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HELIUM-3 INSIDE ATOLL BARRIER REEF INTERSTITIAL WATER : A CLUE FOR GEOTHERMAL ENDO-UPWELLING

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Abstract. Interstitial waters from boreholes in the reef conglomerate of Tikehau atoll (S.W. Pacific) contain positive anomalous concentrations of dissolved inorganic nutrients compared to adjacent oceanic and lagoonal waters. These anomalies have been interpreted by geothermal circulation of deep oceanic waters penetrating the porous reef carbonates and ascending through the atoll flanks by thermo-convective advection as already proposed for other atolls. We present here a new strong evidence of this geothermal circulation inside atoll reefs from the record of helium-3 anomalies in borehole waters of Tikehau atoll. These results bear directly on three controversial aspects of reef history : the efficiency of thermal energy for circulation of reef pore waters, the sources of nutrients to support the net productivity of reef ecosystems, the early diagenesis of reef foundation carbonates.

Introduction

The endo-upwelling concept is born from the question raised by the atoll high productivity in the central desert region of the tropical ocean. The first support for the geothermal endo-upwelling model of Rougerie and Wauthy [1986, 1990] came from nutrients data obtained from deep wells at Mururoa atoll (23°S, 140°W).

According to this model deep oceanic water penetrates and ascends by thermo-convective advection through the porous and permeable reef carbonates overlying the volcanic foundation and, thereby, provides the nutrients required for the metabolism of the superficial reef organisms. At the level of the Antarctic Intermediate Water (AIW), the water enters the reef flanks at depths of 500 m or more and, due to its high CO_2 concentration and low pH (Table 1), dissolves some of the carbonate ; Aissaoui et al. [1988] have noted recently "that present centripetal sea water circulation induces marine dissolution below 655 m around the periphery of Mururoa atoll". Thus, deep oceanic waters entering and, locally dissolving the reef carbonates, are heated by the geothermal flux and ascend due to thermal convection to become the nutrient-rich interstitial waters sampled in the boreholes. These endo-upwelled nutrients then sustain the huge autotrophic production of the algal-coral ecosystem living on the crest and on the seaward slope of the atoll.

Atoll interstitial water properties

At Tikehau atoll, Tuamotu Archipelago (15°S, 149°30W), interstitial waters from four boreholes (35 m depth) drilled on the reef flat were sampled bimonthly during 1989. The samples were drawn at different depths from permanently inserted tygon polytubes and analyzed (oxygen, nitrate, phosphate, silicate, ammonia, alkalinity, pH) within a few hours of collection in the laboratory at Tikehau. The results of seven sets of analyses of borehole interstitial waters and of adjacent lagoonal and oceanic waters are presented in Table 1.

These data clearly indicate that the interstitial waters in the reef are nutrient-rich : concentrations of inorganic dissolved phosphate, nitrate and silicate are 7 to 20 times higher than the surrounding ocean and lagoon and are similar to concentrations at 500 m in the upper Antarctic Intermediate Water (AIW). These findings support the geothermal endo-upwelling model.

The atoll as a biological singularity within the oceanic tropical desert

Reef ecosystems found in clear oligotrophic tropical waters are net exporters of organic matter and would not survive unless the long-term value of the photosynthesis/respiratory ratio exceeds 1. They require a permanent input of nutrients provided by the endo-upwelling mechanism. Our data for dissolved oxygen indicate that there is an apparent oxygen utilization (AOU) of 3 l/m^3 within the porous reef carbonate (or framework) which may be the result of biodegradation of organic matter derived from the living veneer on the reef surface [Guilcher, 1988]. A graphical estimate of the amount of re-mineralized phosphate released to the interstitial waters is 0.35 $mmole/m^3$ which correlates with the value of AOU. In addition, these data suggest that about 30 % of the phosphate (Figure 1) come from biorecycling and that 70 % of the phosphate consist of imports originating directly from AIW surrounding the deep atoll flanks and brought near the reef surface by endo-upwelling.

The main limitation of the use of dissolved inorganic nutrients, oxygen, pH and alkalinity as clues for assessing the reality of the endo-upwelling process is that those parameters are not conservative, being involved in biological cycles.

In order to strengthen the significance of these results and therefore the validity of our model, other conservative parameters or markers were needed : it appeared that helium-3 anomaly could constitute a good candidate.

Helium-3 anomaly in reef interstitial water

Previous work [Lupton and Craig, 1981] on the large-scale distribution of ^3He in the deep Pacific ocean has shown that primordial ^3He is being dispersed from hydrothermal venting on the East Pacific Rise. This has led to an ^3He-enriched plume centered at about the depth of the ridge crest (2500 m). The plume spreads westward into the central Pacific, including the Tuamotu archipelago, where helium anomalies up to 35 % (at 2000 m depth) can be detected [Ostlund et al,

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TABLE 1.
Chemical properties of interstitial (averaged from n borehole data during 1989), lagoonal, shallow and intermediate (500 m) oceanic waters, (Tikehau atoll). Oceanic data from 1986-1989 R.V. Marara cruises [J. Rancher, pers. com.].

data	depth	salinity	O_2	PO_4-P	NH_4-N	NO_3-N	SiO_3-Si	pH	total alk	redox pot.
n	m	‰	l/m^3	nutrients (mmole/m^3)					eq/m^3	mV
					interstitial water					
21	10	35.5	1.3	1.1	0.6	4.8	7.1	7.55	2.25	100
21	20	35.6	1.4	1.1	0.4	5.4	6.5	7.62	2.22	100
21	30	35.6	1.2	1.0	0.5	6.6	8.8	7.66	2.15	100
					lagoon					
21	0-20	36.0	5.4	0.2	0.5	0.2	0.8	8.35	2.33	180
					ocean					
6	0-100 (TSW)	36.2	5.0	0.1	0.2	0.1	0.7	8.30	2.30	200
6	500 (AIW)	34.5	2.8	1.8	0.1	25	12	7.90	2.40	100

1987]. Hence, ^3He can be used as a tracer to detect the presence of intermediate depth Pacific water in reef interstitial water.

Sampling for helium was done from Tikehau interstitial water in October 1989. Copper tubes were flushed and then filled directly with interstitial water from the polytubes of three of our boreholes and sealed with clamps. In the laboratory, the 40 cm^3 seawater samples were extracted and their dissolved gaseous component analyzed for helium-3 and helium-4 by mass spectrometry following the routine analytical procedure used in Saclay [Jean-Baptiste et al, 1988]. In addition, an oceanic helium profile was made a few miles off Tikehau atoll from the R.V. Marara. Helium-3 data are given (Table 2) in delta % values, i.e by the deviation of the isotopic ratio $^3He/^4He$ of the sample to the atmospheric isotopic ratio (R_A=1,384.10^{-6}) :

$$\delta = ((^3He/^4He)_{sample}/(^3He/^4He)_{atm} - 1) \times 100$$

The mean accuracy is ± 0.3 % for delta values.

The δ^3He values of the borehole samples show a progressive increase with depth. Moreover, at each depth, the δ^3He value is significantly in excess relative to the oceanic mixed layer value between the surface and 150 meter depth (typically ranging between -2.2 % and - 1 %).

The δ^3He values of the borehole samples linearly correlate with the measured salinity (Figure 2). Also indicated is the salinity/δ^3He plot from the surface to 800 m for the open ocean outside the atoll. This δ^3He/salinity relationship suggests the mixing of two end-components : a) tropical surface waters (TSW) with δ^3He values between -2.2 % and -1 % and salinity between 36 ‰ and 36.5 ‰ and b) deeper waters of lower salinity and higher helium-3 content. The

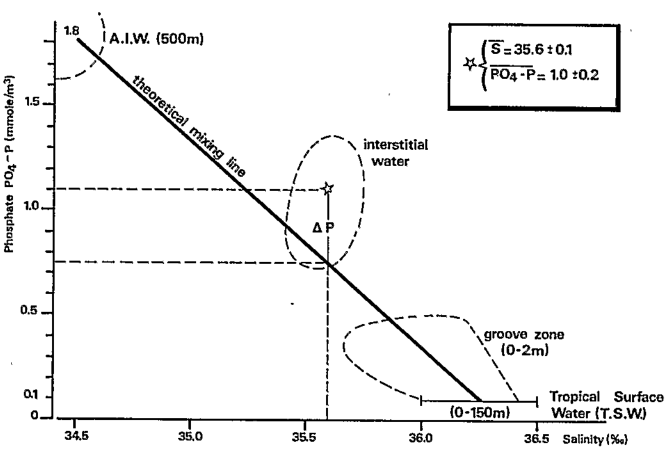

Fig. 1.1. Inter-relation between salinity and dissolved phosphate concentration in AIW and tropical surface water (TSW). Interstitial water salinity averages 35.6 ‰ between 10 and 30 meters depth. At this salinity, the measured mean PO_4 concentration of 1.1 mmol/m^3 is in excess compared to the theoritical value obtained through the mixing line AIW/TSW (0.75 mmol/m^3). Interstitial water salinity is stable (unchanged by precipitation, evaporation or biological processes) within the matrix.

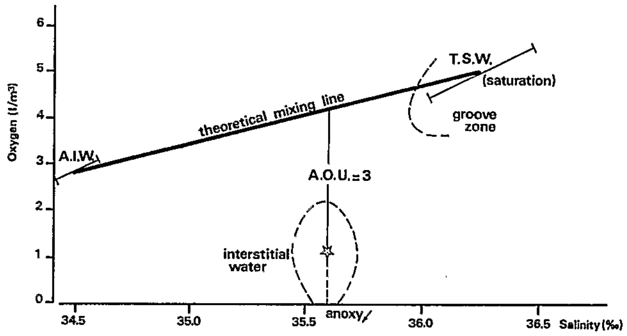

Fig. 1.2. Inter-relation between salinity and dissolved oxygen concentration in AIW and TSW. Interstitial borehole water characteristics average 35.6 ‰ for salinity and 1.2 l/m^3 for dissolved oxygen content. At this salinity the theoritical mixing line indicates that the oxygen concentration should be 4.2 l/m^3. The apparent oxygen utilization (AOU) of 3.0 l/m^3 can reflect the "in situ" biodegradation of organic matter, a process able to release the 0.35 mmol/m^3 of excess inorganic phosphate (Figure 1.1).

TABLE 2.
δ^3He data for borehole and open ocean waters (accuracy ± 0.3 %). For the borehole samples, the Δ^4He values (^4He excesses relative to the solubility equilibrium concentrations in %) and the $^3He/^3He_{sol}$ ratio (absolute ^3He content divided by the solubility equilibrium ^3He) are given, too.

boreholes				open ocean	
depth m	δ^3He %	Δ^4He %	$^3He/^3He_{sol}$	depth m	δ^3He %
12	-0.15	5.2	1.050	0	:
12	0.42	3.8	1.081	:	:
20	1.00	4.7	1.057	:	-2.2
20	0.70	5.7	1.064	:	to
28	2.15	1.2	1.046	:	-1.0
30	2.50	-	-	:	:
				150	:
				400	2.5
				600	5.3
				800	10.8

characteristics of this end member are defined by the intersection between the mixing line and the oceanic salinity/δ^3He diagram : they correspond to the upper AIW with a salinity of about 34.5 ‰ and δ^3He ranging between 8 % and 10 %.

From the oceanic δ^3He profile, this corresponds to a "recharge" depth of about 700-800 m for the oceanic waters penetrating the atoll which is in good agreement with the nutrient data discussed above.

Our interpretation of Figure 2 relies on the assumption of a conservative behavior of ^3He. In fact, there could be two possible additional sources of helium-3 in the system :

a) - "geothermal" helium-3 which might be added on the way from the underlying bedrock (with positive or negative δ^3He, depending on its mantellic or crustal origin). In such a case, one can determine the hydrothermal component from the plot of the absolute ^3He concentrations against the ^4He excesses (Table 2) : the linear slope of the function plotted represents the isotopic ratio of the additional helium. This situation is usually encountered in water column helium data close to hydrothermal vents [Lupton and Craig, 1981]. In our data, the isotopic ratio of the added helium (responsible for the slight Δ^4He excesses - see Table 2) simply corresponds to some atmospheric air incorporated to the sample during the sampling procedure.

b) - tritiumgenic helium-3 : our salinity data indicate that the sampled pore waters are more than 75 % near surface ocean waters. Those waters have a significant although low tritium content (1.6 TU at Geosecs station 326, 14°3 S - 126° W, 1974) [Ostlund et al., 1987]. Isolation of this water from the atmosphere could result in accumulation of helium-3 produced by tritium decay. The magnitude of this ^3He signal depends on the history of the tritium oceanic surface concentration over the last 30 years and on the velocity of the fluid convection inside the reef (in the range 0.01 m/d - 1 m/d) [Rougerie and Wauthy, 1986, 1990]. From the available tritium data [Ostlund et al., 1987], we think that this contribution is most likely of the order of δ^3He = 0.5 %. Therefore, we believe that our conclusions are not

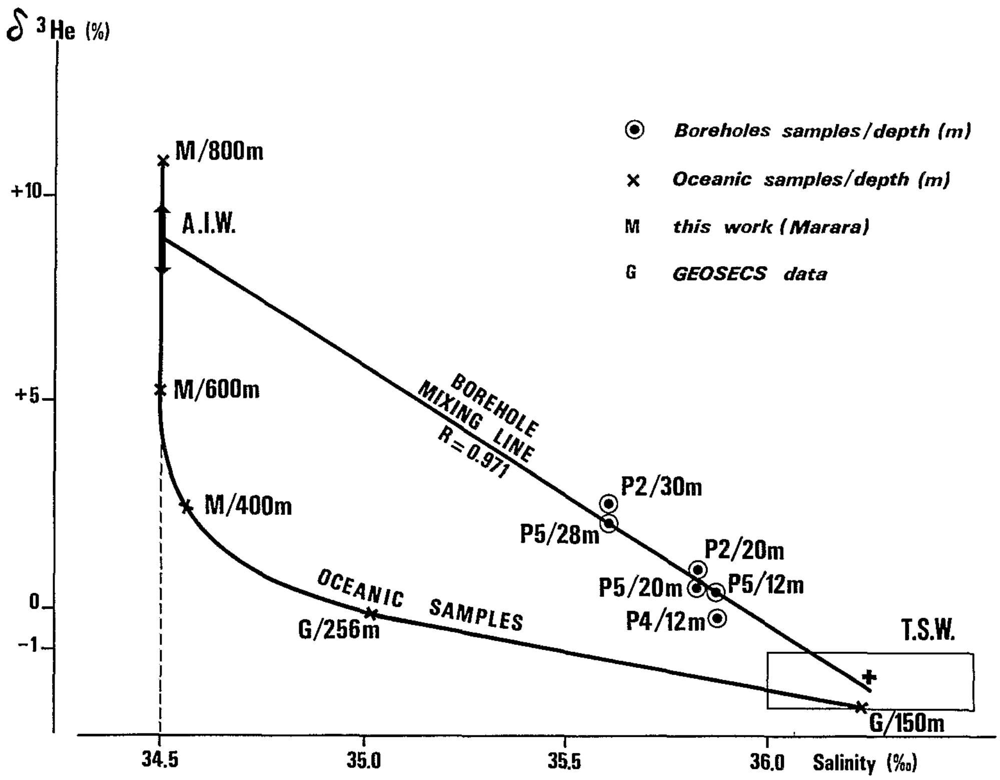

Fig.2. Helium-3 versus salinity between AIW and TSW. Oceanic samples show negative δ^3He values close to the equilibrium atmospheric value in TSW (the 0-200 meters depth layer above the thermocline) and positive value below. Values in boreholes agree remarkably well with the theoritical AIW/TSW mixing line. This result can only be explained by AIW upward (or endo-upwelled) flow through the reef limestone. GEOSECS data are from Station 326 (14°3 S-126°W) ; 20/05/1974) [Ostund et al., 1987].

significantly affected although the estimated "recharge" depth of 700-800 m may be slightly overestimated. Future measurements will include deeper sampling levels (where the tritium effect will be totally negligible) and will bring a clear answer to that question.

Implications of results

Our helium-3 data give evidence for the endo-upwelling mechanism and bear directly with some controversial aspects of reef history.

Reef communities and ecosystems are very complex and highly integrated with a restricted set of controlling environmental factors [Fagestrom, 1987]. The flux of near-surface interstitial water with high nutrient concentration appears to play a major role in driving the ecosystem. Therefore, it is apparent that our chemical borehole data will provide a better understanding of the detailed functions of the superficial communities as well as certain aspects of reef diagenesis [Schroeder and Purser, 1986].

The early diagenesis of deep limestones from various islands and atolls is well documented [Machel and Mountjoy, 1986 ; Aharon et al., 1984]. Dolomitization is presumed to result from the penetration of deep ocean water that is undersaturated with respect to calcite below 900 m but still supersaturated with respect to dolomite [Saller, 1984].

Geologists and biologists have engaged in a long-running debate over the origin of fluoroapatite found atop some uplifted oceanic atolls [Aharon and Veeh, 1984]. The endo-upwelling model supports recent investigations suggesting that these phosphate accumulations may have formed from diagenesis of lagoonal muds [Burnett et al., 1989] or by direct precipitation from phosphate saturated sub-lagoonal interstitial water [Rougerie et Wauthy, 1989].

Others have shown the presence of large-scale geothermally driven circulation through limestones in the Florida East Plateau [Kohout, 1965] and the West Florida continental shelf [Fanning et al., 1981]. Thermal profiles and geochemical signatures indicate that oceanic water penetrates these porous platform limestones at depths of 500-1000 m where it undergoes geothermal warming and ascent by thermo-convection. These processes function on a global scale and play major roles in carbonate diagenesis. Finally, the endo-upwelled water seeps out through the upper framework, supplying essential nutrients to the highly productive superficial algal-coral ecosystem, thus assuring its long-term survival in open oceans known for their low nutrient concentrations.

The helium-3 marker data presented here in the shallow interstitial borehole waters demonstrate for the first time the evidence of upward migration of reef pore fluids and emphasize the potential importance of the endo-upwelling as the driving mechanism of carbonate rock diagenesis, reef building and coral ecosystem growth.

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