Volcanic $^3$He Outgassing along the East Pacific Rise, as evidenced by $^3$He in the water column

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Abstract

$^3$He concentrations in the water column from four WOCE transects and data from WOA05 were analyzed to determine if there is a trend in volcanic activity as one moves from deep oceanic crust divergence (e.g. the East Pacific Rise) to continental crust divergence (e.g. the Gulf of California and into the Salton Sea Trough), and to map circulation at depth in the east Pacific Ocean.

Background

Tectonic plate boundaries are classified as one of three types based on their relative motions: divergent, convergent, and transform. Divergent plate boundaries are characterized by lithospheric thinning resulting in the formation of new oceanic crust, the development of rift valleys bounded by axial ridges, increased crustal heat transport, and localized regions of geothermal activity and volcanism, which release traceable compounds, like $^3$He (http://volcanoes.usgs.gov/hazards/gas/), into the environment.

The East Pacific Rise, a divergent plate boundary, located in the east Pacific Ocean, extends from the Gulf of California south until it joins the Pacific-Antarctic Ridge (approximately near 55 S latitude and 130 W longitude) (Figure 1). It forms the plate boundary between the Pacific Plate to the west and the North American, Riviera, Cocos, and Nazca Plates to the east (http://www.britannica.com/EBchecked/topic/176756/East-Pacific-Rise). Active volcanism and hydrothermal venting occur throughout the entire length of the East Pacific Rise, releasing volcanic gases into the water column, including $^3$He.

$^3$He is an ideal tracer for understanding ocean circulation because it is frequently measured, is conservative (Talley et al. 2011). Recently, several studies, including Downes et al. (2012), have used $^3$He with great success to trace the circulation of ocean waters.
Methods

Four transects – P04, P17, P18, P19 – were selected from the World Ocean Circulation Experiment (WOCE) Hydrographic Program One Time Survey due to their close proximity to the East Pacific Rise. Since $^3$He in the water column was the primary focus of this study, only the bottle data from these four transects were analyzed using the Java Ocean Atlas (JOA) software (J. Swift; http://joa.ucsd.edu/). The bottle data were filtered for data containing $^3$He concentrations, known in the JOA software as DELHE3. These filtered data were developed into maps, cross-sectional property profiles, and property vs. property graphs to determine the scope of the dataset.

Next, the data from the four transects were combined into one dataset, plotted as a map, and used in several calculations. First, sigma-2 was calculated to provide a reference surface local to the water containing the highest concentrations of $^3$He. Using a cross-sectional sigma-2 profile, a range of sigma-2 containing the highest $^3$He concentrations was visually determined. To quantitatively support the visual determination of the sigma-2 range associated with the observed high $^3$He plumes, extrema calculations were used to filter for the maximum $^3$He concentration identified at each station and their respective sigma-2 value. These calculated results were graphed with the maximum $^3$He concentration as a function of sigma-2. This determined range was then utilized in a station calculation to isolate the maximum $^3$He concentration found within the range; the results were plotted as a map.

Lastly, using the high $^3$He sigma-2 range as a guide, data from the Pacific Ocean dataset of the World Ocean Atlas (WOA) – 2005 was consulted to look for any large-scale patterns that might be indicative of the circulation of waters influenced by East Pacific Rise $^3$He volcanic outgassing. Integration calculations were completed for temperature, salinity, and oxygen with
respect to sigma-2 over the high $^3$He sigma-2 range. The results of these integrations were plotted on the Pacific Ocean map and were visually analyzed for trends.

**Results**

Visual analysis of the cross-sectional $^3$He profiles for each of the four transects reveals that the highest concentrations of $^3$He are found over a range of about two to three thousand decibars, the surface waters have extremely low concentrations, and the bottom waters have slightly elevated concentrations (Figure 3). The highest concentration of $^3$He found in the P04 transect (Figure 3A) was immediately above a bathymetric high and tapered off in concentration toward the west. In the P17C transect (Figure 3B), the region of highest $^3$He concentration was rather isolated near the northern extent of the dataset. The P18 and P19C transects (Figures 3C and 3D, respectively) had similar concentration distributions to each other, mid- to high $^3$He concentrations extending from the northern extent of the data south, with several localized regions of high concentrations.

Once, plotted as a combined dataset, it became clear that the regions of high $^3$He fell in the same narrow sigma-2 range across all four transects – between 36.7 and 37.0. This was verified by plotting the maximum concentration of $^3$He vs. the sigma-2 value of the maximum concentration of $^3$He (Figure 4). There is a clear spike in the $^3$He concentrations up to about 40% within the narrow sigma-2 range of 36.7 and 37.0. Additionally, there is a distinct exponential-type trend in increasing $^3$He concentrations from about 35.7 to the peak at just below 37.0.

To show the spatial distribution of the high $^3$He plumes at depth, the four transects were plotted as a map with each sampling station colored according to the maximum $^3$He concentration observed within the sigma-2 range of 36.7 and 37.0 (Figure 5). This plot shows that the regions of high $^3$He concentration appear to be isolated to a large region centered at the
equator in the east Pacific Ocean. The highest $^3$He concentration, 40.030%, was found along the P04 transect at a latitude of 9.500N and a longitude of 104.165W and a sigma-2 of 36.954.

By using the high $^3$He sigma-2 range as a guide, integration plots of temperature, salinity, and oxygen were developed to determine if there was any large-scale patterns that might be associated with volcanic outgassing in the waters of the east Pacific Ocean (Figure 5A-C). The integration plot for temperature has the most obvious trend along the East Pacific Rise; there appears to be a slight temperature increase in the water column of about $0.1^\circ$C directly above the East Pacific Rise (Figure 5A). The temperature variation is so apparent that one could easily trace the location of the East Pacific Rise for the majority of its length. A less clear trend exists in the salinity integration (Figure 5B). Within the high $^3$He sigma-2 range, segments of the East Pacific Rise exhibit slightly depressed salinity values – about 0.03 psu lower than the surrounding waters. The lowest salinity depressions occur in three localized regions. The Oxygen integration (Figure 5C) shows no clear trend related to the East Pacific Rise, but an apparent trend of high Oxygen in the southern Pacific Ocean at depth with increasing lower Oxygen concentrations toward the north.

**Conclusions and Discussions**

The highest $^3$He concentration plume found along the P04 transect at latitude of 9.500N and longitude of 104.165W, occurs directly above an apex in the bathymetry. Based on the shape of the plume above the apex, it appears the apex might be the vent of the plume (Figure 3A). This hypothesis is confirmed; according to the USGS database of worldwide active volcanoes, an unnamed submarine volcano exists at latitude of 9.83N and longitude of 104.30W (http://volcano.oregonstate.edu/oldroot/volcanoes/alpha.html).
By examining the spatial relationships of the four transects and the locations of high $^3$He within each transect, hypotheses regarding the extent of high $^3$He plumes were made. There appears to be plume extensions tapering to lower concentrations to the west at about latitudes 9°N, and 8°S, but at 30°S there appears to be a plume tapering to the east. The tapering affect seen in these plumes may be the result of at depth circulation carrying waters high in $^3$He away from their source. The proposed westward circulation at 9°N, and 8°S and the proposed eastward circulation at 30°S consistent are with the Pacific Ocean geostrophic circulation at 2000 and 2500 dbar in Reid (1997).

The temperature and salinity variations noted in the WOA05 integration plots are skewed and the observed patterns seen above the East Pacific Rise may not be present in the steady state of the ocean. Because the integration calculations made were with respect to the high $^3$He sigma-2 range of 36.7 to 37.0 and at a sigma-2 value of 37.0 bathymetry along the East Pacific Rise prevents data collection, the final result which was plotted is biased toward the temperature, salinity, and Oxygen measurements taken at a sigma-2 value of 36.7. A slight variation in the temperature and salinity of the waters above the East Pacific Rise may still be present but cannot be constrained in the datasets used in this study.

The observed trend seen in the Oxygen integration – high in the southern Pacific Ocean and lower in the northern Pacific Ocean – is consistent with the general understanding of Pacific Ocean overturning, currents, and residence time (Talley et al. 2011).

Due to the lack of data publically available in the Gulf of California, no new $^3$He concentration analyses were conducted. Furthermore, because the transects crossed the southern East Pacific Rise obliquely limited data is available to hypothesize about variation in volcanic activity along the ridge. As such, it is recommended that future research cruises follow the apex
of the East Pacific Rise from its conception in the southern Pacific Ocean into the Gulf of California to clearly define potential $^3$He vents. Additionally, two cruises should be conducted that parallel the apex of the East Pacific Rise – one to the west and one to the east – to identify the extent of $^3$He plumes, which may be indicative of circulation at depth.

References


http://www.britannica.com/EBchecked/topic/176756/East-Pacific-Rise

http://volcanoes.usgs.gov/hazards/gas/

http://volcano.oregonstate.edu/oldroot/volcanoes/alpha.html
Figures

Figure 1: From: https://www.uwgb.edu/dutchs/GeolColBk/SmCol/S amerPlateSmColLabel.gif

Figure 2: Mercator: –171.00--30.00,–72.00–44.00
Figure 5:

Figure 6: