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Bomb-test ^{90}Sr in Pacific and Indian Ocean surface water as recorded by banded corals

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We report here measurements of bomb-test ^{90}Sr activity in the $CaCO_3$ skeletons of banded head forming corals collected from nine locations in the tropical Pacific and Indian Oceans. Density variations in skeletal carbonate demarcate annual growth bands and allow one to section individual years. Measurements of ^{90}Sr activity in the annual bands reconstruct the activity of the water in which the coral grew. Our oldest records date to the early years of the nuclear era and record not only fallout deposition from the major U.S. and Soviet tests of 1958–1962, but also the huge, and largely unappreciated, localized inputs from the U.S. tests at Eniwetok and Bikini atolls during 1952–1958. In the 1960's the ^{90}Sr activity in Indian Ocean surface water was twice as high as activity levels in the South Pacific at comparable latitudes. We suggest that substantial amounts of northern hemisphere fallout moved west and south into the Indian Ocean via passages through the Indonesian archipelago. Equatorial Pacific ^{90}Sr levels have remained relatively constant from the mid 1960's through the end of the 1970's in spite of ^{90}Sr decay, reflecting a large-scale transfer of water between the temperate and tropical North Pacific. Activity levels at Fanning Is. (4°N, 160°W) appear to vary in conjunction with the 3–4 year El Niño cycle.

1. Introduction

Knutson et al. [1] demonstrated that apparent changes in density observed in X-radiographs of cross sectioned coral heads were related to seasonal changes in growing environment. Moore and Krishnaswami [2], Nozaki et al. [3], Druffel and Linnick [4], and Druffel [5,6] have subsequently used the X-ray technique to section coral heads from many locations for the purpose of measuring the ^{14}C activity of individual growth years. These measurements have been used to document changes in the ^{14}C activity of ocean surface water caused by both nuclear bomb tests [2–5] and the burning of ^{14}C-free fossil fuels [4,5], and to track climatological effects over the last several hundred years [3,6].

We report here measurements of bomb-test ^{90}Sr in banded coral skeletons from nine locations in the tropical Pacific and Indian Oceans. ^{90}Sr is a relatively long-lived fission product (half life = 28 years) of the atmospheric bomb tests conducted during the 1950's and early 1960's. It has no natural sources. Following a large nuclear test radioactive debris is injected into the stratosphere where it is dispersed around the globe. It mixes down to the troposphere over a one- or two-year period where it is rapidly scavenged by hydrological and chemical processes in the lower atmosphere [7]. ^{90}Sr falling on land is generally retained within soils, while that falling on the ocean follows the ocean currents as a passive tracer of the ocean's circulation. The distribution of bomb-produced tritium in the ocean has been widely used to study circulation and mixing processes in the ocean [8–11]. Much less use has been made of ^{90}Sr for a number of reasons; the large volume of water required (50–100 liters), the difficulty in separating Sr from seawater, and a low signal to noise ratio regarding background and blank radioactivities.

As an ocean tracer, ^{90}Sr has a singular virtue: the ^{90}Sr to Ca ratio incorporated into coral skeletons is the same as the ^{90}Sr to Ca ratio in seawater. Corals average out seasonal variations in the ^{90}Sr content of surface water and spare one the trouble of separating Sr from seawater. By measuring the ^{90}Sr activity of individual coral growth bands, one

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can determine a time history of the ^{90}Sr activity of the water in which the coral grew. Coral ^{90}Sr records give us a backward glimpse of oceanic fallout concentrations in the early years of the nuclear era before water sampling programs were underway. We will show below how the early time histories of ^{90}Sr in the tropical Pacific and Indian Oceans reveal some unexpected features.

2. Results

Fig. 1 shows the locations of the nine sites where corals were selected for this study. Seven are in the Pacific and two are in the Indian Ocean. Multiple samples were collected at each site in order to obtain a suitable coral head with both a long record and unambiguous banding. Most of the samples were collected within a few meters of the surface from open ocean environments (as opposed to enclosed shallows or lagoonal environments). Each reported measurement represents a single yearly growth band which is typically 7–10 mm in width. ^{90}Sr analyses were made on 20–30 g of coral at the Environmental Measurements Laboratory of the Department of Energy in New York City according to the procedures in Harley [12]. The measurements are reported in Table 1 with units of dpm per 100 g of coral, and are decay corrected to the year of band formation. Analytical errors are typically 5–10% [10] and are caused primarily by uncertainty in the background. Where possible, we have tried to estimate the month representing the mid point of each band year based on the thickness of the outer growth band and the month of collection.

Some of the data for the Oahu, Tarawa, and Fiji corals have been reported previously [13]. The banding for the Oahu coral was ambiguous in one section. We therefore drilled a series of tiny plugs (~ 6/band) across the slab in order to resolve seasonal changes in $\delta^{18}O$ associated with the seasonal temperature cycle [14].

Measurements of ^{90}Sr in seawater are usually given in units of dpm/100 l. By coincidence a ^{90}Sr activity measurement in coral with units of dpm/100 g corresponds to a seawater measurement in dpm/100 l. One hundred liters of seawater contain roughly one mole of Ca and 0.01 moles of Sr. In addition, one mole of pure $CaCO_3$ weighs 100 g. A more precise measure of the Ca content of seawater shows that there are 1.06 moles of Ca in 100 l. However, stable Sr is enriched in coral carbonate relative to the Sr/Ca ratio in seawater by 7% [15], making the two sets of units practically equivalent. Toggweiler [13] has shown that ^{90}Sr measurements from a Bermuda coral represent a very satisfactory average of monthly seawater measurements from weather station "E" [16], located a few hundred kilometers from Bermuda.

In Fig. 2 we have plotted ^{90}Sr activity vs. year

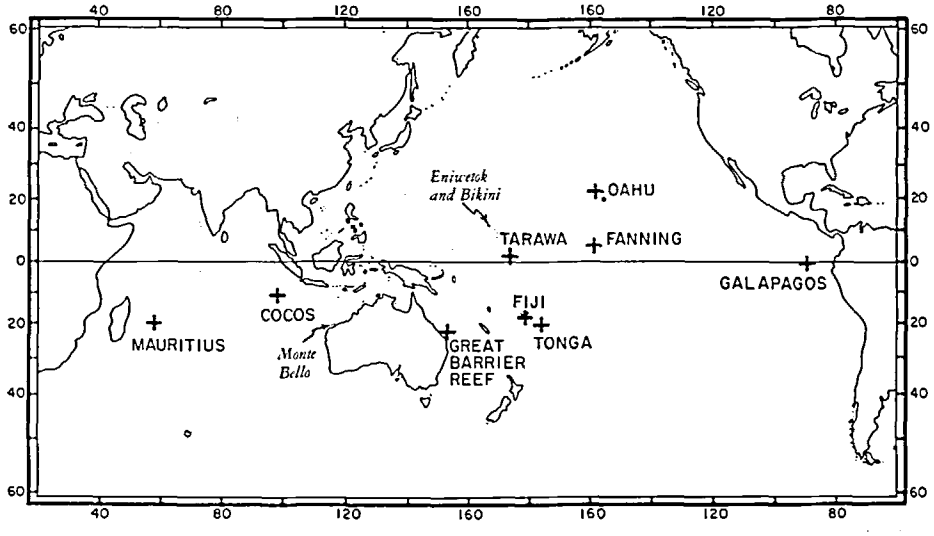

Fig. 1. Distribution of coral collection sites for the study.

TABLE 1

Tabulated coral ^{90}Sr data

Lab No.	Midpoint growth year	^{90}Sr activity (dpm/100 g)
Tarawa		
1537 A	1959.8	15.3±1.2
1537 B	1960.8	12.4±1.1
1537 C	1961.8	11.2±1.2
1537 D	1962.8	13.2±1.1
1537 E	1963.8	15.9±1.1
1537 F	1964.8	17.8±1.2
1537 G	1965.8	16.7±1.1
1537 H	1966.8	17.7±1.1
1537 I	1967.8	16.6±1.1
1537 J	1968.8	16.1±1.1
1537 K	1969.8	17.3±1.3
1537 M	1971.8	15.8±1.1
1537 N	1972.8	14.9±0.9
1537 O	1973.8	16.3±1.0
1537 Q	1975.8	14.2±1.0
1537 R	1976.8	16.7±1.0
1537 S	1977.8	17.2±1.0
1537 T	1978.8	16.1±0.9
Oahu		
1559 A	1958	31.4±2.7
1559 B	1959	34.8±2.5
1559 C	1960.5	26.7±1.8
1559 D	1961.67	33.8±1.8
1559 E	1962.75	43.4±2.0
1559 F	1964.42	59.2±2.6
1559 G	1965.75	48.5±2.2
1559 H	1966.83	41.5±1.9
1559 I	1968.0	36.4±1.8
1559 J	1968.58	34.5±1.7
1559 K	1969.50	28.9±1.4
1559 L	1960.67	36.5±1.8
1559 M	1971.67	36.5±1.8
1559 N	1972.67	31.1±1.5
1559 O	1972.67	30.2±1.5
1559 P	1974.17	28.8±1.6
1559 Q	1975.25	28.9±1.6
1559 R	1976.08	27.8±1.6
1559 S	1976.75	25.5±1.3
1559 T	1977.67	22.9±1.2
1559 U	1978.42	24.9±1.2
1559 V	1979.08	21.2±1.1
Fanning		
1584 C	1951.5	3.4±0.9
1584 E	1953.5	5.5±1.0
1584 F	1954.5	9.7±0.9
1584 G	1955.5	11.4±1.2
1584 H	1956.5	11.2±0.8
1584 I	1957.5	14.9±1.0
1584 J	1958.5	13.6±1.1
1584 K	1959.5	15.6±0.9
1584 M	1961.5	13.1±0.9
1584 N	1962.5	12.4±1.0

TABLE 1 (continued)

Lab No.	Midpoint growth year	^{90}Sr activity (dpm/100 g)
1584 O	1963.5	13.0±1.1
1584 P	1964.5	12.0±0.7
1584 Q	1965.5	17.4±1.2
1584 R	1966.5	14.5±1.6
1584 S	1967.5	14.1±0.7
1584 T	1968.5	16.7±1.1
1584 U	1969.5	17.8±1.1
1584 W	1971.5	15.9±0.9
1584 Y	1973.5	15.7±1.0
1584 AA	1975.5	16.0±0.9
1584 BB	1976.5	18.2±1.1
1584 CC	1977.5	13.6±0.6
1584 DD	1978.9	15.1±0.8
Fiji		
1561 C	1949.5	1.5±1.4
1561 H	1954.5	2.1±1.0
1561 I	1955.5	4.9±0.9
1561 K	1957.5	3.8±1.0
1561 L	1958.5	7.4±1.0
1561 M	1959.5	10.3±1.0
1561 N	1960.5	11.2±1.4
1561 O	1961.5	7.7±0.6
1561 P	1962.5	10.6±1.0
1561 Q	1963.5	11.6±0.8
1561 R	1964.5	12.2±0.7
1561 S	1965.5	11.9±0.8
1561 U	1967.5	10.8±0.8
1561 V	1968.5	13.9±1.0
1561 Y	1971.5	13.2±0.8
1561 AA	1973.5	12.4±0.8
1561 BB	1974.5	12.0±0.6
1561 EE	1977.5	12.1±0.9
1561 FF	1978.8	12.0±0.7
Cocos		
1583 B	1954.0	7.6±1.0
1583 C	1955.0	14.0±1.4
1583 D	1956.0	23.2±1.7
1583 E	1957.0	27.5±1.8
1583 F	1958.0	23.5±1.5
1583 G	1959.0	25.8±1.7
1583 H	1960.0	26.2±1.4
1583 I	1961.0	24.5±1.6
1583 J	1962.0	20.0±1.1
1583 K	1963.0	20.9±1.6
1583 M	1965.0	25.6±1.5
1583 N	1966.0	24.9±1.8
1583 O	1967.0	23.7±1.6
1583 Q	1969.0	21.2±1.9
1583 S	1971.0	19.8±1.1
1583 U	1973.0	23.2±1.6
1583 W	1975.0	17.1±1.3
1583 Y	1977.0	15.5±1.0
1583 Z	1978.0	14.5±0.8

TABLE 1 (continued)

Lab No.	Midpoint growth year	^{90}Sr activity (dpm/100 g)
Mauritius		
1585 B	1968.0	22.7±1.6
1585 C	1969.0	20.9±1.6
1585 D	1970.0	24.8±2.0
1585 F	1972.0	20.3±1.2
1585 H	1974.0	19.0±1.4
1585 I	1975.0	11.8±0.7
1585 J	1976.0	21.5±1.4
1585 L	1978.0	12.0±0.8
Galapagos		
1582 AB	1974	12.7±0.9
1582 CD	1975	13.3±0.9
1582 EF	1976	16.0±1.0
Tonga		
T89-62	1962	8.9±1.3
T89-69	1969	13.3±1.2
T89-71	1971	12.9±1.1
T89-78	1978	11.2±0.9
Great Barrier Reef, Australia		
1578 KL	1969	8.5±1.4
1578 IJ	1971	15.7±1.6
1578 GH	1973	15.8±1.6
1578 EF	1975	10.5±1.1
1578 CD	1977	11.6±1.2
1578 AB	1979	14.1±1.4

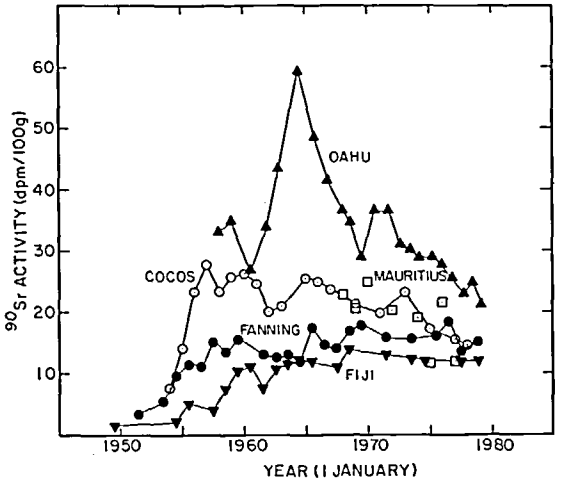

Fig. 2. Time histories of ^{90}Sr activity (dpm/100 g) at Oahu (△), Cocos (⊙), Fanning (●), and Fiji (▼). Indian Ocean data are plotted in open symbols, Pacific data in closed symbols. Tick marks on the time axis represent the first day of the year.

of growth from the Pacific Islands Oahu, Fanning, and Fiji, and the Indian Ocean islands Cocos, and Mauritius. The most prominent feature of Fig. 2 is the activity peak at Oahu in 1964 corresponding to the stratospheric fallout maximum. A burst of testing activity by the Soviet Union in late 1962, before the Limited Test Ban Treaty was to take effect, led to a sharp peak in stratospheric fallout in the northern hemisphere in the spring of 1963 [18]. As fallout levels tailed off over the next few years, surface waters of the mid-latitude North Pacific record a peak in ^{90}Sr activity in 1964. Surface water measurements of tritium in Oahu, Midway, and Adak also recorded maximum values during 1964 [8,18]. After the peak, the ^{90}Sr activity at Oahu fell off rapidly at first and more gradually through the 1970's as ^{90}Sr mixed into subsurface layers of the upper ocean. The decline averaged about 10% per year. A relatively small part of the decline (2.5% yr^{-1}) can be attributed to radioactive decay. The minimum in ^{90}Sr activity recorded at Oahu in 1960 corresponds to the U.S. and Soviet testing moratorium in 1959 and 1960.

The most unexpected finding revealed in Fig. 2 is the difference between the Indian Ocean records and those from the Equatorial and South Pacific. Because fewer nuclear tests were conducted in the southern hemisphere, overall fallout levels were much lower than those in the north [17]. Surprisingly, Indian Ocean ^{90}Sr activity levels recorded at Cocos Is. during the late 1950's are almost as high as activity levels recorded at Oahu. The ^{90}Sr activity at Cocos Is. begins to rise immediately from the earliest band year in 1954, reaching a peak in 1957. A secondary peak about 1965 marks the stratospheric fallout maximum for the southern hemisphere corresponding to the 1964 peak in the northern hemisphere. In contrast, activity levels at Fiji in the South Pacific rise slowly into the early 1960's and remain level through 1980. South Pacific values remain half those in the southern Indian Ocean through 1970. Measurements from a second Indian Ocean coral collected at Mauritius (20°S) support the Cocos values starting in 1969.

Moore and Krishnaswami [2] measured a ^{90}Sr time series from an Indian Ocean coral collected in the Gulf of Kutch (22°N) in the northern reaches of the Arabian Sea. This record displays a characteristic northern hemisphere pattern, reaching a peak value of 30 dpm/100 g in 1964. The

Gulf of Kutch coral records only 10 dpm/100 g of ^{90}Sr in the mid to late 1950's, a value which is much lower than the Cocos coral. The ^{90}Sr time history differences between northern Indian and southern Indian Ocean sites can be attributed to a stratospheric fallout-dominated time history in the north, limited cross-equator exchange, and, as we will show below, a large-scale transfer of North Pacific water to the southern Indian Ocean.

3. Discussion

Cocos Island is located at 11°S latitude in the eastern Indian Ocean. The latitude belt between the equator and 20°S is the zone of minimum fallout as reported by the U.S. Fallout collection network [17]. Global ^{90}Sr deposition in this latitude belt is generally only 1/5 that recorded in temperate northern latitudes. As noted above, activity levels at Cocos Is. are roughly twice the Fiji levels up to 1970. If we assume that levels of ^{90}Sr in the Fiji coral are representative of stratospheric fallout contributions to the surface ocean in the southern hemisphere, then an amount of ^{90}Sr equal in magnitude to the stratospheric fallout was added to the southern Indian Ocean.

Before 1960 few fallout collection stations in the southern hemisphere had begun to operate. Soils from level terrain generally retain all the ^{90}Sr deposited on the surface, enabling one to evaluate the cumulative amount of fallout reaching the earth's surface at a given location. A world-wide series of soil collection efforts during 1957–1967 [19–22], which included samples collected in 1960 at Durban, South Africa, Singapore, and Perth, Australia, showed that fallout adjacent to the Indian Ocean prior to 1960 was no different from fallout at locations adjacent to other ocean basins in the southern hemisphere.

We can think of two possible sources for the high levels of ^{90}Sr in the Indian Ocean during the 1950's. A possible source for some of the activity was a series of nuclear tests conducted by the United Kingdom in Australia between 1952 and 1957. We believe most of the activity, however, can be attributed to tropospheric and close-in fallout generated by U.S. nuclear tests at Eniwetok and Bikini atolls in the western North Pacific between 1952 and 1958. Ocean currents passing through straits in the Indonesian archipelago apparently carried high activity water from the tropical North Pacific to the southern Indian Ocean during the late 1950's. Indeed Fine [40] has proposed that relatively high levels of tritium measured in the southern Indian Ocean during the GEOSECS Expedition in 1978 can be traced to mid-1960's North Pacific sources.

The United States conducted a massive nuclear test at Bikini atoll on 1 March 1954, the 15-megaton "Bravo" test [23], which had a particularly big and documented impact on local fallout within a few hundred kilometers of the test site. Like the earlier 10-megaton "Mike" test in 1952, Bravo was detonated at ground level, vaporizing substantial amounts of reef material into its mushroom cloud. Particles of radioactive debris from Bravo were very much larger ($> 100\times$) than particles generated from air bursts in which the explosion fireball did not touch the earth's surface [7]. As such, an unusually large fraction of the fission yield fell into the ocean within a few hours or days after the tests. Fallout via large particles from surface blasts is referred to as "close-in" fallout.

Adams et al. [31] analyzed large fallout particles from coral island surface bursts. The vaporization of large quantities of $CaCO_3$ provides a high-temperature condensation phase, CaO (condensing at ~ 2600°C), which scavenges radioactive elements as the fireball cools. Without large quantities of a high-temperature condensate, the condensation of radioactive solids occurs only after the fireball has cooled to much lower temperatures, by which time the condensable material is greatly dispersed and forms only small micron-size particles. In a large nuclear explosion, these small particles are carried aloft into the stratosphere from where they become dispersed globally.

The vast majority of U.S. nuclear detonations at Eniwetok and Bikini were small, sub-megaton tests. Rising convective clouds from tests smaller than a few hundred kilotons are not large and hot enough to penetrate the stratosphere [26]. That part of the radioactive yield which is not removed as close-in fallout is dispersed by the winds in the troposphere and is stripped from the air by normal scavenging processes within a few weeks. This fallout is referred to as tropospheric or local fallout. Glasstone [26] has estimated that approximately 2.7 megacuries (MCi) of ^{90}Sr fell into the Pacific as close-in fallout from the Eniwetok and

Bikini tests, while 0.5 MCi fell into the Pacific as tropospheric fallout. As Bowen et al. [27] have pointed out, localized fallout from the U.S. tests represents over half the total inventory of ^{90}Sr in the North Pacific in 1973, even after 20 years of decay.

Eniwetok and Bikini are located within the North Equatorial Current and trade wind belts. Close-in fallout from the U.S. tests would thus have travelled west after the bomb tests. Surface water ^{90}Sr values as high as 3000 dpm/100 l were recorded 570 km west of Bikini atoll in June 1954 [24] shortly after the "Bravo" test. In spring 1955 surface water values up to 850 dpm/100 l were reported north of the Philippines, over 4000 km to the west of the test site [24]. High levels of ^{90}Sr and ^{137}Cs, up to 500 dpm/100 l, were measured in patches off Japan in 1957 and 1958 [25].

To account for the large excess of ^{90}Sr in the Indian Ocean, the bomb debris would have to be carried by surface currents through the straits in the Indonesian archipelago into the southern Indian Ocean. In Fig. 1 we see that the passages through the Indonesian archipelago are found near the latitude of Cocos Is. Wyrtki [28] has estimated that a net flow of 1.5 Sv passes from the Pacific to the Indian Ocean in this area. The flow is highly variable by season, reversing direction for part of the year. Godfrey and Golding [29] and Piola and Gordon [30] have estimated the net flow to the Indian Ocean to be in the neighborhood of 10–15 Sv.

Carter and Moghissi [23] report that the United Kingdom tested three nuclear devises at Monte Bello Is. (20°S, 115°E) off the northwest coast of Australia, one in 1952 and two in 1956. Yields for these tests are listed as < 1000 kilotons. The earlier test was conducted from a ship, the latter two from towers. These considerations are important in determining the degree to which the Monte Bello Is. tests contributed to the ^{90}Sr levels in the Indian Ocean prior to 1960. The presence of close-in fallout from these tests was not documented. Because the 1956 tests were detonated from towers, some earth was undoubtedly caught up in the fireball. This suggests that some close-in fallout may have been generated. Surface winds in the vicinity would tend to carry close-in fallout over the ocean [32].

The U.K. conducted nine tests in mid-continent Australia between 1953 and 1957 [23], which may have added some tropospheric fallout to the Indian Ocean. The U.S. and U.K. also conducted a series of tests near Christmas Island (2°N in the mid-Pacific). The U.K. Christmas Is. tests occurred in 1957–1958 and the U.S. tests in 1962. These probably had a minimal impact in terms of localized fallout since they were all air bursts, the nuclear devices having been carried aloft by aircraft [23].

Folsom et al. [33] man extensive survey during 1960–1961 of ^{137}Cs levels in Pacific and Indian Ocean surface waters. Like ^{90}Sr, ^{137}Cs, is a long-lived fission product (half life = 30 years) with no natural sources which is practically inert in seawater. ^{137}Cs and ^{90}Sr are produced in constant proportions such that measurements of one isotope provide a reasonably accurate measure of the activity of the other. The data show that ^{137}Cs activity levels north of 20°N in the Pacific were relatively uniform during 1960–1961 in contrast to the pronounced patchiness recorded near Japan a few years earlier [25]. To be sure, ^{137}Cs activity in the western North Pacific during 1960–1961 was somewhat higher than activity in the eastern North Pacific. The 1960–1961 ^{137}Cs distribution had apparently been so smoothed out by ocean currents, however, that Folsom et al. do not mention close-in fallout at all, even though most of the ^{137}Cs in the North Pacific at that time can be attributed to this source, according to Glasstone [26] and Bowen et al. [27].

We have averaged all of Folsom et al.'s Pacific data north of 20°N (24 pCi/100 l) and converted units to an equivalent activity of ^{90}Sr in desintegrations per minute. * This calculation yields a projected average ^{90}Sr activity of 31 dpm/100 l, which is in good agreement with ^{90}Sr activity in the 1960 and 1961 bands of Oahu coral (27 and 34 dpm/100 g). In contrast, surface activity levels of ^{90}Sr in the North Atlantic north of 20°N at this time averaged roughly 16 dpm/100 l [16], half what was seen in the Pacific. Surface water in the

Folsom et al. [33] assume that the concentration of stable Cs in seawater is 35 μg/l in calculating the activity of ^{137}Cs per liter of seawater. In their later work [34] this estimate is revised downward to 30 μg/l. We have applied this correction to their earlier work in converting ^{137}Cs activities to equivalent activities of ^{90}Sr.

western North Pacific south of 20°N had an average activity of about 20 dpm/100 l.

Folsom et al. also report on ^{137}Cs activity in surface water south of Indonesia in the eastern Indian Ocean near 10°S. These measurements show that surface water south of the straits in the Indonesian archipelago had an activity level of 30 dpm/100 l (in ^{90}Sr units) which was practically identical to average surface water north of 20°N in the North Pacific. Surface water activity to the east in the South Pacific, was much lower, about 10 dpm/100 l, in good agreement with the Fiji coral. Surface water further west in the Indian Ocean to the south of Cocos Is. averaged about 20 dpm/100 l compared with the Cocos coral (26 dpm/100 g).

Folsom et al.'s data set makes a convincing case that North Pacific water carrying remnants of the Bikini and Eniwetok fallout was flowing into the Indian Ocean in 1960–1961. We conjecture based on the evidence above [24,25] that activity levels in this southward flowing water were much higher a few years earlier. If close-in and tropospheric fallout from the U.K. tests in Australia made a significant contribution to ^{90}Sr levels in the Indian Ocean we expect that initially high surface water activity levels would have dropped rapidly, as was seen in the western North Pacific between the mid-1950's and 1960. The Cocos time history suggests a more sustained delivery of ^{90}Sr. We conclude that Monte Bello Is. fallout may have played a role in the rapid rise in ^{90}Sr activity seen between 1955 and 1956; most of the excess ^{90}Sr activity seen in the Cocos coral, however, came from tropospheric and close-in fallout generated by U.S. nuclear tests at Eniwetok and Bikini. A coral head from a suitable location within the Indonesian islands could firmly resolve the issue.

4. ^{90}Sr in the Equatorial Pacific

In Fig. 3 we have plotted ^{90}Sr time series from the Equatorial and South Pacific islands Fanning (4°N), Tarawa (1°N), and Fiji (17°S), with a few points from the Galapagos (1°S) and Tonga (21°S), on an enlarged scale. The small number of Tonga measurements available to date follow the Fiji data quite closely. Three band years from a small Galapagos coral in the late 1970's plot between the Fiji and Tarawa data.

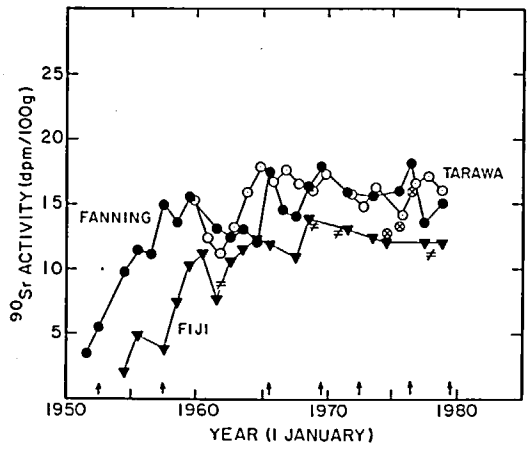

Fig. 3. Time histories of ^{90}Sr activity (dpm/100 g) at Fanning (●), Tarawa (⊙), Fiji (▼), Tonga (≠), and the Galapagos Is. (⊗) plotted on an expanded scale relative to Fig. 2. Arrows at the bottom of the figure denote El Niño years [41].

The most obvious feature of these records is the flatness of the time histories after the stratospheric peak in the early 1960's. The Fanning and Tarawa records show no tendency for ^{90}Sr activity to decrease from 1965 through 1979 even though additional inputs from fallout were practically insignificant after 1966 [17]. The flatness of the ^{90}Sr record contrasts with what might be expected from the record of bomb ^{14}C in the equatorial ocean. Broecker et al. [35] suggest that low $\Delta^{14}C$ values in equatorial surface water are produced by the upwelling of subsurface water which is uncontaminated with respect to bomb ^{14}C. If true, one might expect the equatorial time history of ^{90}Sr to decrease with time as subsurface water with no ^{90}Sr dilutes the fallout input. The convergence of the temperate (Oahu) and equatorial (Fanning) ^{90}Sr time histories in Fig. 2 suggests instead that a large-scale transfer of water has occurred between the temperate and tropical North Pacific.

The inflow of high ^{90}Sr water into the Pacific equatorial zone can be clearly associated with a subsurface, high tritium tongue extending southward under the North Equatorial Current from the eastern North Pacific [8,10,36]. Subsurface, upper thermocline water from both North and South Pacific mid-latitude regions penetrates laterally to within a few degrees of the equator, from where it upwells to the surface as part of the equatorial divergence [37]. A recent study by Quay et al. [38]

of the bomb radiocarbon distribution in an equatorial transect suggests that the flushing of equatorial surface water by mid latitude thermocline water is quite rapid (4–6 years). Quay et al. propose that it is the rapid flushing of equatorial surface water with temperate thermocline water, rather than the upwelling of sub-thermocline water within the equatorial zone, which has held down the $\Delta^{14}C$ content of equatorial water.

Along the bottom of Fig. 3 are arrows indicating years in which El Niño events occurred in the equatorial Pacific [39]. In 1957, 1965, 1969, and 1976, ^{90}Sr activity at Fanning Island was higher than in the preceding year or the following year by 10–20%. The only El Niño year in which no peak activity is recorded is 1972, a year for which no sample has yet been run. In the El Niño year 1976, ^{90}Sr activity in the Galapagos coral was higher than in the previous two years. This phenomenon is not observed at Tarawa with any significance. During normal, non-El Niño years, water flowing past Fanning Island is part of the westward flowing South Equatorial Current (SEC) which originates near the coast of South America. Coastal water off Peru and in the vicinity of the Galapagos Islands is normally cool as a result of intense upwelling. During El Niño years, the westward flow of the SEC and the coastal upwelling slacken, and warm water from the north invades the coastal region carrying higher ^{90}Sr activity. It is curious that the Fanning coral records the same effect seen in the Galapagos but not the coral from Tarawa. During El Niño years, water in the vicinity of Fanning Island must be part of an expanded North Equatorial Counter Current carrying a stronger northern hemisphere ^{90}Sr signal than the SEC.

5. Conclusions

In most areas of the ocean where radioactivity from nuclear weapons testing has been measured, activity levels in surface water can be reconciled with measured fallout from globally dispersed stratospheric sources. Time histories of ^{90}Sr recorded by Pacific and Indian Ocean corals show, however, that tropospheric and close-in fallout from U.S. Pacific nuclear tests at Eniwetok and Bikini in the 1950's elevated surface activity levels in both the North Pacific and southern Indian Ocean to values well in excess of those expected from stratospheric inputs. This conclusion is consistent with Bowen et al.'s [27] estimate that roughly half of the 1973 inventory of ^{90}Sr and ^{137}Cs in the North Pacific could be attributed to localized fallout from the Eniwetok and Bikini tests. The rapid rise and sustained high level of ^{90}Sr in the southern Indian Ocean during the mid 1950's, which is recorded by the Cocos Is. coral, documents large scale transport of surface water from the tropical North Pacific across the equator into the southern Indian Ocean. Much uncertainty remains, however, regarding the contribution of localized fallout to the southern Indian Ocean from 1950's nuclear tests in Australia by the United Kingdom.

The convergence of North Equatorial Pacific and mid-latitude North Pacific ^{90}Sr activity levels through the 1970's underscores the claim by Quay et al. [38] that equatorial surface water is rapidly flushed by upwelling mid-latitude thermocline water. ^{90}Sr activity levels in the Fanning and Galapagos corals appear to be higher during El Niño years, indicating increased penetration of northern hemisphere water into the equatorial region.

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