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³He in Indonesian Seas: Inferences on deep pathways

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Abstract: Helium isotope measurements from the Indonesian Seas, and from the Java-Australia Dynamic Experiment cruises define mantle ³He sources and deep water spreading patterns. ³He sources in the Sulawesi Sea and in the Makassar Strait are found, but these are prevented from spreading into the Banda Sea and the Indian Ocean by blocking sills. A major mantle source is identified below 2000m in the Flores Sea. The ³He distribution suggests that the Banda Sea water migrates westward along the floor of the Flores Sea, upwells and then advects the high ³He Flores signal. A tongue of higher-than-ambient ³He on the Indian Ocean side of the Flores chain indicates a deep outflow of the Flores and the Banda Sea water into the Indian Ocean near 1300m.

Introduction

The Indonesian Seas study is a cooperative project between the Indonesian and US oceanographic institutions. It was designed to collect hydrographic and tracer information in the Indonesian Seas in two monsoon seasons to study the Pacific-to-Indian Ocean connection with two cruises in August 1993 and in February 1994. Hydrographic parameters, oxygen, nutrients, primary productivity, CFCs, tritium, and helium isotopes were targeted for the study. The Java-Australia Dynamic Experiment (JADE) is a cooperative project between the Indonesian and French oceanographic institutions. Its main goal was to quantify the Pacific-Indian Ocean throughflow by combining hydrographic, current meter and tracer measurements at the exit (Indian Ocean) of the Indonesian Seas with cruises in August 1989 and March 1992 [Fieux et al., 1994]; see Fig. 1 for map.

The Indonesian Seas have attracted a great deal of interest from oceanographers because the region has the most complex

make up of all marine environments. Upper ocean circulation varies seasonally under the influence of monsoons. Because of extremely complex topography, tides are suspected to enhance vertical diffusivity in the upper layers an order of magnitude compared to that for the average ocean [Field and Gordon, 1992]. The Pacific Ocean waters pass through this region into the Indian Ocean as part of the global thermohaline circulation [e.g. Fine, 1985; Gordon, 1986].

³He can be found enriched five to ten-fold, with respect to the atmosphere, in the mantle component that is injected at submarine hydrothermal sites or volcanos into deep or bottom waters [e.g. Craig et al., 1975]. At depth ³He provides a unique tracer for the deep circulation, because generally below a few thousand meters hydrographic indicators show nearly uniform distributions. For example, its emanation from the East Pacific Rise (EPR) and westward spread is the best evidence for the deep central Pacific circulation [e.g. Lupton and Craig, 1981]. This high ³He core remains close to the level of injection (≈2000m depth) across the Pacific, while magnitude of the anomaly is reduced to one-half of the maximum observed adjacent to the EPR. Similarly large excesses of ³He are observed in the Indian Ocean over the mid-oceanic ridge system with the magnitude of the large scale features being nearly half of that in the Pacific [Ostlund et al., 1987]. Decreasing magnitude of the deep helium anomaly from the Pacific to Indian Ocean is a potential tool in determining the extent of deep exchange provided that they are not modified in the Indonesian Basins.

The Southeast Asian Archipelago is a tectonically active region, dotted with active and extinct volcanoes. It is not surprising to encounter sources due to hydrothermal venting or submarine volcanism. It is in fact surprising that many more sources are not indicated by the results of the present survey. The crust of the Banda Sea is believed to have originated in the Mesozoic era from a spreading center to the northwest of the present location of this sea and the southwestern part of the Banda Sea had formed by a

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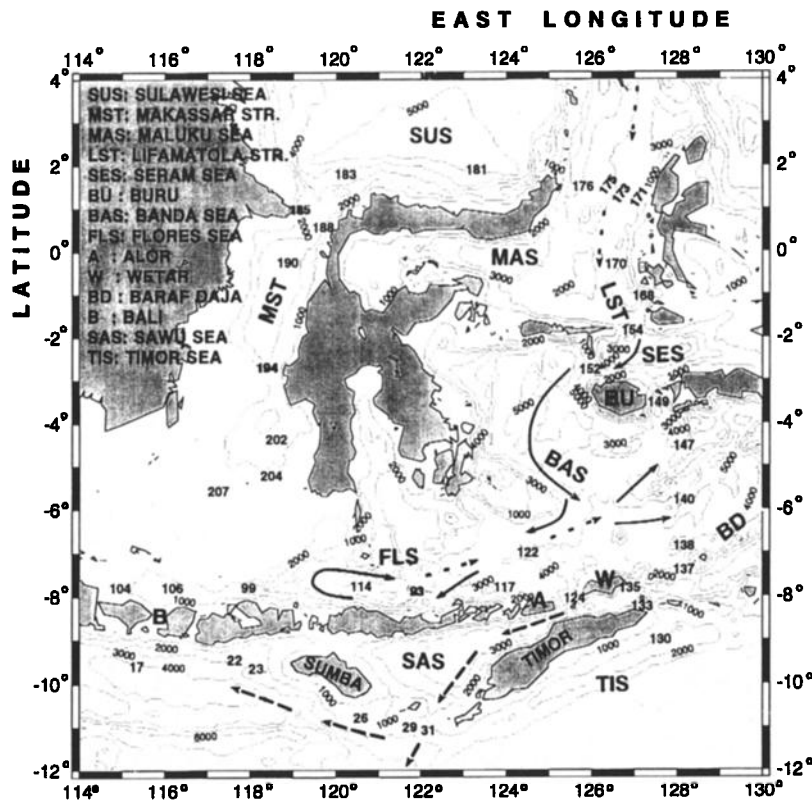


Figure 1. Map of the region of study. Numbers greater than 90 show the location of Indonesian Seas stations; smaller, Eastern Equatorial Indian Ocean stations. The deep Pacific input, and the suggested circulation from He data are sketched by the arrows: - - -> at 1800-2000m; —> at 2500m; - · - ·> at 1200-1300m.

depression between 123° E and 127° E [Lapouille *et al.*, 1985]. These boundaries therefore might be considered as likely sites for tectonic activity.

Results and Discussion

Helium measurements were made mass-spectrometrically, the Indonesian Seas samples at the University of Miami and the Java-Australia Dynamic Experiment samples at the Saclay facility. The $^3\text{He}/^4\text{He}$ ratios are expressed as an anomaly with respect to the same ratio in air [see e.g., Jean-Baptiste *et al.*, 1992]. Uncertainty in $\delta^3\text{He}$ varies between 0.2% and 0.4%. An intercalibration was performed satisfactorily between the two helium laboratories. The two data sets were merged without any adjustments based on the very good agreement between the University of Miami results and the Saclay measurements from 1984 in the Sulawesi Sea [Belviso *et al.*, 1987]. The results are presented in transects in Figs. 2-a to 2-e. Here we discuss the distribution of ^3He signal below 1000m for each transect to deduce a pattern for deep circulation.

Sulawesi transect ($\approx 1.5^\circ$ N, Fig.2-a) data are in very good agreement with previous measurements from this region of [Belviso *et al.*, 1987] and with measurements from the WOCE Pacific P5 line along $\approx 10^\circ$ S [W.J. Jenkins, private comm.]. The controlling sill separating the Sulawesi Sea from the open Pacific Ocean occurs between the Mindanao and Kawio islands (5° N; 125.5° E) and is approximately 1400m deep. The magnitude of helium anomaly below 1700m at the eastern stations 171, 173, 175 establishes the magnitude of $\delta^3\text{He}$ baseline in the Indonesian basins to be 19% or less.

Values greater than 20% at station 181 below 2200m are likely due to a local mantle source. However, this water is isolated by bottom topography and cannot spread into the Makassar Strait or Seram, Banda, Flores Seas.

Makassar transect ($\approx 119^\circ$ E, Fig.2-b) is similar to the Sulawesi transect. The Makassar Strait is about 2000m deep. Higher than baseline helium signal below 1500m can again be attributed to local tectonic ^3He sources. This feature is isolated from the Flores Sea by the 500m sill at the southern end of the Makassar Strait. It also seems to be isolated from the deeper high ^3He within the Sulawesi Sea, but perhaps a higher spatial resolution would detect a linkage.

Flores transect (7.8° S, Fig.2-c) shows the largest ^3He anomalies in the entire survey. At station 114 the magnitude of the anomaly is greater than 25% centered at approximately 2500m. That the signal persists at a relatively high magnitude at stations 93 and 122 indicates an eastward spread of the deep waters of western Flores Sea. Station 114 where we observe the greatest $\delta^3\text{He}$ lies close to a north-south transform fault, which is presumably a likely location for tectonic activity [Lapouille *et al.*, 1985].

A conspicuous feature on the eastern end of the transect is marked with low helium signal ($\approx 15\%$). This lens, centered at 1800m at stations 122 and 124, appears to have a Pacific origin, as there is no accompanying salt signal to suggest that it might have been advected from the Sawu Sea.

Banda Sea transect ($\approx 128^\circ$ E, Fig.2-d) shows a striking feature centered at 2500m and marked with ^3He anomalies of approximately 22%. The vertical extent of this feature is only about 200m, but horizontally it is widely distributed within

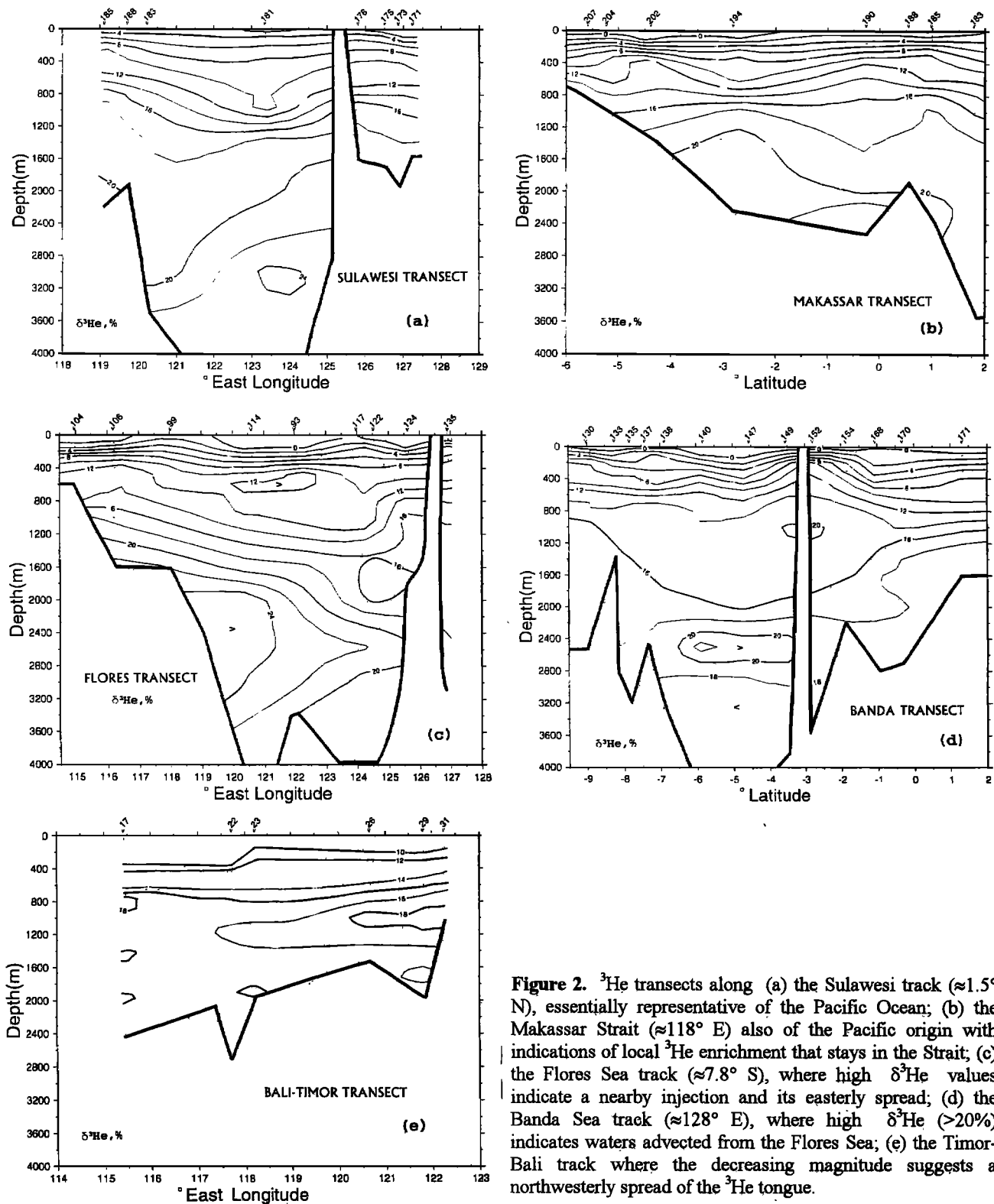


Figure 2. ^3He transects along (a) the Sulawesi track ($\approx 1.5^\circ$ N), essentially representative of the Pacific Ocean; (b) the Makassar Strait ($\approx 118^\circ$ E) also of the Pacific origin with indications of local ^3He enrichment that stays in the Strait; (c) the Flores Sea track ($\approx 7.8^\circ$ S), where high $\delta^3\text{He}$ values indicate a nearby injection and its easterly spread; (d) the Banda Sea track ($\approx 128^\circ$ E), where high $\delta^3\text{He}$ ($>20\%$) indicates waters advected from the Flores Sea; (e) the Timor-Bali track where the decreasing magnitude suggests a northwesterly spread of the ^3He tongue.

the Banda Sea. The origin of this feature may be either advection from the Flores Sea to the west or from a ^3He source to the east, along the Banda Arc Islands (southeastern limits of the Banda Sea). However, an eastern source may be ruled out on the basis of silica data [Van Bennekom, 1983]. Silica, near hydrothermal sources, is linearly correlated with mantle helium [Broecker, 1980]. Silica distribution in the Banda Sea

does not suggest an accompanying helium anomaly. This leaves the alternative that the anomaly is an advected feature from the Flores Sea. The depth and magnitude of the eastward-spreading helium signal of the western Flores Sea match the Banda Sea feature. Temperature and salinity data are nearly uniform below 1000m in the Flores and Banda Seas and do not confirm or contradict this pathway. No silica data

from the Flores Sea are available for a comparison with the Banda Sea figures of [van Bennekom, 1983].

2000m sill of the Lifamatola Strait provides the deep connection with the Pacific. Temperature, salinity and oxygen data across this sill show that the deep Pacific water (>1700 m) sinks here and is the source for the deep Seram, Banda and Flores basins [Broecker et al. 1986; van Aken et al., 1988]. The Flores Sea is closed on the west with a sill at about 500m. Although the basin reaches depths below 5000m, there is a ridge on the east ($\approx 121^\circ$ - 122° E) rising to less than 2000m. However, a gap in the ridge provides deeper connection with Banda Sea at about 2500m at approximately 8° S; 122° E. A probable deep circulation envisioned here has deep water flowing from the Lifamatola Strait into the Banda Sea with a branch migrating west through the gap, upwelling in the western Flores Sea and returning to the Banda Sea at around 2000m depth with the high ³He signal.

Such a scheme is expected from buoyancy considerations: the dense Lifamatola Strait overflow water displaces the more buoyant resident water in the connected basins inducing a vertical return flow. We cannot *a priori* discount a horizontal cell between the Banda and Flores Seas that might induce the observed ³He pattern, however the dynamic properties of the Indonesian Basins, as presently known [e.g., Ffield and Gordon, 1992], favor a vertical cell circulation.

Given the present vertical sampling resolution and the remoteness of the Flores Sea from the controlling Lifamatola sill, this scenario is not entirely unexpected. This circulation is shown schematically in Fig. 1.

Indonesian Seas oxygen data show a maximum in the Seram Sea in the 1600-2000m range, and also a slight maximum at the Banda Sea stations at 1900-2000m level [Gordon and Ilahude, in prep.]. These suggest that the Lifamatola Strait water just above the sill spreads on a more horizontal plane into the Banda Sea, and are consistent with relatively low ($\approx 16\%$) $\delta^3\text{He}$ values at about 2000m between stations 140 and 147. Although an input from the Timor Sea, where the ³He signal is low, could induce the observed pattern, the high salinity of the Timor Sea water is not detected in the Banda Sea, and the sill between the two is more than 200m too shallow for this feature. Spatial resolution of the helium sampling does not allow better characterization of the Lifamatola Strait water and its correlation with the Banda Sea water.

A high helium envelope at 900m at two stations in the north Banda Sea is probably due to a shallow local source in the Seram Sea, where the Pacific water mixes before entering the Banda Sea. The spread of this feature must be limited as it has not been encountered at any other location.

Bali-Timor transect ($\approx 10^\circ$ S) shows the Banda Sea outflow into the Sawu Sea at 1250m in the form of a plume marked with $\delta^3\text{He}$ values between 17-18%. This plume appears to spread southwest in the Sawu Sea with a branch turning to northwest south of Sumba. At two southern stations ($\approx 17.5^\circ$ S; 117° E, not included in the figures) helium anomaly is unchanged at 17-18% at $\approx 1300\text{m}$. At the core of the ³He plume at Station 17, an approximate volumetric mixing ratio of 2:1 is indicated respectively for the Banda and Sawu waters based on both helium anomaly and salinity. The depth and location of the Banda outflow indicated by ³He anomaly supports the conclusion of [Wyrtki 1961] that water between 1000 and 1200m flows from the Banda Sea into the Sawu Sea, based on temperature-salinity-oxygen analysis.

Summary

³He of mantle origin in the Indonesian Seas suggests an overturning deep circulation between the Flores and Banda Seas. The spread of the Banda Sea Water in the Indian Ocean side is also clearly traceable. It must be born in mind that the causes of ³He injection at depth, hydrothermal activity or underwater volcanism, are transient events by nature. Therefore the conclusions based on a "snapshot" map of ³He are limited by the steady state assumption. Nevertheless present exploratory survey demonstrates the potential use of ³He in the Indonesian Seas. With carefully placed transects and greater vertical sample resolution, a more definitive characterization of the deep overturning circulation could be accomplished.

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