comprehensive model was proposed for predicting the movement of radionuclides. Instead, simple worst case models were used to cover specific transport paths. The criteria for dumping limits was to be a dumping rate which would not lead to an unacceptable exposure to humans even if dumping continued for up to 25 000 years.

For each ocean or ocean basin, it was suggested that an average long-term bottom concentration be determined and used as input to all the food chains, even those which originate in the surface waters [IAEA 1978a]. The average bottom concentration was to be obtained from Shepherd's rectangular channel advection model (Section 6.3) or, equivalently, from a one-dimensional diffusion model. These models assume that the ocean is well mixed horizontally and calculate the balance between the dumping rate, diffusion towards the surface and removal by radioactive decay. Removal of radionuclides by sedimentation was considered to be too poorly understood to be included in the model. A low vertical eddy-diffusivity of 1 $cm^2\ s^{-1}$ was recommended for the models so that the calculated average bottom concentrations will be conservative, i.e. an upper limit.

For radionuclides with half-lives of about 30 years, the average bottom concentration is about 10 times the concentration determined by the uniform mixing model (Section 6.1). The bottom concentration for radionuclides with longer half-lives is closer to the uniform mixing model results. For short-lived radionuclides, it was reasonable to include some decay during the transit time from the dumping site to the point of exposure. The IAEA consultants [IAEA 1978b] who investigated the radiological aspects of defining the dumping limits used a transit time of three years, which is two orders of magnitude less than the upwelling time discussed earlier in this report (e.g. Section 3.3).

Individual dumping sites might be subject to short-term events which could lead to higher contributions to the food chains. The advisory group considered two processes - the plume of contaminated water flowing downstream from the dumping site, and deep convective mixing which sometimes occurs when very cold winds sweep across the ocean. The plume could cause contamination of commercial fish whose food chain originates near the ocean floor. The advisory group considered a fishing ground 1500 km downstream from the dumping site. At this distance, the plume could have spread to a width of 150 km and be about 600 m high. With a current velocity of 1 cm s^{-1}, the specific activity would be 10^{-6} Ci m^{-3} (3.7×10^4 Bq m^{-3}) for a release rate of 1 Ci s^{-1} (3.7×10^{10} Bq s^{-1}). Higher concentrations would exist nearer the site, but the plume would be narrower and the smaller area affected would only form part of the food chain of fish for potential commercial exploitation.

Deep convective mixing events have been observed in the Northwest Mediterranean Sea and the Labrador Sea in winter. These are transient events

and lead to mixing down to more than 2 km depth for a duration of one or two months and potentially could cause a rapid transport of deep water to the surface. The advisory group included the effect of dumping into an isolated basin which has poor ventilation and is subject to deep mixing events. The specific concentration for a nominal basin proved to be 10^{-6} Ci m^{-3} (3.7×10^{4} Bq m^{-3}) for 1 Ci s^{-1} (3.7×10^{10} Bq m^{-3}), which is the same as the result for the plume model.

Deep mixing can only occur if the surface water is sufficiently saline for offshore winds to reduce the temperature enough to increase the density to that of deep water. Provided that waste sites are selected in tropical or subtropical locations, this should not occur. There is no way for the water temperature to be greatly reduced in the tropical conditions of the North Indian Ocean. Some mixing, perhaps down to 2000 m, does occur in the Arabian Sea due to double diffusion of the warm, very saline water from the Red Sea into the underlying cold, less saline water. The salinity of the North Pacific water is too low for mixing to occur to great depths even if the water is close to freezing.

To cover all short-term effects that might occur, the advisory group suggested that a minimum specific concentration of 10^{-6} Ci m^{-3} (3.7×10^{4} Bq m^{-3}) for 1 Ci s^{-1} (3.7×10^{10} Bq s^{-1}) be used.

The consultants [IAEA 1978b] considered the radiological implications of the oceanographic model. They investigated the various pathways that could lead to the radiation exposure of humans, related the exposure of critical groups to the dose limits recommended by the International Commission on Radiological Protection (ICRP), and recommended the upper limits for the radioactivity of dumped wastes in Table 4. In most cases, the exposure to marine organisms is less than the limits recommended for humans. This will not be true close to the dumping site, and it is possible that some benthic organisms at the dumping site will be killed. The area involved will be a very small fraction of the total ocean floor and the effect can probably be compared with the removal of the local fauna when buildings are constructed on land. Nevertheless, the buildup of radioactivity in the sediment and in benthic organisms at the dumping site will need to be monitored.

The IAEA [1978c] dumping limits (Section 2.1) are based on the recommendations of Table 4. For administrative convenience, and to avoid the difficulty of carrying out a detailed analysis of the waste, it was decided to

group all β/γ-emitters with half-lives greater than 0.5 years. This was considered justified because only small amounts of the long-lived β/γ-emitters were expected in the waste and calculations used to derive the limits were very conservative.

The recommended dumping rate for α-emitters is 10^5 Ci y^{-1} (3.7×10^{15} Bq y^{-1}), but this is reduced to 10^4 Ci y^{-1} (3.7×10^{14} Bq y^{-1}) for radium-226 and supported polonium-210; these rates are comparable with the natural input of α-activity into the ocean. The natural release of dissolved radium-226 into World oceans is about 50 kCi y^{-1} (1.8×10^{15} Bq y^{-1}) which scales to 4000 Ci y^{-1} (1.5×10^{14} Bq y^{-1}) into a 10^{17} m^3 ocean. The dissolved uranium currently added to the oceans by the World's rivers is about 2×10^7 kg y^{-1} [Sackett et al. 1972] which is equivalent to 7000 Ci y^{-1} (2.6×10^{14} Bq y^{-1}) each of uranium-238 and uranium-234, and 300 Ci y^{-1} (1.1×10^{13} Bq y^{-1}) of uranium-235. The radioactive decay of the 4×10^{11} Ci (1.5×10^{22} Bq) of potassium-40 present in the World's oceans [Burton 1975] corresponds to the removal rate of 300 Ci y^{-1} (1.1×10^{13} Bq y^{-1}). The removal rate of potassium-40 calculated from its ocean residence time of 7×10^6 years (Section 6.1) is 6×10^4 Ci y^{-1} (2.2×10^{15} Bq y^{-1}).

Shorter-lived radionuclides in the waste can undergo considerable radioactive decay before reaching the surface waters. This decay factor was not directly included in the model because of the slight chance that faster vertical transport processes might exist. Most radionuclides will take at least five hundred years to reach the surface waters, and for many radionuclides there will be enhanced downward transport by association with sedimenting particles.

The IAEA model is applicable to any ocean basin, but it is based on the concept of isolated basins. The ocean circulation discussed in Section 3 shows that there are very few isolated basins and that the ocean circulation patterns connect the different oceans. This does not affect the derived dumping limits, but it needs to be considered when the ultimate destination of derived radionuclides is predicted.

Most ocean dumping so far, and in the foreseeable future, has been carried out in the North Atlantic. The circulation pattern of bottom water (Section 3) suggests that North Atlantic bottom water will flow south of Africa into the Indian and Pacific Oceans. Hence, if radionuclides dumped in the North Atlantic do reach the surface, it is more likely to be in the Indian

TABLE 4
DUMPING RATE LIMITS FOR OCEAN DISPOSAL RECOMMENDED BY IAEA CONSULTANTS [IAEA 1978b]

Radionuclides	Single Site Ci y^{-1}	Finite Ocean Volume (10^{17} m^3) Ci y^{-1}
Group A:		
^{226}Ra and very long-lived β/γ emitters, e.g. ^{129}I, ^{126}Sn and ^{99m}Tc	10^4	10^4
Group B: α-emitters plus ^{14}C, ^{210}Po.	10^5	10^5
Group C: ^{90}Sr, ^{137}Cs and most β/γ emitters	10^7	10^8
Group D: Tritium and short-lived β/γ emitters	10^{11}	10^{12}

1 Ci y^{-1} = 3.7×10^{10} Bq y^{-1} .

or Pacific Oceans. The time-scale for flow will be at least hundreds of years and the activity will be mixed with a greater volume of water. Hence the local surface concentration of radionuclides will be much less than the limiting values used in the IAEA model, which were based on a 10^{17} m^3 ocean and a three-year transit time. The ocean circulation is a closed pattern, and the fact that Atlantic water might flow into the Pacific does not change the dumping limits in the Atlantic. This is because the definition of the limits includes the possibility that dumping sites might be established in all the oceans and bottom water from potential sites in the Indian and Pacific Oceans will eventually flow into the Atlantic Ocean. By the time any bottom water reaches the surface, it will be transported well away from its origin and be mixed with a vast volume of other water. With the present state of knowledge of deep water circulation, it is only possible to suggest mean circulation paths; one has to come back to the uniform mxing model to determine the long-term average.

7. CONCLUSIONS

Although the circulation in the Pacific and Indian Oceans could be discussed in general terms, the knowledge of the circulation is inadequate to give firm predictions of the dispersion, destination or transit times for pollutants released at the ocean floor. For the foreseeable future, it seems likely that dumping limits will have to be defined on the basis of simple models like those used by the IAEA. The World oceans form a single interconnected system of water masses with flow from one ocean to another. Dissolved material released at the bottom of one ocean will spread to the surface at a location remote from the dumping site, very likely in another ocean.

The study of the Pacific and Indian Oceans has not revealed any reasons to invalidate the IAEA oceanographic model. If anything, the study suggests that the model is very conservative. The very long upwelling time for bottom water in the real ocean means that radionuclides with half-lives less than fifty years will have decayed by several orders of magnitude before they spread to the surface. There is no evidence in either the Indian or Pacific Oceans for deep mixing events which might shorten the upwelling time. To be quite certain that a dumping site is not subject to deep mixing events, sites should be selected in tropical or subtropical waters, e.g. latitudes less than 45°. This study has not investigated the possibility of biological transport

producing an enhanced upward transport of some radionuclides.

Sedimentation was not included in the IAEA model. For some long-lived radionuclides this could be the dominant removal process. Further study and experimental data on the incorporation of materials in the sediments might allow the dumping limits on some very long-lived α-emitters to be eased. In the meantime, the current dumping limits ensure that there will be no undue buildup of activity.

The ocean receives many chemicals from human activities [Goldberg 1976] including radioactive materials. Up to the instant when the nucleus decays, each radionuclide acts as an ordinary atom and takes part in the normal chemical reactions of the element. Hence the studies of the transport and dispersal of radionuclides in the ocean is directly applicable to the transport and disposal of many other forms of pollution.

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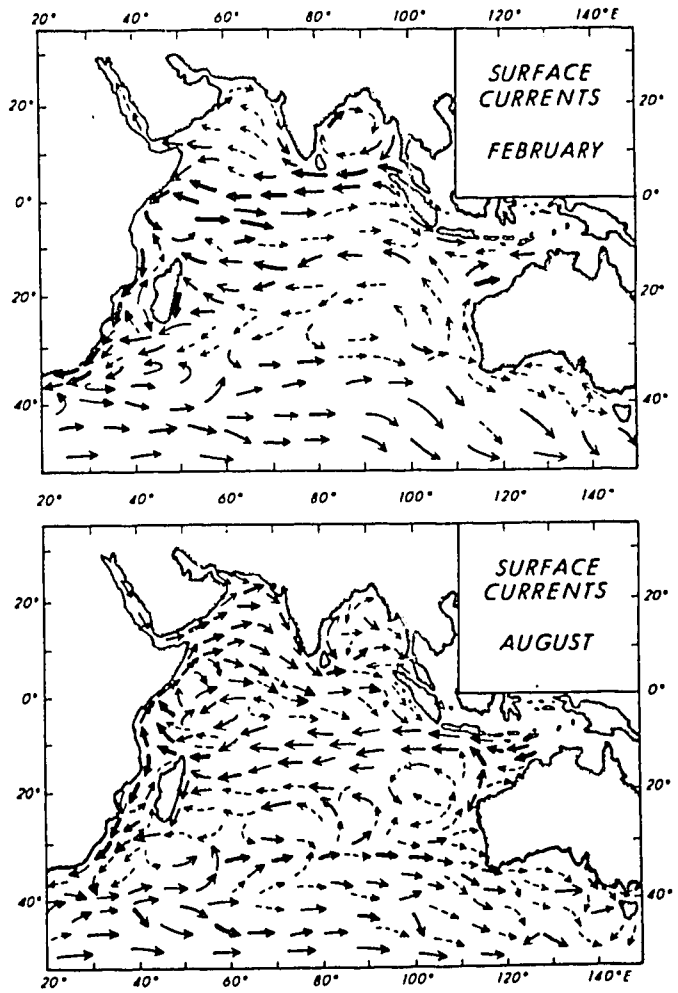


Figure 1. Surface currents of the Indian Ocean (source: Wyrtki 1973)

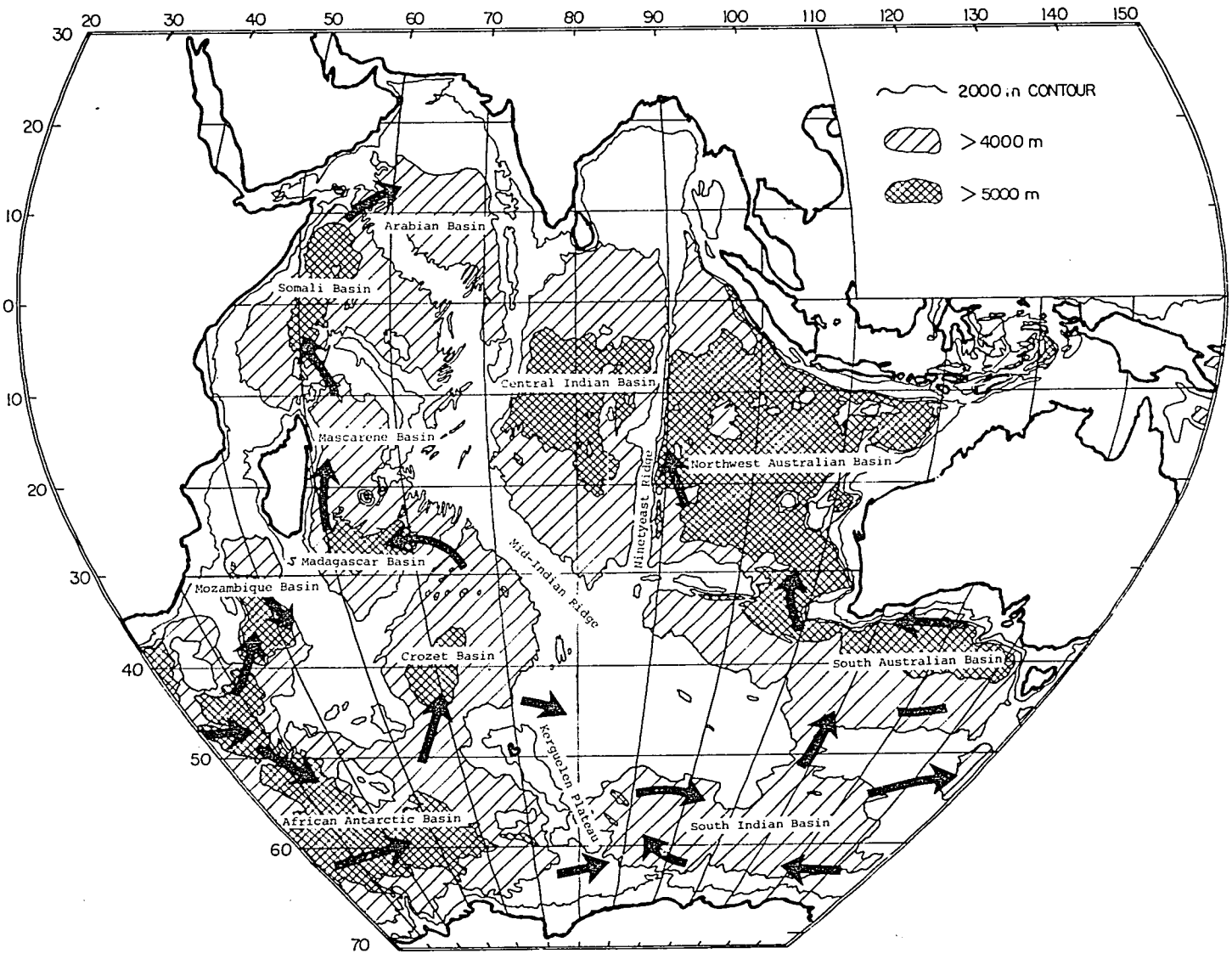


Figure 2. Bathymetry of the Indian Ocean (source: Wyrtki 1971) showing the flow of bottom water

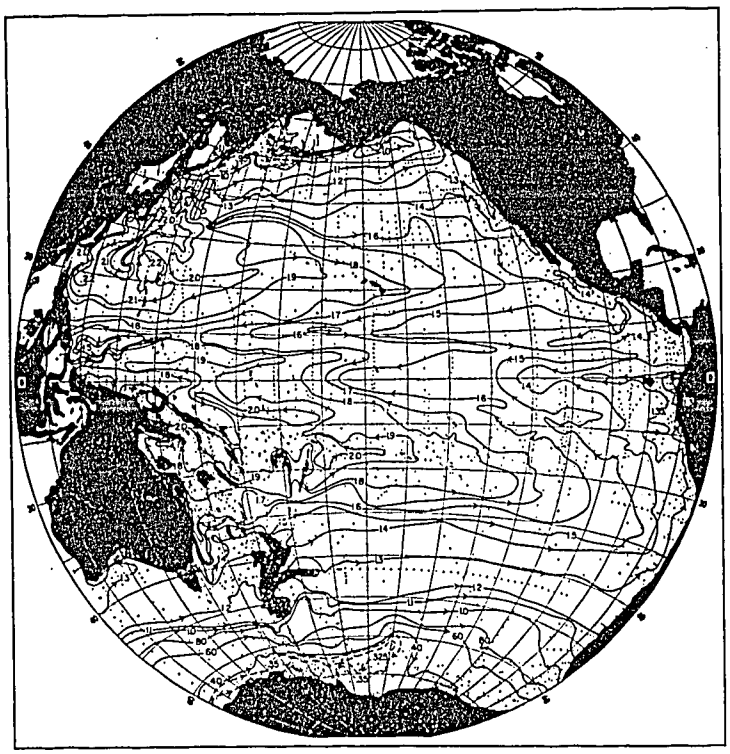


Figure 3. The surface topography (in dynamic metres) in winter of the Pacific with reference to 1000 m depth (source: Reid and Arthur 1975). The mean surface currents tend to flow along lines of constant geopotential anomaly as shown by the arrows, except very close to the equator

Figure 4. Bathymetry of the Pacific Ocean (source: Mantyla 1975). Areas less than 3 km are shaded and the 4 km and 5 km isobaths are shown

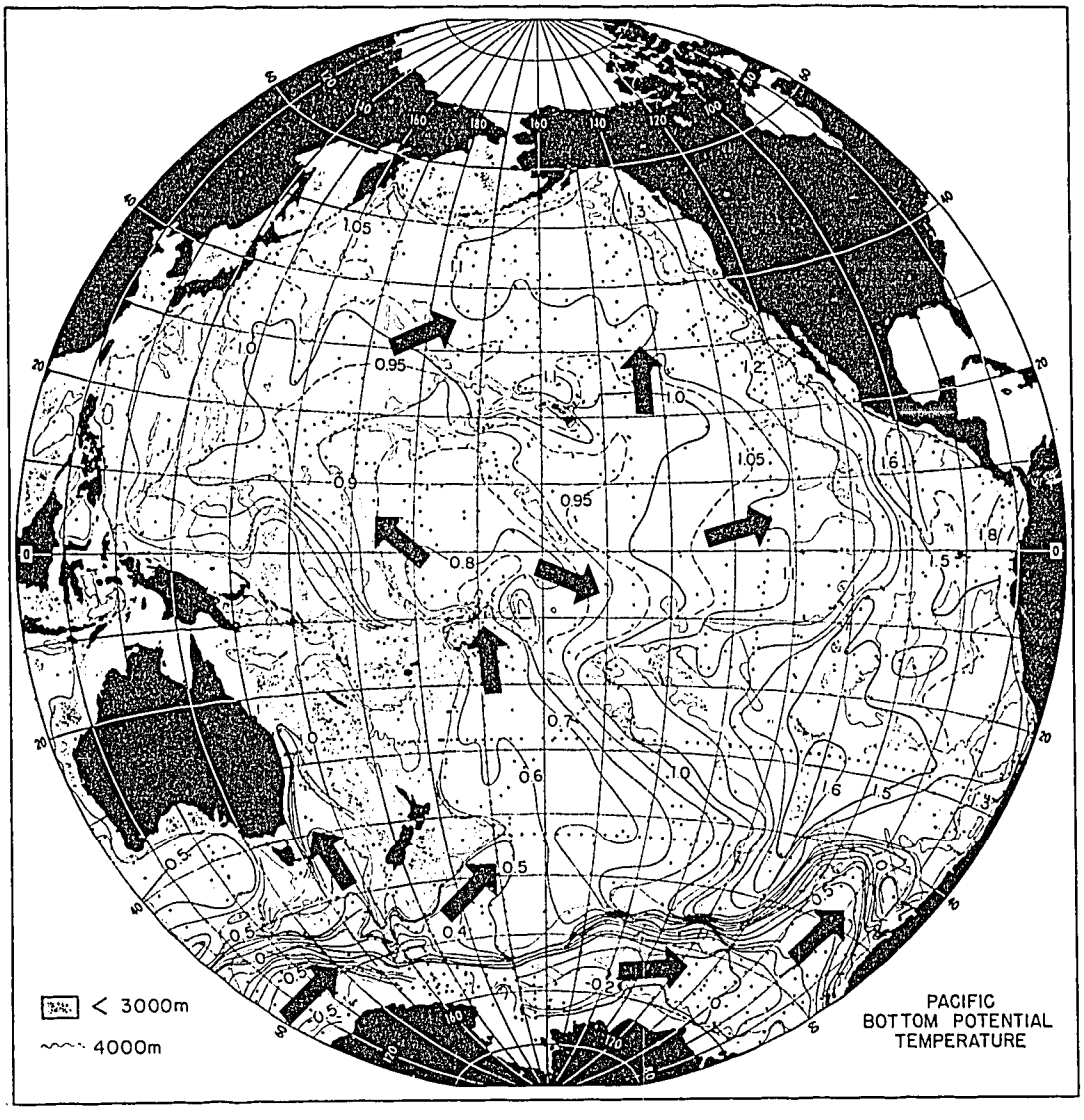


Figure 5. Distribution of near bottom potential temperatures in the Pacific (source: Mantyla 1975) showing the flow of bottom water

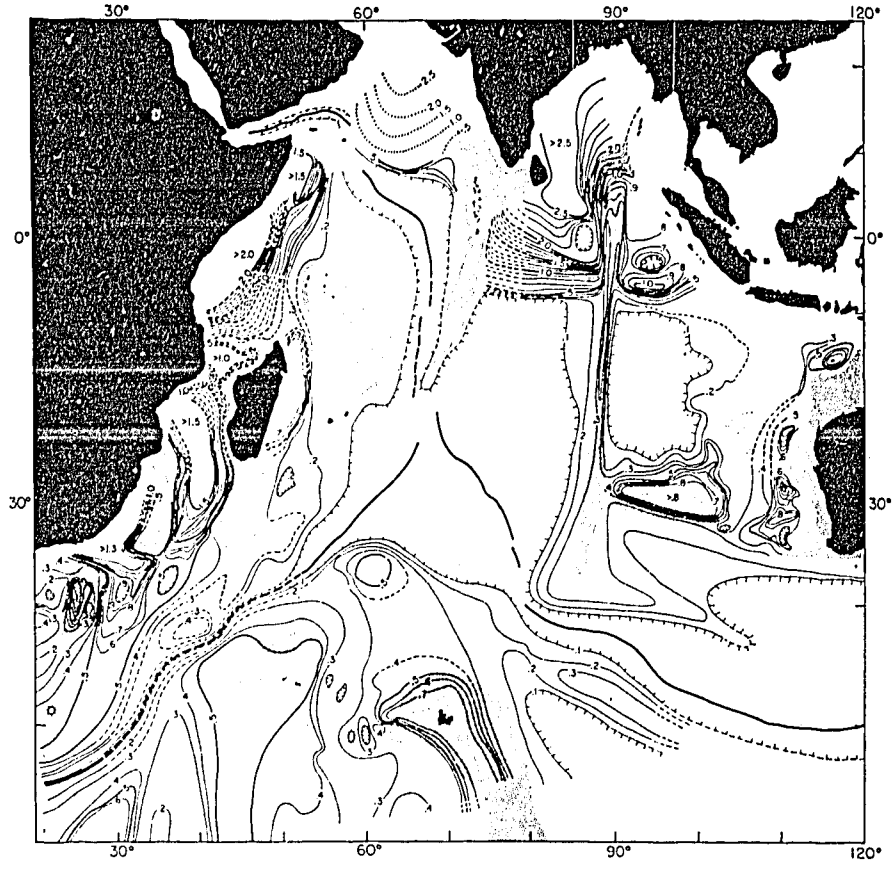


Figure 6. Thickness of unconsolidated sediment in the Indian Ocean. Contours are in reflection time, but approximately correspond to kilometres (source: Ewing et al 1969)

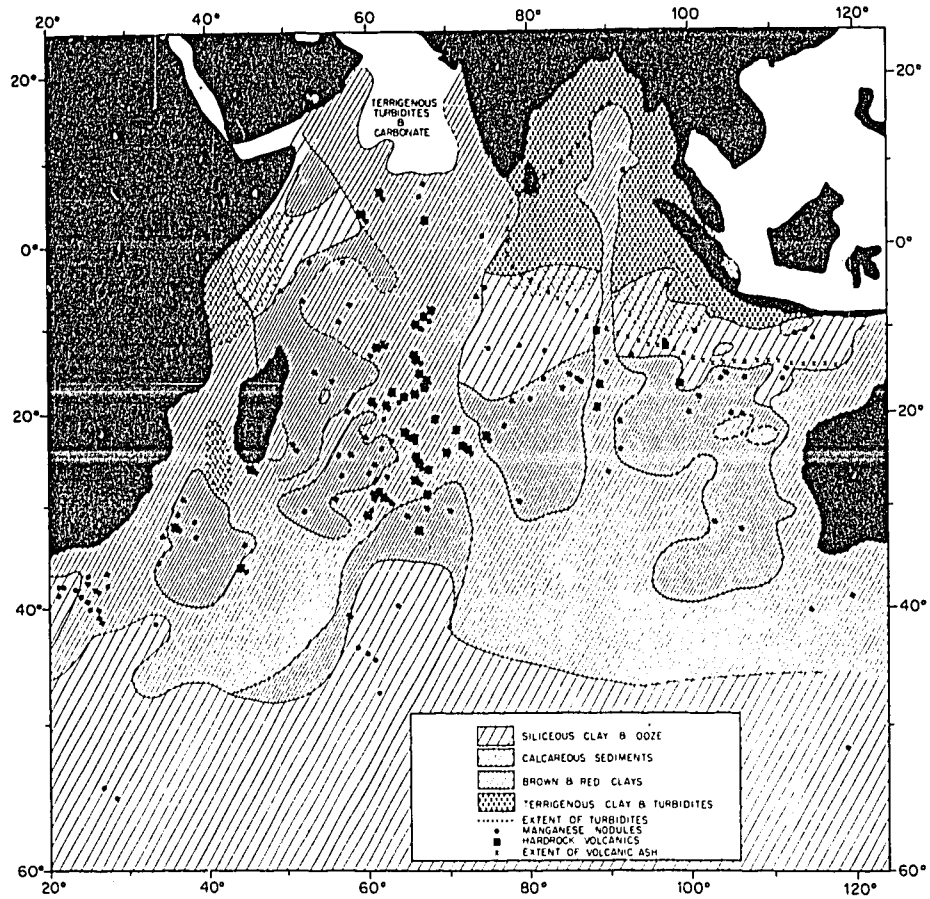
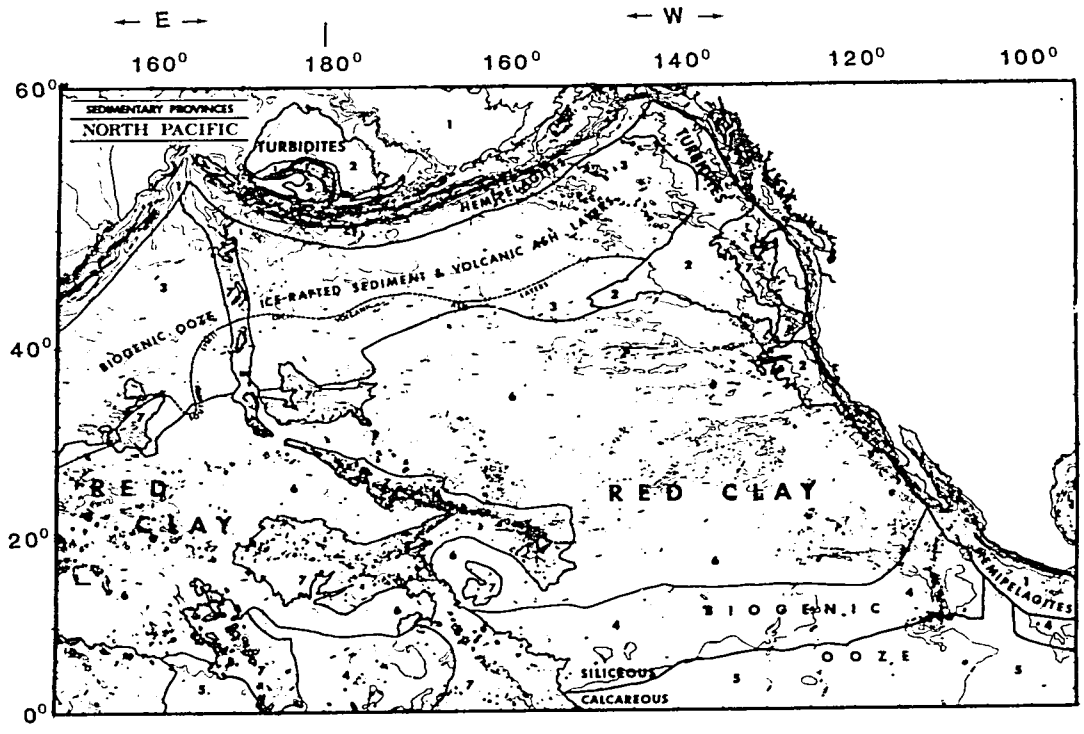


Figure 7. Sediment distribution in the Indian Ocean (source: Venkatarathnam and Hayes 1974)



LEGEND

1. TERRIGENOUS HEMIPELAGITES
2. TERRIGENOUS TURBIDITES
3. PELAGIC OOZE - BIOGENIC SILICEOUS - DIATOMS
4. PELAGIC OOZE - BIOGENIC SILICEOUS - RADIOLARIA
5. PELAGIC OOZE - BIOGENIC CALCAREOUS
6. RED CLAY
7. CARBONATE OOZE RELATED TO TOPOGRAPHIC HIGHS

Figure 8. Sediment distribution in the North Pacific (source: Horn et al 1974)

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