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Chemical and tracer studies in coral reef interstitial waters (French Polynesia): implications for endo-upwelling circulation.

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Abstract

Six boreholes drilled down to 33 m in Tikehau atoll (Tuamotu) and down to 50 m in Tahiti barrier reef permitted to describe some of the main features for the composition of interstitial waters and to compare them with the surrounding ocean surface water. These interstitial waters are characterized by : a significant depletion in CFC characteristic of waters deeper than 400 m, confirming the internal upward transport of Antarctic Intermediate Water (AIW); $\delta^{18}O$ values intermediate between high Tropical Oligotrophic Water (TOW) and low AIW ones, high concentrations in inorganic nutrients with silicate concentrations increasing sharply with depth and reaching 10 to 50 times the oceanic values of TOW, high Fe and Mn concentrations corresponding with anoxic environments, $\delta^{13}C$ values of ΣCO_2 lower than in the TOW due to bacterial oxidation of organic matter; a significant enrichment in aliphatic hydrocarbons and fatty acid methyl esters which is not consistent with a downward transport of organic matter formed in the upper coral veneer of the reef; the presence of biomarkers indicative of the thermal maturation of dissolved organic matter. These observations demonstrate that interstitial waters are originating from both AIW, flowing upwards through the carbonate, and TOW entering the reef, as previously stated in the endo-upwelling concept.

Introduction

Coral reefs are considered as permeable calcareous frameworks where porosity fluctuates in a wide range due to dissolution-cementation sequences and calcification-sediment deposition processes. Submarine or aerial dissolution processes and tectonic geophysical constraints favored the formation of fractures, solution uncomformities or megaporosity voids (Buddemeier and Oberdorfer, 1986). The ensuing megaporosity network forms preferential circulation pathways which, depending on the importance of the interconnections linking the voids, can significantly enhance the potential water motion.

A wide variety of forces may be applied to the internal pore water generating a complex circulation pattern inside the basement of coral reefs. Previous hydrologic investigations focused on the structure and formation of brackish water lenses and their mixing with marine waters (Johannes, 1980; Lewis, 1987). Recent concern has been given to the hydrodynamic effect of head gradients on interstitial water (Buddemeier and Oberdorfer, 1988; Roberts et al., 1988). Head gradients, due to hydrodynamic disequilibria between the open-ocean and the lagoon, are responsible for a significant mixing of the interstitial waters with the ocean surface waters. However, such a mixing process just concerns the top layer of the reef from the surface down to no more than a few tens of meters. Less attention has been given to the density gradients and to the flow they can generate inside a reef matrix. High salinity waters, for example, was proved to migrate from the lagoon of an enclosed atoll to the open ocean through the limestone walls of the reef (Rougerie, 1983).

Furthermore, coral reefs are porous structures overlying or fringing a volcanic basement, the latter being a geothermal heat source which can generate an ascending flow due to the warming of the interstitial water (Mink, 1964; Souza and Voss, 1987). Significant progress in the understanding of these geothermally driven convective flows have mainly come from studies on Enewetak (Birch, 1956; Swartz, 1958; Samaden et al., 1985) and Mururoa (Aissaoui et al., 1986) atolls. Evidence of marine deep water intrusion into the limestone basement and significant geothermal gradients within the carbonate framework are central to the hypothesis of convective transport: Antarctic Intermediate Water (AIW) infiltrates the limestone structure below 500 m, is warmed in the vicinity of the volcanic basement and ascends through the limestone framework to the top of the reef (Rougerie and Wauthy, 1986; 1988). This process, called geothermal endo-upwelling has significant potential for explaining some fundamental geological and biological processes in coral reefs. Identification of the various sources of energy and nutrients and their respective importance for the storage and cycling of carbon is a major concern for reef scientists (Kinsey and Hopley, 1991). It is generally emphasized that natural variation in coral reef geomorphology makes it unlikely that a single theory will explain all aspects of reef functioning. From an ecological point of view, coral reef ecosystems seem diverse and subject to variable environmental constraints when compared one to another. Geothermal endo-upwelling could be among the most significant of these constraints controlling the ecological variability of coral reef ecosystems and thus needs to be further investigated.

Research on this topic has been initiated and pursued on different atolls and barrier reefs in French Polynesia, located in the south tropical gyre and well known as an oligotrophic area with low nutrient concentrations (PO_4 = O.2, NO_3 = 0.1 and SiO_3 = 1 mmol m^{-3}) and low gross primary production (30 gC m^{-2} yr^{-1}). Furthermore, extensive investigations in physical oceanography in this part of the Pacific (5 to 25° south) show the oligotrophic mixing layer to be more than 100 m deep and mean surface currents (under trade wind regime) to range between 15 and 25 cm s^{-1}. Such conditions yield a Reynolds number (inerty versus viscosity ratio) of less than 10, so local or regional upwellings due to eddy formation or island effect are very unlikely to occur (Rancher and Rougerie, 1992). In archipelagos of French Polynesia as well as others in the South Pacific Ocean, the occurrence of coastal upwelling or doming able to drive new nutrients upward to the algo-coral ecosystem has never been evidenced. The sole significant island effect to be recorded so far was a lagoonal effect around both high islands and open atolls (Le Borgne et al., 1985; 1989) with a net export of both dissolved and particulate material through passes (Bourret et al., 1979).

Investigation area

The South Pacific subtropical oligotrophic area is very different from other locations in the Pacific where new nutrient inputs proved to be of significant importance; these include the Australian Great Barrier Reef where tidal jets occur at the vicinity of passes (Hamner and Wolanski, 1988) or the Pacific Equatorial divergence where upwelling is generated (Wyrtki and Eldin, 1982). In the oligotrophic context of Tuamotu and Society archipelagos the permanent supply of nutrients has to be adressed. To test the endo-upwelling hypothesis, four boreholes numbered P1, P2, P4 and P5 (9-35 m deep) located on the high energy crest (surf and swell zone) and a fifth hole P3 (17 m deep) located on a pinnacle in the lagoon were drilled in November-December 1988 at Tikehau atoll, Tuamotu Archipelago (Fig. 1). In addition a deeper hole P6 (50 m deep) was drilled in April 1990 in the barrier reef of Tahiti, Society Archipelago. Results from P5-P6 and P3 will only be discussed in the present study as they are representative of undisturbed interstitial waters from coral reef barriers and protected reef, respectively. P4 (11 m deep) located close to P5 give detailed information on the top layer of the reef which are not directly relevant with the aim of the present study and P1-P2, due to the vicinity of the flat island, are subject to the disturbing influence of the fresh water lens.

Materials and methods

After recovering the sedimentary cores for geological study, the holes were fitted with polypropylene tubing for sampling the interstitial water by peristaltic pumping at various depths in each borehole. The water was analysed for temperature, dissolved oxygen, pH, redox potential and alkalinity immediately after sampling. The colorimetric analysis of inorganic nutrients (NO_3, NO_2, PO_4, SiO_3, NH_3) was done in the laboratory within a few hours of collection. Samples were stored in sealed flasks for the measurement of salinity in Tahiti. The routine determination of these parameters (nearly every two months) was complemented with the occasional analysis of metals, conservative tracers, organic biomarkers and stable isotopes. Chlorofluoromethane (CFM, F12) was analysed within a few hours of collection using the gas chromatographic method. Mg, Cd, Fe and Mn were analysed by atomic absorption spectrometry. The stable isotope compositions of water ($\delta^{18}O$) and dissolved inorganic carbon ($\delta^{13}C$) were analysed using mass spectrometry according to previously described analytical procedures (Pierre et al., 1991). Two lipid biomarker classes, aliphatic hydrocarbons (HC) and fatty acids methyl esters (FAME), were studied in dissolved organic matter using gas chromatography and gas chromatography/mass spectrometry.

Results and discussion

1 - conservative tracers : salinity, CFM (F12) and ^{18}O

Salinity is a conservative tracer giving valuable information on the origin and the mixing of water. The first observation is that interstitial salinities (Table 1) in Tikehau (35.66 ± 0.10 psu) as well as in Tahiti (35.74 ± 0.09 psu) are slightly but significantly lower compared with the open ocean surface waters (about 36.00 ± 0.10 psu). Because boreholes P5 and P6 were drilled through a barrier reef platform quasi-permanently flushed by ocean waves no mixing of meteoric water or groundwater with interstitial waters may occur. These salinities can be explained by the mixing of low salinity AIW (34.5 psu) with high salinity TOW (36.0 psu) injected inside the top of the reef by wave energy. When compared to the Tikehau situation (Rougerie et al., 1991), the higher salinity range in the Tahiti boreholes reflect a higher salinity of the TOW at the latitude of Tahiti.

Since 1940, CFC have been anthropogenically introduced in the atmosphere through refrigerants, aerosol propellants, foams, etc. They are very useful oceanic tracers because they are conservative in seawater. The CFC (F12) concentration is homogeneous (0.8 to 1.0 ± 0.1 pmol kg^{-1}) in the oceanic mixed layer from the surface down to 200 m and sharply decreases with depth becoming almost undetectable in the AIW below 400-500 m (Fig. 2). Interstitial waters show a noticable F12 deficiency with concentrations around 0.5 ± 0.1 pmol kg^{-1} in Tahiti below 30 m and around 0.2 ± 0.1 pmol kg^{-1} in Tikehau below 10 m. In interstitial waters the depletion of F12 with depth can only be explained by the input of F12-depleted waters from at least 400 m for Tahiti and 500 m for Tikehau. In Tahiti, this water penetration occurs at level corresponding to the volcanic basement. The F12 concentrations in interstitial waters are significantly higher in Tahiti than in Tikehau. This could be explained by a lower efficiency of Tahiti barrier reef in constraining the geothermal convective flow within the framework. The geology of Tikehau and Tahiti and the geomorphology of the cores yielded arguments supporting this interpretation. Tikehau atoll has experienced recent (Holocene) surrection (Harmelin-Vivien, 1985) and dolomite, which is known as carbonate with high hydraulic conductivity, was identified on the whole core from the top of the reef down to 34 m depth. In Tahiti, the Holocene-Pleistocene transition is laying at about 35-40 m depth (Montaggioni, 1988) and down to 50 m depth the core was mainly formed of aragonite and magnesian calcite with numerous solution unconformities (Dejardin, unpublished results). Differences in F12 concentrations between Tahiti and Tikehau atoll may thus be partly explained by differences in geological structure

The heavy stable isotope of oxygen ^{18}O is also a conservative tracer of the water molecule. Surface oceanic $\delta^{18}O$ values depend on the precipitation-evaporation balance; the resulting $\delta^{18}O$-salinity relationship implies that ^{18}O variations in interstitial waters parallel the salinity ones.

A description of the origin of waters mixing inside the reef structure is given through the F12-$\delta^{18}O$ diagram (Fig. 3) where a specific distribution appears:

- from surface down to 20 m depth the interstitial waters are richer in $\delta^{18}O$ than TOW at the same depth but with the same concentration of F12. These data confirm the intensity of TOW penetration inside the upper part of the reef, the positive anomaly in $\delta^{18}O$ being due to high isotopic fractionation through evaporation in the very shallow waters above the reef.
- from 30 to 50 m depth the interstitial waters result from the mixing of shallow waters and of waters depleted in F12 coming from depth greater than 400 m : once again, the interstitial waters have no relationship with the oceanic waters of the same depth. The discontinuities in the tracer

behaviour probably result from major discontinuities in the reefal structure such as fracturation or dissolution-cementation, both inducing high porosity.

2 - Redox, pH, nutrients, metals and $\delta^{13}C$

Physico-chemical parameters are summarized in Table 1 for boreholes P3 and P5 in Tikehau and P6 in Tahiti. In boreholes P5 and P6, positive redox potential values in the first 20 m together with the presence of free oxygen confirm the turbulent penetration of aerated TOW through the outer margin of the reef. Oxic conditions progressively disappeared below 30 m marking the major influence of bacteria consuming free oxygen in the interstitial waters. In the lagoon pinnacle (borehole P3), negative redox potential and absence of free oxygen show that anoxic conditions prevails from near the surface to 17 m depth due to low wave energy.

Values of pH in the interstitial water decrease with depth, from 7.8 at the surface to 7.7 at 33 m in Tikehau and 7.6 at 50 m in Tahiti. These values are significantly lower than those from the adjacent oceanic or lagoonal waters (8.2-8.3). Such pH imply correlative changes in the chemical equilibrium of dissolved inorganic carbon with possible dissolution effect on the carbonate framework, especially inside the anoxic zone.

Nitrate plus nitrite are dominant nitrogenous species in the oxic zones where ammonium concentrations are low (1 mmol m^{-3} or less). Reducing conditions result in the disappearance of oxydized N species and a large increase in ammonium, to more than 10 mmol m^{-3} in the P6 borehole of Tahiti where strong anoxic conditions occur at depth. There is also an increase in phosphate with depth, the concentrations rising to more than 1 mmol m^{-3} below 30 m in both Tahiti and Tikehau boreholes.

The occurrence of high nutrient concentrations in coral reef interstitial waters has been extensively discussed (Rougerie and Wauthy, 1986; 1988; Rougerie et al., 1992). High nutrient load is a common feature of interstitial waters in sediments (Entsch et al., 1983; Balzer et al., 1987; Van Raaphorst et al., 1990) and coral reefs (Sansone et al., 1988) which results from the remineralization of organic matter and consumption of dissolved oxygen leading often to anoxia. Thus, the remarkable thickness of the oxic layer in the barrier reefs demonstrates that these porous structures, located in areas of high oceanic energy, are continuously splashed and invaded by highly oxygenated TOW. The data from Tahiti show that the oxic layer of about 20-30 m thick overlies a permanent anoxic layer, with a sharp transition zone where suboxic conditions occur.

In both Tahiti and Tikehau sites silicate concentration in interstitial waters increase with depth; higher silicate concentrations were measured in the Tahiti borehole. Tribble et al.(1990) measured similar high silicate concentrations in the interstitial waters from Cheker reef in Hawaii and suggest it may originate from the recycling of sponges and diatoms within the reef. However, in boreholes from Mururoa atoll, concentrations in silicate, low in the top layer of the reef, were reported to increase strongly at a depth of 450 m close to the volcanic basement (Rougerie, 1983; Rougerie and Wauthy, 1992). Furthermore, the strong difference between the silicate concentrations in interstitial waters from Tahiti barrier reef and Tikehau atoll reef are very unlikely to be accounted for by differences in sponge and diatom recycling. We suggest that the excess in silicate evidences the prior contact of interstitial waters with the underlying volcanic bed rock which lies closer to the surface (150-200 m depth) in the Tahiti barrier reef than in Tikehau atoll (Rougerie et al., 1992).

In the Tahiti borehole high silica concentrations are associated with Fe and Mn enrichments (Table 2) and discontinuities in Fe and Mn profiles coincide with the redox potential discontinuity. Similarly high concentration in both Fe and Mn are measured in P3 borehole where strong reducing conditions prevail. High level in dissolved Mn and Fe are classically observed in the pore waters of anoxic sediments (Jorgensen, 1983). However, Fe concentrations largely higher than Mn concentrations are uncommon for sediment interstitial waters but have been observed in hydrothermal and volcanic environments (Charlou et al., 1991; Fouquet et al., 1991). The values reported for Tahiti borehole thus may evidence the influence of the basalt on the interstitial waters owing to the proximity of the volcanic basement. Nevertheless, such an explanation seems more critical when extended to Tikehau due to strong discrepancy between P3 and P5. Cd was undetectable in all the samples except at 50 m depth in Tahiti where average concentration was 0.23 mmol m^{-3}, well above surface or deep ocean water concentrations. A complementary source of Cd is required which could come from the contact of interstitial waters with the volcanic basement. Our first study on trace metals yielded significant information but needs to be further developped before we can reach more accurate conclusions.

The biogeochemical effects which occur in the interstitial environment are evidenced by the $\delta^{13}C$ values of the total dissolved inorganic carbon which mainly depend on the organic matter production-regeneration rates. The progressive $\delta^{13}C$ decrease with depth is variable due to the contribution of ^{13}C-depleted CO_2 from organic matter oxidation (Boehme and Blair, 1986; Alperin, 1988); these conclusions are similar to those deduced from nutrients and redox measurements. The $\delta^{13}C$-NH_4 diagram (Fig. 4) allows to precise aerobic versus anaerobic oxidation processes : deep Tahiti samples where bacterial sulfate-reduction is acting (H_2S emanations) are the more marked by the ^{13}C decrease and NH_4 enrichments.

3 - Organic Biomarkers

Dissolved aliphatic hydrocarbons (HC) and fatty acids methyl esters (FAME) concentrations are generally lower in the ocean than in the interstitial waters of the Tikehau and Tahiti boreholes where they increase with increasing sampling depth. This trend shows that HC and FAME inputs from the upper coral veneer of the reef cannot account for the high contents found in the deep interstitial waters. In the near-surface levels contribution of autochtonous biological sources (algal-coral system) is evidenced by relatively high concentrations and by the presence of polyunsaturated FAME and short chain odd-carbon numbered n-alkanes. Furthermore, in these levels the abundance of long chain odd-carbon numbered n-alkanes indicates contribution from terrestrial higher plants. These imprints are very low in the deeper levels where bacterial inputs prevail and the n-alkane profiles point to significant early diagenetic alterations mainly induced by the bacterial activity. The latter is also evidenced by the increased values of the ratio iso+anteiso C17 FAME versus linear C17 FAME (Fig. 5) as well as by the relative abundances of branched iso and anteiso n-alkanes. The presence of a series of pentacyclic triterpanes with a thermodynamically stable 17α-21β configuration and a 22S-22R epimerization revealed that the organic matter has undergone thermal maturation processes. Such processes may have occurred in the deeper framework of the reef due to geothermal activity over geological time. The detection of maturity markers in boreholes less than 50 m deep strongly suggests that pore fluids follow an ascending movement from the volcanic basement up to the top, leaching mature organic matter probably trapped in the carbonate framework.

Conclusions

Some of the parameters reviewed in this paper provide significant evidence that interstitial water of coral reefs originates from deep ocean water infiltration. Such signatures of deep oceanic origin in the upper few tens of meters of the reef indicates that convective transport of interstitial water occurs in the core of coral reef carbonate framework and in the underlying aerial volcanics (Fig. 6). The implications resulting from this upward convective flow, conclusively reported to be a geothermally driven mechanism (Samaden et al., 1985), are diverse and depend on both the petrology of the substrates and the speed of the water flow passing through it.

There is a growing knowledge of the role of thermo-convective process in geological cycling and diagenetic processes such as carbonate dolomitisation (Saller, 1984; Aharon et al., 1987; Wilson et al., 1990), phosphate accumulation in atoll in the form of insoluble fluoro-apatite (Bernat et al., 1991) or anomalous natural radioactivity of atolls in the Pacific (Whitehead, 1991).

The endo-upwelling concept has generated some controversy in the marine biology community. It appears to conflict with other recent works which considered net production in whole-reef budgets to be very low, indeed close to oligotrophic ocean net production (Crossland et al., 1991). This implies that coral reefs mainly rely on very efficient nutrient recycling (Smith and Kinsey, 1988). Both endo-upwelling and recycling are not mutually exclusive processes but the recycling of organic matter must be associated with new nutrient inputs which cannot be fully provided by the oligotrophic ocean. The net productivity of reefs yields production versus respiration ratios (P:R) ranging between 0.5 (decaying) and 5.5 (highly productive) (Hatcher, 1990). Part of this variability can be accounted for by the fact that these studies have been conducted on very different parts of the reef from the reef flat to the lagoon. Studies dealing with the first ten meters of the outer rim have been rarely attempted because of practical difficulties related to high wave energy (Hamner and Wolanski, 1988) and are imperatively required if a realistic estimate of whole reef production is to be determined. Measurements made in inner reefs, patch reefs and pinnacles are easier to do but they neglect the most productive part of the reef for which the respective importance of the different nutrient sources must be clarified.

Whether endo-upwelling is primarily of geological or biological importance depends on the intensity of the convective flow. Future investigation on the topic will focus on the direct quantification of this flow as well as on a better discrimination of the signal of the deep water origin using deeper drillings. We hope that these new steps in our research on convective interstitial water transport will provide valuable documentation on the upward flow rate and of its subsequent impact on diagenetic processes and biogeochemical cycling in coral reefs.

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Table 1 - Average (top), standard deviation (middle) and data number (bottom) values for the physico-chemical parameters of interstititial waters from Tahiti barrier reef P6 (from May 1990 to January 1992), Tikehau atoll reef P5 (from March 1989 to January 1992) and Tikehau pinnacle P3 (from February 1989 to January 1992). Nutrient concentrations in mmol m^{-3}, pH in pH units, salinity (S) in psu and redox potential (Eh) in mV.

	TAHITI P6					TIKEHAU P5				TIKEHAU P3		
Z(m)	1	5	20	30	50	11	19	27	33	4	10	17
NO_2	0.14	0.10	0.12	0.21	0.10	0.13	0.13	0.31	0.12	0.11	0.17	0.29
	0.09	0.04	0.08	0.06	0.05	0.13	0.10	0.33	0.17	0.11	0.11	0.17
	15	15	15	15	30	36	36	35	35	33	34	34
NO_2+NO_3	2.63	1.47	1.20	0.16	0.09	3.37	2.45	3.74	1.07	0.27	0.18	0.29
	1.53	1.43	0.97	0.06	0.05	1.41	2.07	1.49	1.57	0.42	0.11	0.18
	15	15	15	15	30	36	36	35	35	33	34	34
NH_4	1.00	1.71	0.82	11.55	10.04	0.32	1.13	0.43	1.65	5.24	6.75	7.62
	0.84	1.03	0.80	3.94	3.72	0.27	1.35	0.40	1.05	2.71	1.87	1.82
	14	15	14	15	30	30	32	27	31	28	30	30
PO_4	0.75	0.91	1.17	1.63	2.23	0.49	0.68	0.72	1.16	1.00	1.01	1.08
	0.15	0.29	0.59	0.28	0.56	0.21	0.24	0.26	0.42	0.40	0.32	0.29
	15	15	15	15	30	36	36	35	35	33	34	34
SiO_3	17.27	21.79	22.13	63.40	80.53	3.38	4.74	5.90	7.21	1.64	1.96	2.90
	6.12	5.71	3.38	10.55	8.68	2.39	2.64	3.39	2.50	0.73	0.79	0.90
	15	15	15	15	30	36	36	35	35	30	31	34
pH	7.83	7.75	7.72	7.61	7.63	7.76	7.74	7.73	7.72	7.70	7.56	7.55
	0.19	0.17	0.09	0.12	0.12	0.09	0.09	0.09	0.10	0.14	0.11	0.13
	8	9	9	9	18	36	36	35	34	32	34	34
S	35.82	35.73	35.74	35.78	35.74	35.83	35.76	35.69	35.66	35.69	35.95	35.99
	0.16	0.12	0.11	0.07	0.09	0.22	0.21	0.22	0.10	0.26	0.10	0.09
	15	15	15	15	30	34	34	33	33	33	34	34
Eh	+216	+156	+105	-133	-124	+110	+92	+121	+44	-121	-154	-167
	20	75	99	27	20	85	98	88	122	97	34	22
	14	14	14	14	27	19	18	17	18	16	17	16

Table 2 - Trace metals (May 1991, n=2) and average redox potential (see Table 1) in the interstitial waters from Tahiti barrier reef (P6), Tikehau atoll reef (P5) and Tikehau pinnacle (P3).

		Z	Fe	Mn	Cd	Eh
		(m)		(mmol m^{-3})		(mV)
Tahiti	P6	1	0.29	0.02	<0.01	+216
	P6	5	0.59	0.05	<0.01	+156
	P6	20	1.49	0.05	<0.01	+105
	P6	30	28.02	0.09	<0.01	-133
	P6	50	6.16	0.15	0.23	-124
Tikehau	P5	11	<0.02	<0.02	<0.01	+110
	P5	19	<0.02	<0.02	<0.01	+92
	P5	27	<0.02	<0.02	<0.01	+121
	P5	33	0.20	<0.02	<0.01	+44
	P3	4	5.71	<0.02	<0.01	-121
	P3	10	12.12	0.40	<0.01	-154
	P3	17	8.95	0.25	<0.01	-167

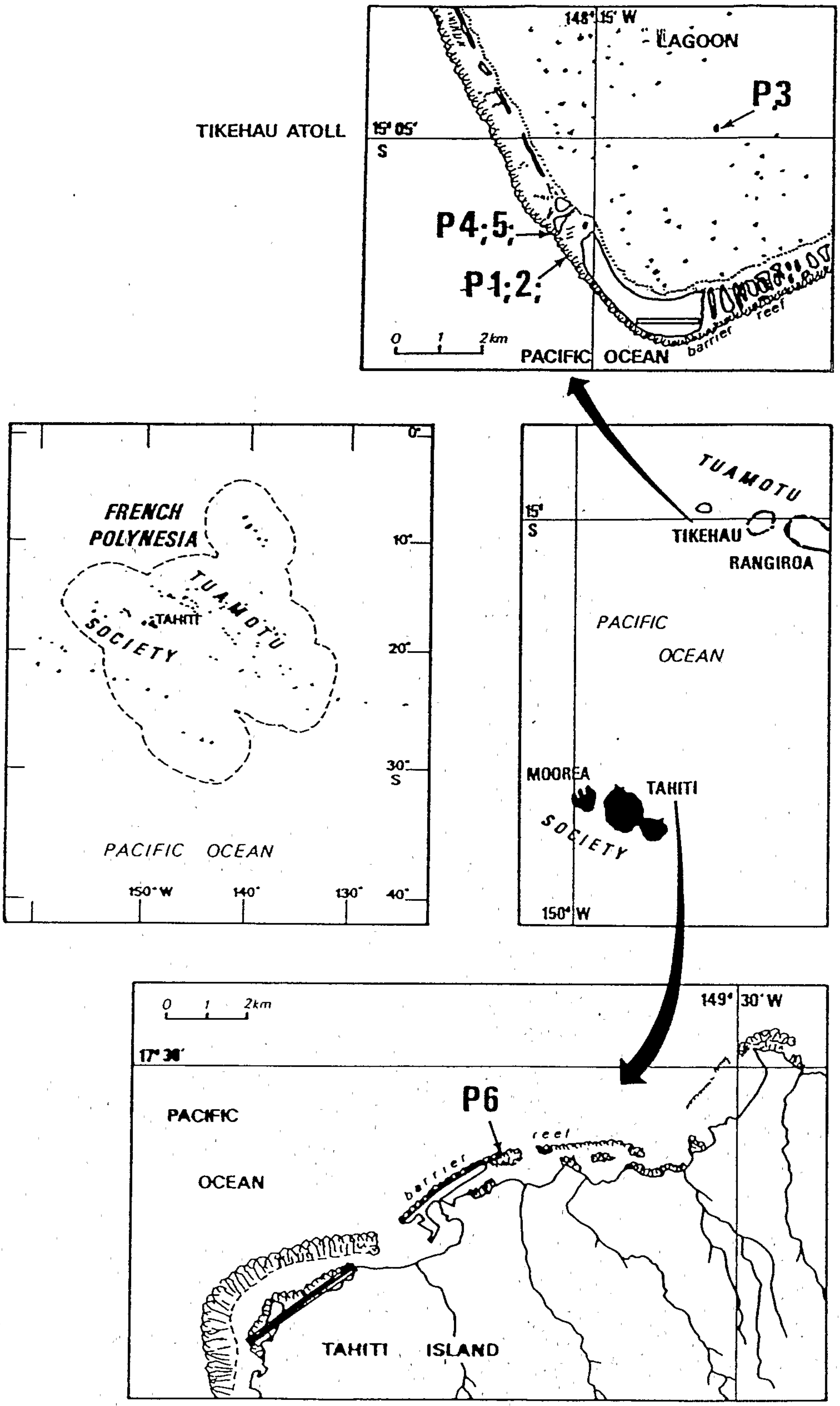

Figure 1 - Location and borehole sites for Tikehau atoll (top) and Tahiti barrier reef (bottom). Data for the present study are mainly from Tikehau P3 and P5 and Tahiti P6.

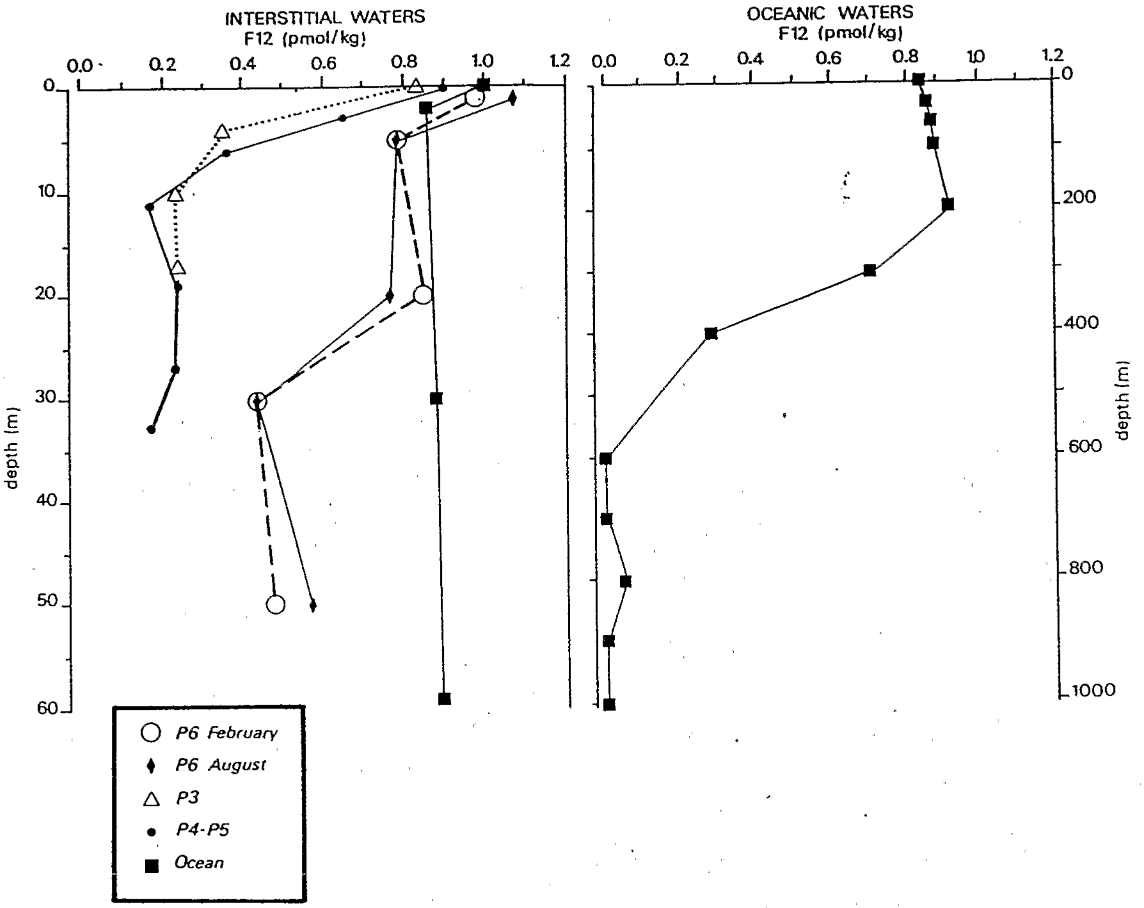

Figure 2 - Vertical F12 profiles for Tikehau (P3 and P5) and Tahiti (P6) interstitial waters and for the surronding ocean. For comparison the oceanic profile down to 1000 m has been plotted on a different scale. Natural variability was ±0.1 pmol kg^{-1} for interstitial waters and ±0.01 pmol kg^{-1} for oceanic waters.

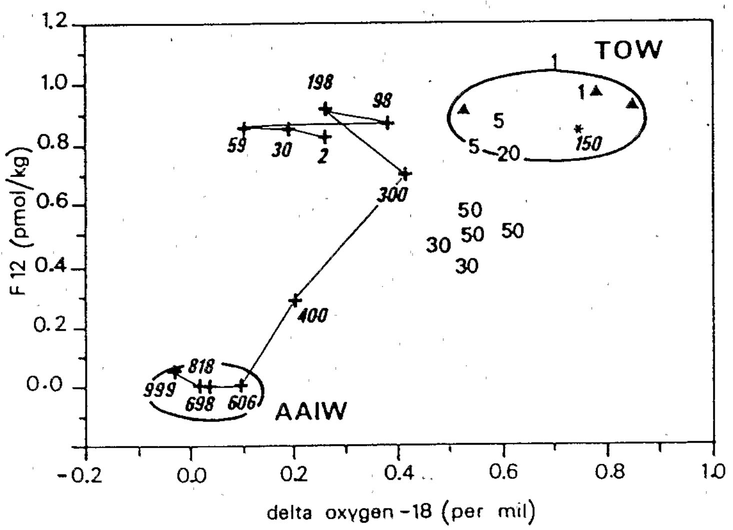

Figure 3 - F12-δ^{18}0 diagram for february and august 1991 with mention of sampling depth in the Tahiti borehole (P6) and the surronding ocean. (+) identifies data from a typical oceanic profile from the surface to 999 m depth, (*) identifies average values for waters from the salinity maximum at 150 m depth, (▲) identifies values for oceanic waters sampled on top of the reef and experiencing strong evaporation, depth values plotted alone identify data from borehole P6. Circles represent the scattering of values for Tropical Ocanic Water (TOW) and Antarctic Intermediate Water (AIW).

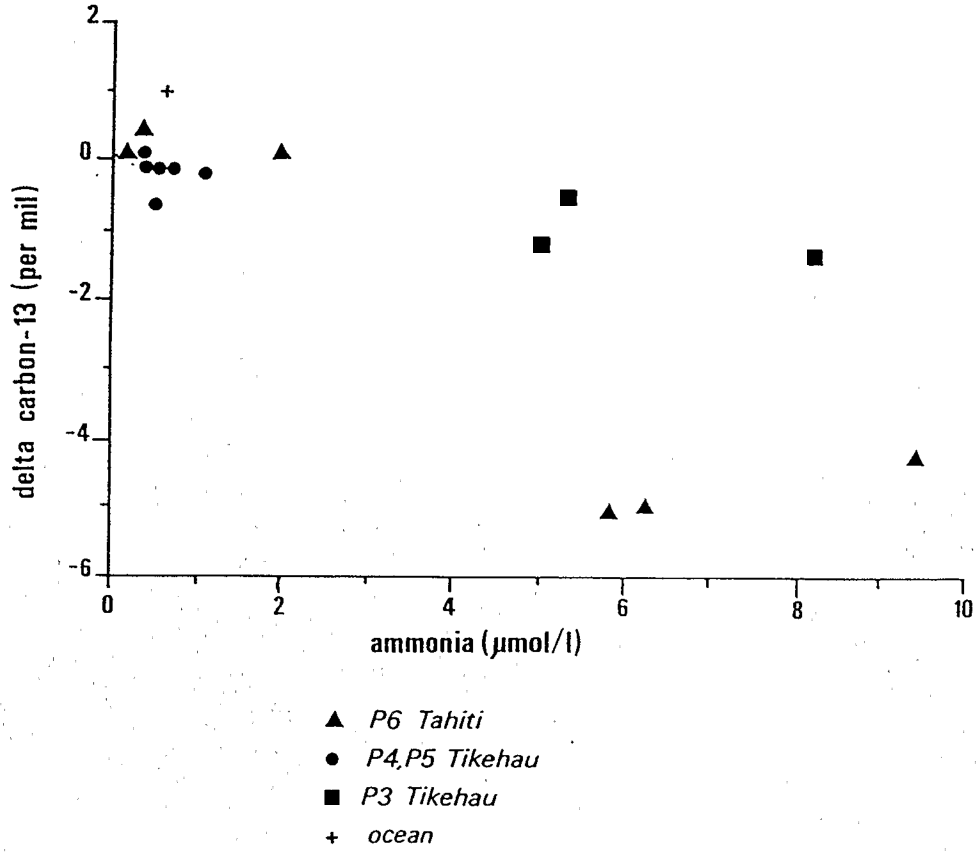

Figure 4 - $\delta^{13}C$-NH_4 diagram for interstitial waters from Tahiti P6 and Tikehau P3-P4-P5 boreholes; the surface oceanic reference is also plotted for comparison.

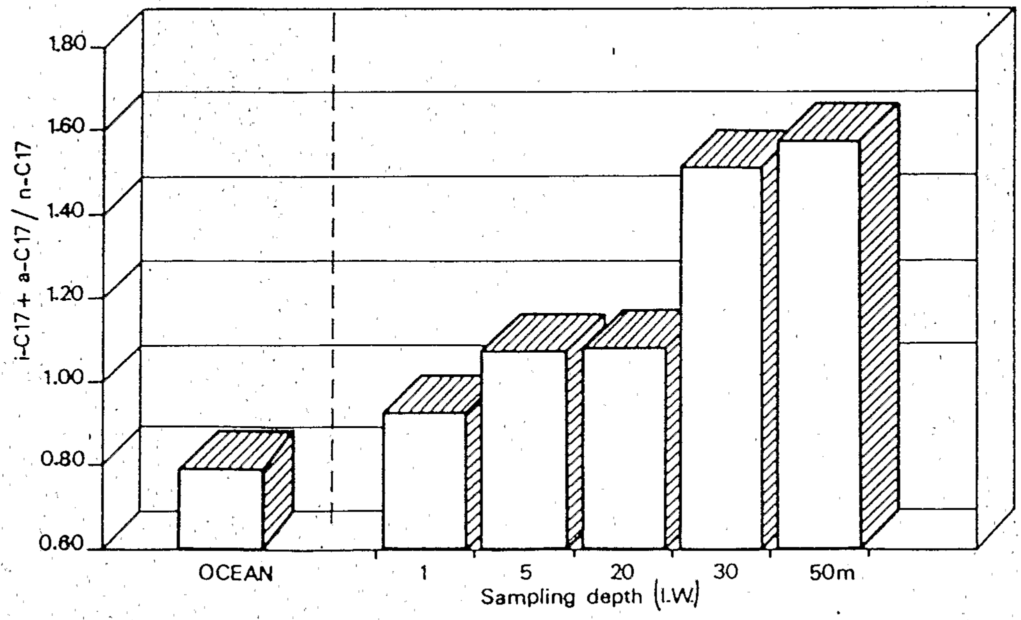

Figure 5 - Ratio for iso+anteiso C17 FAME (fatty acid methyl ester) versus linear C17 FAME at different depths in Tahiti interstitial waters (P6) and at the surface of the ocean.

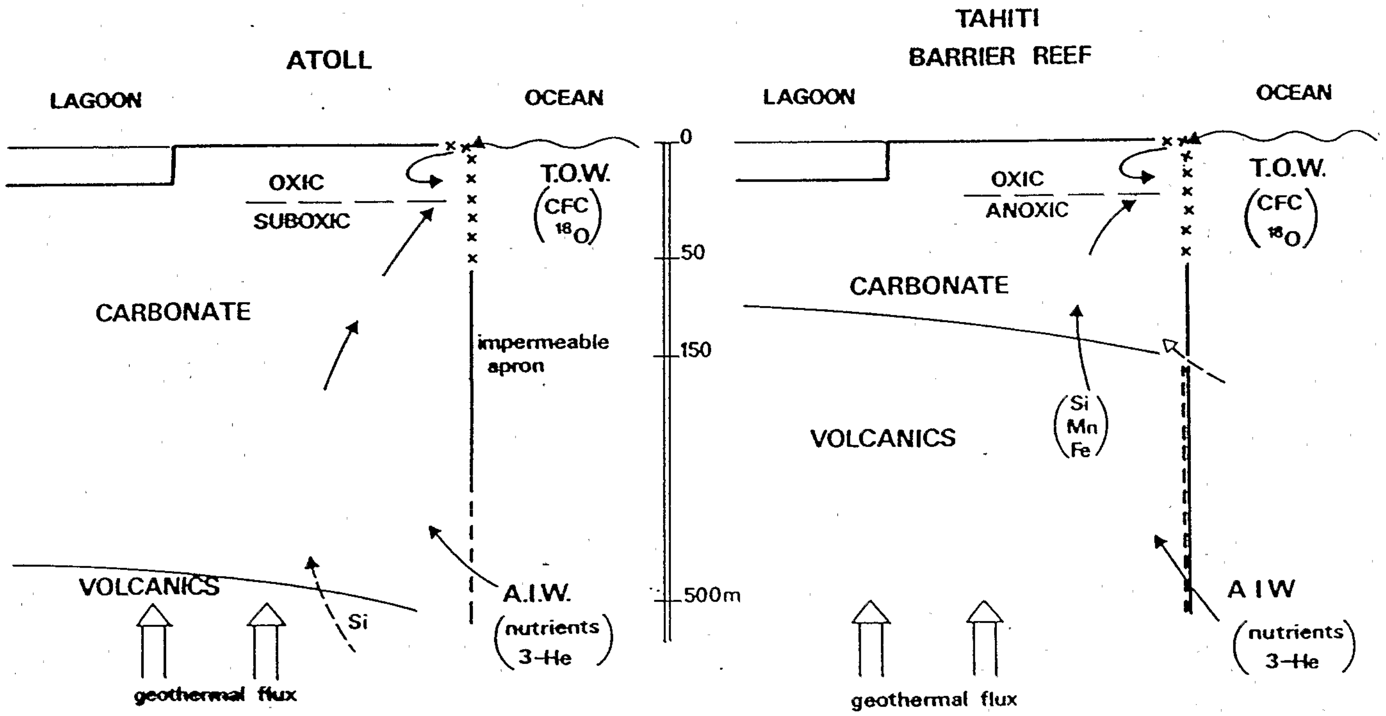

Figure 6 - Alleged circulation and chemical exchanges inside atoll and barrier reef as infered by conservative tracers (salinity, ^{3}He, CFC, trace metals and stable isotopes). Convective upward transport from Samaden (1985) and Rougerie and Wauthy (1986) for carbonates and from Mink (1964) for volcanics.