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Coral Reefs

The endo-upwelling concept: from geothermal convection to reef construction

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Abstract. Measurements of interstitial waters in deep wells (0–500 m) in Mururoa and in shallow bores (0–35 m) in Tikehau (French Polynesia) have shown high contents of dissolved nutrients and relatively low salinities, implying a deep oceanic origin. Studies of specific thermal fields within these atolls and carbonate platforms have led to models of deep oceanic water circulation by convection resulting from upward geothermal heat flow. Cold, low-salinity, low-pH, high-CO_2, nutrient-rich deep oceanic water pervades the permeable atoll, where it loses density by heating related to geothermal heat flow, subsequently rising to seep out through the outer rim. New nutrients are thus continuously provided, enabling the reef-building community (algae + corals) to thrive in optimal conditions for photosynthesis and carbonate precipitation. This "geothermal endo-upwelling" concept is defined and its role in atoll trophic networks is emphasized as a necessary and sufficient process for reef net production and organic matter exportation. The endo-upwelled flow can then be viewed as a key factor for internal diagenesis, as early cementation of reef framework and dolomitization of deep limestone. Generalization of this interstitial, deep seawater circulation is discussed and linked to previously described thermal convection models in Florida or raised atolls.

Introduction

A series of 75 atolls situated in the Central South Pacific make up the Tuamotu archipelago, which is oriented

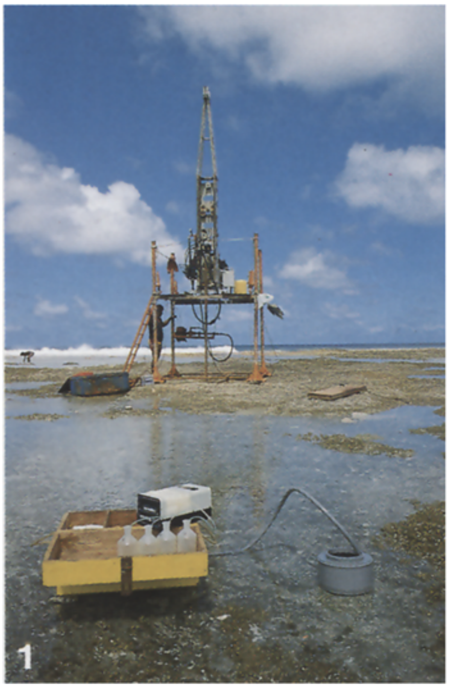

Fig. 1. Drilling on the barrier reef of Tikehau Atoll (Tuamotu) (December 1988 to March 1989) by ORSTOM team led by Dr. F. Rougerie. *Foreground* 30-m-deep hole has been permanently fitted with a four channel polythylene hose; sampling is by peristaltic pump with 100 ml/min flow rate. Dissolved nutrients O_2, pH, salinity, alkalinity are measured in the ORSTOM facility on this atoll. *Background* Drilling of a second hole, 3.5 cm in diameter, closer to the outer algae-coral rim of the barrier reef. These operations are performed as a tentative validation of the geothermal endo-upwelling process and are financially supported by ORSTOM (TOA Department) and INSU/CNRS (France)

Fig. 2. Drilling of a 50 m hole through north Tahiti barrier reef in April 1990. This hole has been fitted with polytubes, enabling easy peristaltic pumping of interstitial water at 6 different levels

Fig. 3. Atoll reef flat with the groove and spur zone. The huge productivity of the algae-coral crest is sustained by the seepage of the endo-upwelled flow, CO_2 and rich nutrients. Organic calcification and early cementation constitute the biological and geochemical signals of this low-energy hydrothermalism process

along a southeast-northwest axis. Each atoll consists of an annular coral reef rim bearing one, or several, flat islets (motus) some meters above sea level. The enclosed lagoon, often with disseminated reef patches and pinnacles, may communicate with the ocean through one or several passes. The atoll is covered on its oceanic side by spectacular growth of reef-building corals, algae, and associated benthic populations which are constantly impacted by waves (Fig. 3). These mechanical processes transport part of the important carbonate materials produced by the reef with a mean calcification rate of about 3 kg/m^2/year $CaCO_3$ and low net production (Gladfelter 1985). Thus, there is a constant exportation/sedimentation process toward the lagoon, the finest particles reaching its central parts (Chevalier et al. 1969), and also along the outer reef slope by gravitational processes. Sedimentation controls permeability: the finest sediment tends to obscure reef pores, lowering permeability. Thus, the bottom of the lagoon may be expected to have low permeability, with the exception of particular localities with thriving pinnacles and fringing reefs. In contrast, on the outer rim, wave action and oceanic flushing prevent accumulation of fine particles. Reef plate and forereef slope sediments tend to be highly permeable, although lithified, while lagoonal sediments are both fine-grained and unconsolidated. The outer slope is largely protected by cements, forming an impermeable carapace that reduces the input of surface oceanic water (Atkinson and Davies 1984).

The permeability of limestone and dolomite forming these atolls varies from 1 mDa to 30 mDa, while the volcanics of the basement have permeabilities of less than 1 mDa. Carbonate porosity, which ranges from mini- to megapores, averages 30%, enabling large volumes of interstitial water to saturate the framework. Unfortunately, relatively little research has been devoted to the study of internal fluids in atolls (Oberdorfer and Buddemeier 1986), mainly because of logistic difficulties.

Interstitial water properties of reefs in the Tuamotu Archipelago

Tikehau Atoll (15° S, 148° W)

Four wells, ranging in depth from 9 to 37 m, were drilled on the Holocene reef flat of Tikehau Atoll (Tuamotu) in 1988 (Fig. 1). Drilling sites were close to the ocean, being approximately 30 m from the algal ridge; elevation above sea level is about 10 cm during calm weather, but during high tides or surges, 10–50 cm of oceanic waters cover this platform, filling the lagoon from which excess water flows out through a western pass. Polyethylene tubings were inserted, each consisting of four 3-mm internal diameter tubes enclosed in a 2-cm-diameter PVC external hose. Following insertion, coral sand was poured into the remaining space to reduce vertical mixing of interstitial water. Screening at three or four differents levels facilitated sampling with peristaltic pumps powered by 12-V batteries. The cores whose retrieval rates reached 100% were sent to the University of Paris-Orsay (B. H. Purser) for dating and study. These cores exhibit numerous millimeter- to centimeter-sized vacuoles.

Water sampling was performed with flow rates of 50–150 ml/min. Dissolved oxygen and pH were measured directly (under an umbrella) using specific electrodes. For other parameters three plastic bottles of 100-ml capacity were filled for each specific depth, stored in a dark icebox and rapidly transported to a small field laboratory in the atoll village. Salinity was measured with an Autolab salinometer (Sydney, Australia) and nutrients with a Yvon Hitachi spectrophotocolometer (Tokyo, Japan), according the methods defined by Aminot and Chaussepied (1983).

Data from successive sampling series (December 1988 to April 1989) are presented in Table 1.

Excessively high content of dissolved inorganic nutrients appeared to be an important property of these in-

Table 1. Characteristics of interstitial waters (averages of values recorded in wells II, IV and V on the Barrier Reef, wells I and III being polluted to 10 m with fresh meteoric water accumulating under the emerged motu). Other data from Tikehau Lagoon and adjacent ocean; *n*, number of data

Depth	Salinity	Nutrients						Total Alkalinity	
Z	S	O_2	PO_4-P	NH_4-N	NO_3-N	SiO_3-Si	pH	(Eq/m³)	*n*
(m)	‰	l/m³	mmole/m³						
4	35.4	1.7	0.81	0.5	3.8	5.1	7.82	2.33	6
12	35.3	1.3	0.92	0.3	3.4	6.5	7.85	2.28	12
30	35.4	1.4	0.88	0.2	5.6	8.8	7.81	2.25	12
Lagoon									
0–20	36.0	5.6	0.15	0.5	0.2	0.8	8.45	2.40	10
Ocean (vicinity of the atoll)									
0–50	36.0	5.4	0.05	0.1	0.1	0.7	8.42	2.43	4
500	34.8	3.6	1.0	0.1	10.0	10	8.00	2.34	4

terstitial waters: reactive silicate and inorganic nitrate values reached 10 times those in either lagoonal or oceanic surface waters. Dissolved inorganic phosphate in interstitial waters is about 6 times that in lagoonal water and 10 times that in the oligotrophic waters in the vast South Pacific central gyre surrounding Tuamotu Archipelago (Wauthy 1986). The dissolved oxygen content is lower than in the open surface systems that surround the reef, being somewhat above 1.0 l/m³, which may be interpreted as indicating internal consumption of oxygen within the framework, possibly by the classic mechanism of oxidation/remineralization of detritic organic matter. However, two aspects must be considered: first, endogenic production of nutrients as important as those measured in these interstitial waters would have totally exhausted the original oxygen, the saturation level being 4.5 l/m³ at 28° C; second, if nitrate was produced locally by in situ remineralization, the intermediate steps of lower state oxidation would have been detected: neither NH_4 nor NO_2 was observed to exceed the 0.5 mmol/m³ level. Measurements made within the surge channels on the outer flat rim of Tikehau Atoll indicated nutrient concentrations somewhat higher than those in adjacent oceanic waters. The 0.2–0.4 mmol/m³ in dissolved phosphate found in these grooves tend to support the concept of interstitial water seeping out at these particular localitions, permanently "swept" by high-energy waves.

The Tikehau Atoll case is clearly different from that described in Oahu (Hawaii) by Sansone et al. (1988), where biogeochemical measurements have demonstrated the existence of nutrient-rich but oxygen-depleted interstitial water within the first few meters of Checker Reef; inside this rather sandy reef, which is situated close to the volcanic shore of the high island and not strongly affected by oceanic energy, oxygen is totally absent, and ammonia is the predominant, if not the exclusive, nitrogen molecule. This type of reef where reducing conditions are a logical consequence of high sedimentary organic input and relatively low permeability, is quite different from a highly porous reef that is constantly flushed by clear oceanic waters.

In Tikehau Atoll the discrepancy between interstitial and lagoonal/surface oceanic pH is more than 0.6 of one pH unit, which means that the dissolved $CaCO_3$ and CO_2 systems are not in ionic equilibrium. Total alkalinity and salinity are 0.1 Eq/m³ and 0.6‰ lower, respectively, within the reef mass in which the rainfall/evaporation budget can be ignored. As salinity is not altered by biological processes we can utilize this stable parameter as a reference against which the possible origin of this interstitial water can be discussed. In the open ocean around atolls, as everywhere in the tropical South Pacific, salinity decreases from subsurface maxima of around 36.2‰ down to 600 m, where Intermediate Antarctic Water reaches a minimum salinity of 34.5‰. Thus, water sampled below 400 m will have a salinity ≤ 35.5‰ and relatively high nutrient content, which is the main property of this deep water. As indicated in Table 1, there is close agreement between the properties of deep oceanic water and near-surface interstitial waters. The question, therefore, concerns the nature of the mechanism that would allow deep oceanic water to reach the top of the atoll. We will attempt to find an answer in the extensive series of data and results already published.

Mururoa Atoll (22° S, 139° W)

In this atoll, deep wells penetrate to volcanic basement at minimum depths of 180 m. Specific interstitial water samples were collected from these wells in 1980–1981 and 1986–1987, and chemical and nutrient contents evaluated using classic oceanographic methods.

During the first period, sampling was effected by means of PVC hydrological bottles with "messengers" dropped down a steel wire: data from nine wells, each with two stations, and from ten sampling levels from surface to 500 m depth, give a sound basis for definition of the general properties of the interstitial column (Rougerie et al. 1984). In 1986–1987, sampling was by peristaltic pumping from polyethylene tubes permanently fitted in five wells. Five complete series of interstitial waters from eight levels were analyzed, and the results were found to be in good agreement with previous measurements. These data, together with oceanic stations measured around Mururoa Atoll, have been combined and are expressed as vertical profiles in Fig. 4.

The most striking attribute shown by this set of data concerns the high amounts of nutrients within the interstitial waters, down to volcanic basement situated at betweeen 350 and 500 m according to well position. Within the reef, vertical nutrient gradients always increase from

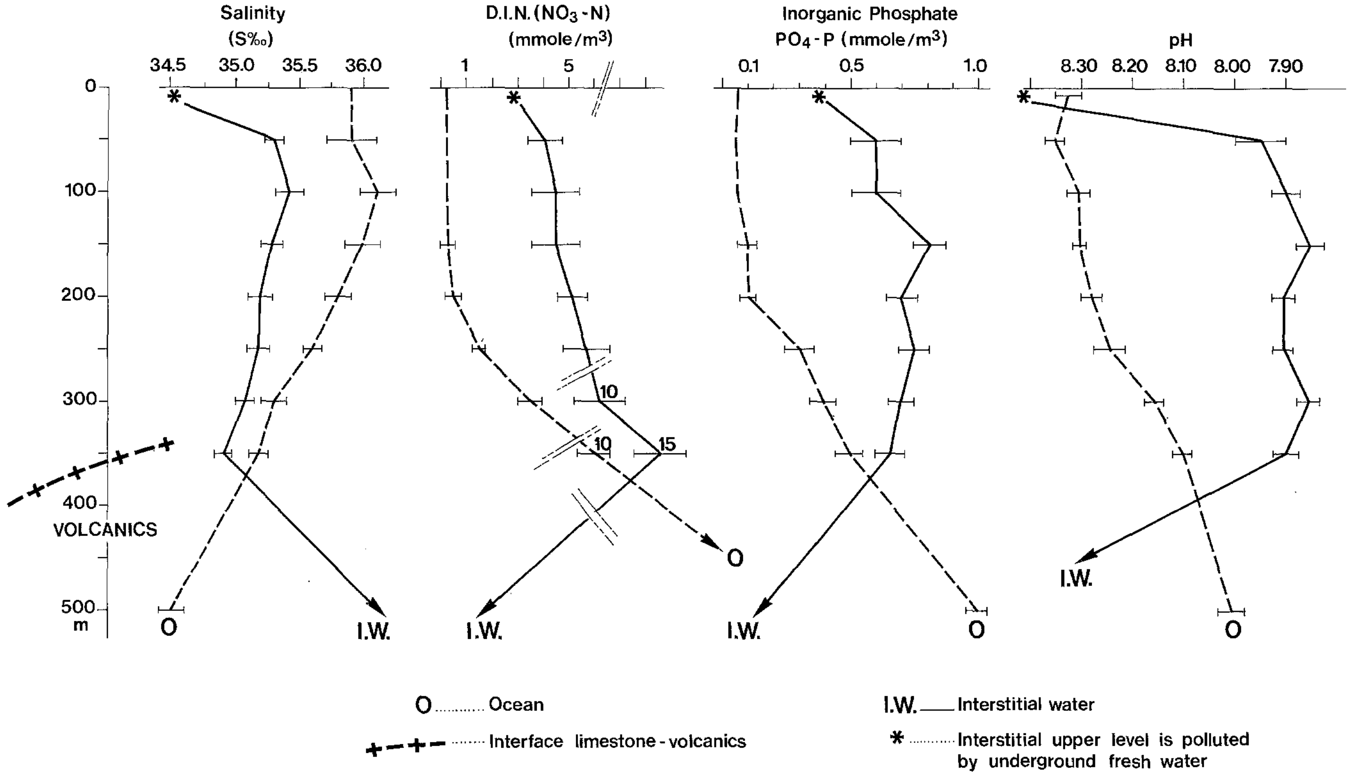

Fig. 4. Vertical profiles in Mururoa Atoll showing physical properties of interstitial waters. Averaged data and standard deviation from 9 wells in 1981 and 5 wells in 1987. Oceanic data by R.V. Marara in the vicinity of the atoll: averages from five stations in 1986–1988

above down toward the basement zone: concentrations of dissolved inorganic nitrate are 4 ± 0.8 mmol/m^3 in the upper part and reach 15 mmol/m^3 at 350 m depth. The trend is the same for phosphate and, particularly, for silicate, which ranges from 10 in near-surface waters to more than 60 mmol/m^3 at the volcanic transition zone. Although quite distinct in the upper part of the water column, interstitial and oceanic profiles intersect near 350 m, where salinity, nutrients and pH values are comparable (Rougerie, 1983). This fact can best be explained as a consequence of oceanic seawater penetrating into the limestone structure, particularly at the level of the volcanic sedimentary transition zone. From a geochemical point of view, such a movement of oceanic water can be facilited by intrinsic properties of the water present at the transition level and below, i.e., Intermediate Antarctic Water, which is known to have content a high of nutrients and CO_2 and low pH (Pytkowicz et al. 1975). These properties cause such water to be undersaturated in aragonite below 300 m and undersaturated in calcite below 1000 m: dissolution in the lower part of the limestone cap may favor water penetration into the atoll, where it subsequently flows upward; this possibility of penetration is impaired by an intense marine cementation (Aissaoui and Purser 1986) in the upper parts where surface oceanic waters have low CO_2 content, high pH and, consequently, a $CaCO_3$ oversaturation rate of 3–5. Within the volcanic basement, low permeability and porosity preclude easy penetration of oceanic water although there is some superficial alteration along the transition zone: leaching of volcanics increases the silicate content of the limestone interstitial water, this element originating both from deep oceanic water and from basaltic basement.

Another direct proof that oceanic water penetrates the limestone mass has been given by Lam (1974); from tide gauges in holes drilled some meters across the reef flat, he was able to record the oceanic tide signal, even though it was weaker and there was a time lag compared with the open oceanic system. These data sets provide key evidence of hydraulic continuity between interstitial and oceanic waters.

Thermal field

In their report on Mururoa Atoll, Atkinson and Davies (1984) present vertical thermal profiles, both in the ocean and within the atoll (Fig. 5 a): although relatively close at surface levels, these two curves diverge rapidly at depth owing to the greater negative thermal gradient of oceanic water. At a depth corresponding to the volcanic transition zone the discrepancy between the temperatures of the two systems is about 4° C. In the volcanizone the geothermal gradient reverses and becomes positive with depth, indicating the importance of this basement as a source of heat capable of warming the oceanic water penetrating the porous carbonates. It is interesting to note that the minimum on the thermal profile occurs at a depth of about 350 m, indicating that an active mechanism evacuates a large part of the heat provided by the volcanic basement: this cooling may be due to the effect

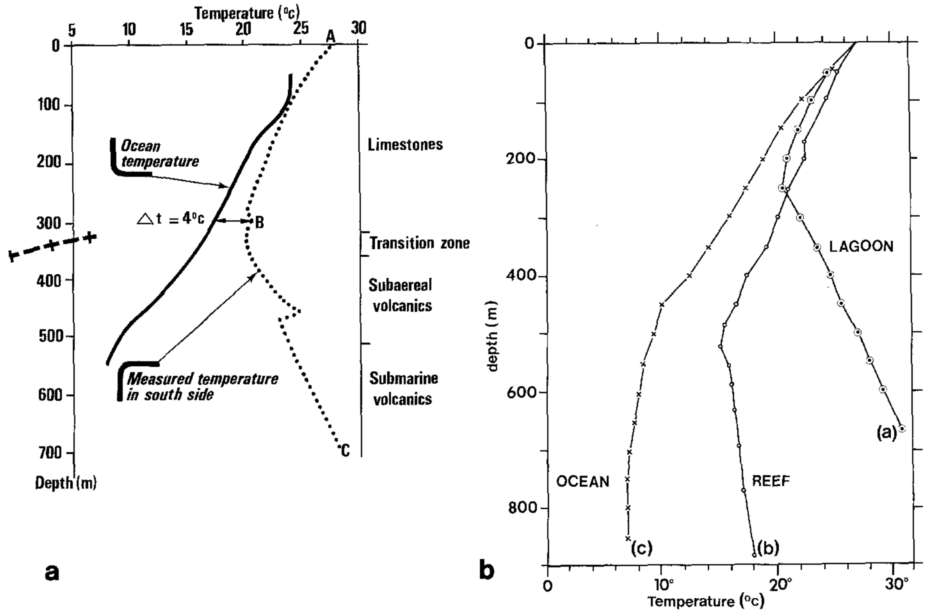

Fig. 5. a The geothermal gradient measured in well Zoé situated on the south side of the atoll, together with ocean temperature measured immediately to the south of the atoll. [From Atkinson and Davies (1984)] **b** Vertical thermal profiles in Mururoa atoll, *a* sublagoonal zone, *b* reef zone, *c* in ocean [From Caristan (1989)]

of the cold oceanic water surrounding atoll basement. Figure 5 b for Mururoa Atoll illustrates the averaged vertical profiles below the reef periphery and central lagoon zone (Caristan 1989).

Geothermal convection within porous carbonates

Atolls

Based on numerous thermal data from deep wells drilled in Mururoa Atoll, Samaden et al. (1985) have developed a model that applies satisfactorily to Eniwetak Atoll (Fig. 6) where the sedimentary sequence attains at least 1300 m along the outer flanks. This model depends on conduction and convection through the permeable atoll in order to explain the measured thermal field. The upward motion of interstitial water is driven by the pressure gradient resulting from the warming of this water at the limestone-basalt interface by geothermal flow. The atoll is idealized as a cone of porous material (isotropic or not) limited at the base (3000 m) by an impermeable surface (hot source) and on the external flanks by cold oceanic waters. Cold oceanic water enters principally between 350 and 1150 m via the external slope, notably through the layers with the highest permeability, enhanced by dissolution. The ascent of water occurs mainly in the peripheral parts, the heated water ultimately diffusing through the floor of the lagoon and, more vigorously, on the outer reef. The calculated vertical upward velocity for mean permeability is 0.4–1.5 cm/day. As noted by Caristan (1989), these basic figures, obtained from matrix computation, could be largely exceeded in view of the relatively open pore system demonstrated by Aissaoui et al. (1986) and Purser and Schroeder (1986).

Thus, oceanic seawater penetrating the porous carbonates and subsequently in contact with volcanic base-

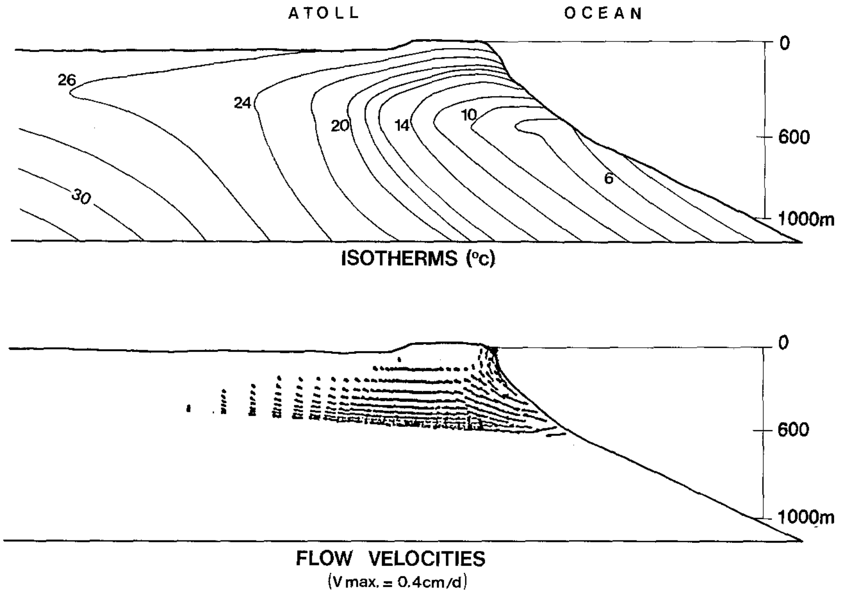

Fig. 6. Model of interstitial sea water flow (by both conduction and convection) to account for the internal thermal field of Eniwetak Atoll. [After Samaden et al. (1985) and Caristan (1989)]

ment is progressively heated. Because of the cumulative heat buildup made possible by the absence of eddy diffusion, this interstitial seawater loses density and begins to move upward: slow circulation by convection is then established within the porous material, enabling deep oceanic water to circulate toward the top of the atoll. On the whole, in their model of the internal circulation, Samaden and other French workers (Y. Caristan, personal communication) are in basic agreement with Swartz (1958), whose abstract states that:

> The close parallelism between the thermal profiles in the drill hole and the ocean leaves little question that the character of the thermal profile in the atoll is largely a result of cooling by the adjacent ocean...

In summary Swartz emphasizes that:

> The evidence presented strongly suggests that forced convection in all probability constitutes a major factor in the transfer of heat from the coral atoll to the sea.

The Florida model

In a paper published in 1965, Kohout summarizes the hydrogeology of the thick carbonate-evaporite sequence that extends from land surface to the oil horizons at depth of about 11,500 feet below sea level in southern Florida. He sets forth the few known facts concerning the hydrology of the deep water-bearing rocks and discusses a hypothesis concerning the cyclic flow of salt water related to geothermal heating in the Floridan aquifer.

Specific considerations of data and field observations drawn from these deep wells in southern Florida lead Kohout to state:

> Upward geothermal heat flow raises the temperature of the aquifer water and generates a thermal convective circulation. Eventually, the upward component of the convective circulation brings the sea water into contact with fresh water moving seaward from the karst region of central Florida.

Figure 7 depicts the flow pattern schematically. Thus, a specific internal circulation pattern relatively similar to that established for an atoll is deduced from the southern Florida thermal field. Kohout's conclusion is unequivocal:

> Cold, dense sea water in the Gulf of Mexico and the Florida Straits becomes warmer and less dense as it flows inland into cavernous dolomitic limestone. It then flows upward by convection, and after mixing with fresh water it returns to the sea by upward leakage through confining beds or by discharge through submarine springs (and seeps on the continental shelf and slope).

Discussion: the endo-upwelling concept

These various independent studies, which were not originally aimed at evaluating geothermal flux, arrive at the same conclusion: any permeable mass, such as a carbonate buildup, is easily impregnated at depth by cold oceanic waters, which are affected by a light warming owing to the geothermal effects from the underlying basement. This warming triggers a density decrease which leads to upward movement of this interstitial water. Circulation by convection is maintained as long as the geothermal heat is sustained. This process stimulates displacement of deep oceanic water toward the upper levels in atolls, supplying chemical and nutrient properties, as previously detected in Mururoa Atoll (Rougerie 1983). Such upward movement of subsurface oceanic water towards the surface is classically called "upwelling" in oceanography; we have suggested the term "endo-upwelling" (Fig. 8) to describe this geothermally driven circulation within a porous atoll (Rougerie and Wauthy 1986). Many implications of this new concept, whose schematic modeling is presented in Fig. 9, have been considered in an earlier article (Rougerie and Wauthy 1988).

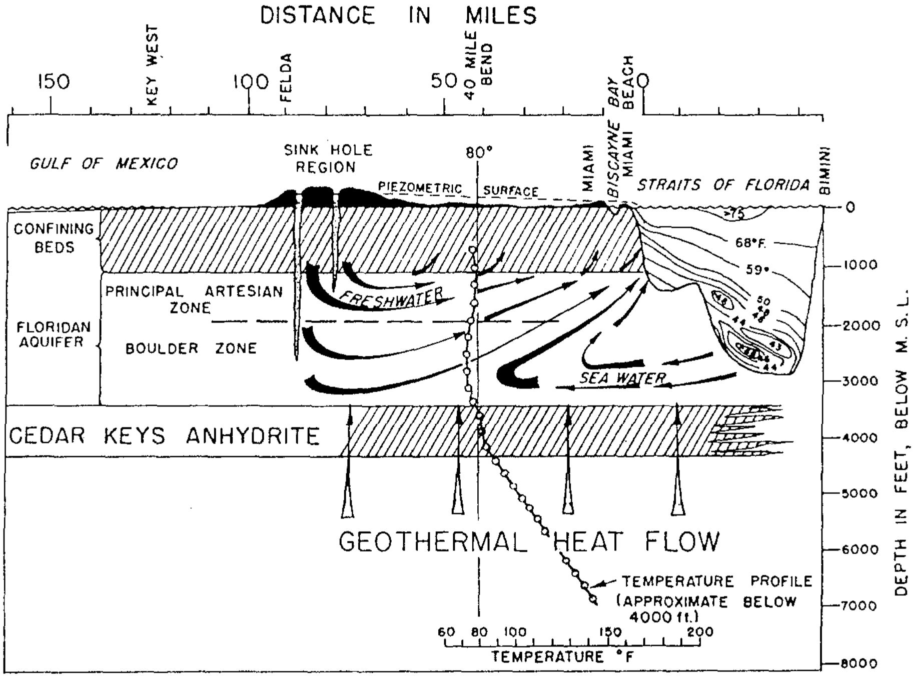

Fig. 7. Idealized section through Florida showing concept of cyclic flow of sea water induced by geothermal heating (Kohout 1965)

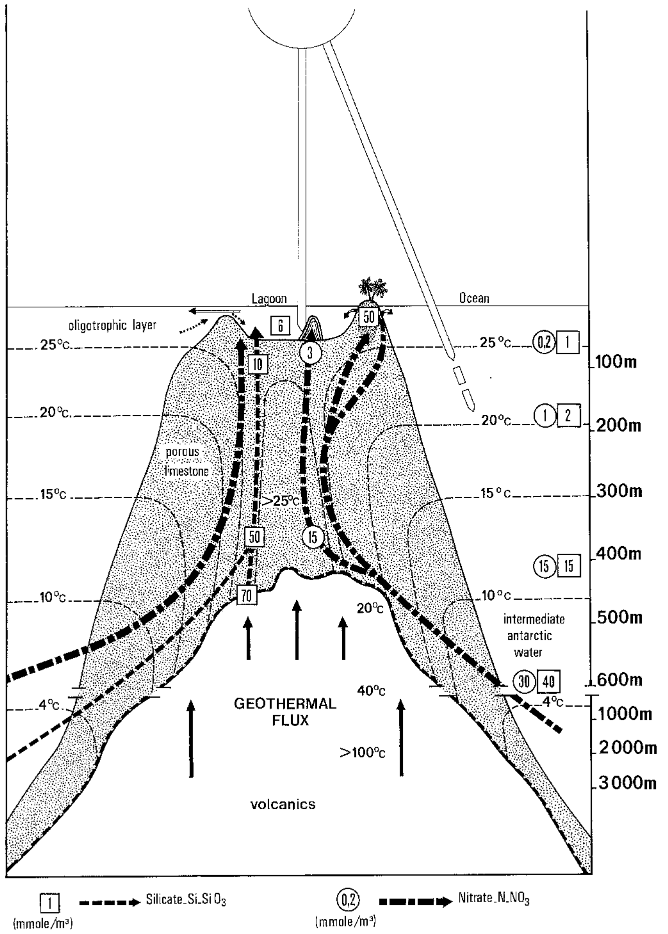

Fig. 8. Geothermal endo-upwelling. The geothermally driven ocean water circulation in an atoll and the relations between nutrient-rich upwelled water, high organic production and localization of coral reefs

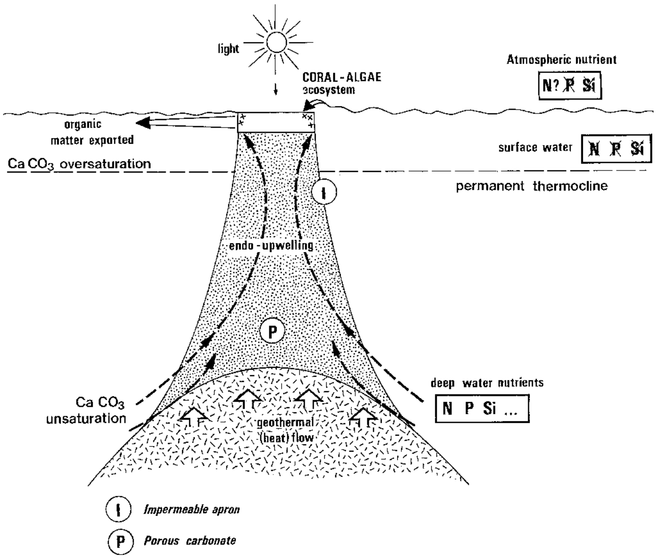

Fig. 9. Schematic illustrating the geothermal endo-upwelling process

The coral ecosystem and its nutrient requirements

Upwellings generated by wind stress in open oceans or along coasts always have the same positive effect of bringing new nutrients into the euphotic layer: the level of primary production is enhanced accordingly, zones of permanent or semi-permanent upwelling coinciding with maximum oceanic production (Koblenz-Mishke 1965). Within the upwelling areas along the Chili-Peru coast or the eastern equatorial belt, primary productivity is approximately 1 g.C/m^2/day. In the central part of the South Pacific, where a vast gyre leads to quasi depletion of nutrients within the photic layer, productivity is as low as 0.1 g.C/m^2/day. Atolls forming the Tuamotu Archipelago are situated within this clear, oligotrophic water which, paradoxically, was thought to be able to sustain a gross photosynthetic carbon fixation of 4 to 12 g.C/m^2/day in reefs (Smith and Kinsey 1976). In fact, there is now reason to believe that interstitial water nutrients displaced upward by convective circulation play a key role in coral ecosystems. Although mixotrophic and able to feed by heterotrophy on small plankton, corals function mainly by autotrophy, because of their endosymbiotic zooxanthellae. In common with all algae or phytoplanktonic cells, zooxanthellae require nutrients in order to photosynthesize organic material for coral tissue growth. Thus, endo-upwelling can satisfy the prerequisites of coral ecosystems. If we compare the nutrient content in interstitial waters from Tikehau Atoll and those from the equatorial upwelling in Central Pacific (160°–140° W) we note a close similarity (Table 2). This is not surprising, since both upwelled and endo-upwelled water originate from the same rich subsurface water located below the mixed layer (Fig. 10).

As discussed previously, geothermal convection sustains an upward circulation at speeds calculated in millimeters per hour (Samaden et al. 1985) or about 1 cm per hour according to our indirect method based on the replacement rate of nutrient losses through the pass (Rougerie et al. 1984). These values are lower than upward velocities of well established oceanic upwelling, which are typically around 1–10 cm per h. However, as already pointed out, interstitial endo-upwelled water is probably

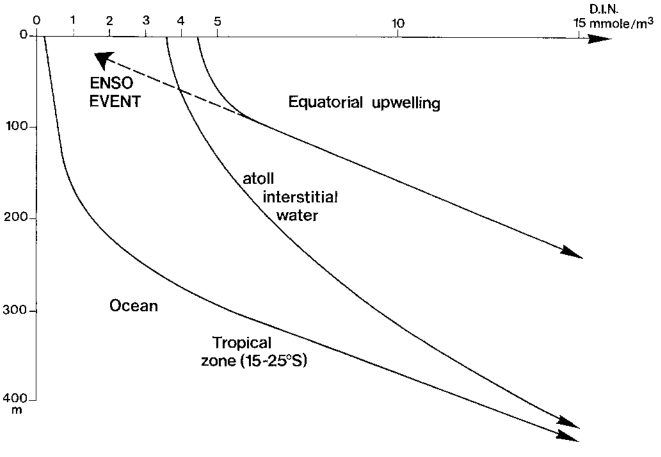

Fig. 10. Vertical profiles of dissolved inorganic nitrogen (mainly NO_3-N) in tropical zones, equatorial upwelling and within a porous atoll (equatorial upwelling disappears during ENSO events)

Table 2. Relations between nutrient content, primary productivity and dynamical process

	PO_4–P mmol/m^3	NO_3–N mmol/m^3	O_2 l/m^3	Primary productivity g.C/m^2/day	Vertical speed	Dynamical process
Atoll, interstitial water (0–50 m)	0.8 ± 0.1	4 ± 1	1.3 ± 0.3	Algae-coral benthos 4–10	cm/day[a] to cm/h[b]	Geothermally driven endo-upwelling
Equatorial water (0–50 m) (160°–140° W)	0.6 ± 0.2	4 ± 1	4.4 ± 0.2	Phytoplankton 0.5–1.5	1–10 cm/h[c]	Upwelling (Ekman divergence)
Tropical water (0–50 m) (gyre)	0.1	0.1	5.0 ± 0.4	0.1	cm/day	Downwelling (Ekman convergence)

[a] Samaden et al. (1985)
[b] Rougerie et al. (1984)
[c] Rotschi and Jarrige (1968)

ascending mainly through the megaporosity network inside the carbonate framework, and not only through matricial pore permeability. The essential factor is that nutrients can continuously reach the top of the atoll and are available to reef communities.

Webb et al. (1975) made some intriguing observations on Eniwetak Atoll, where oceanic water running over the reef flat contained high amounts of inorganic nitrate (DIN). They interpreted this enrichment as the result of rapid atmospheric nitrogen fixation by Cyanophycae algae. However, as their first station was (only) about 40 m downstream from the crest of the algal ridge, this high DIN signal (mainly NO_3 and no NO_2) could have resulted from endo-upwelled nutrients seeping through the spur and groove zone.

In their studies of interstitial water within living corals such as *Porites*, Risk and Muller (1983) record high amounts of nutrients, including silicate, associated with free oxygen. Observations in submarine caves on St. Croix have been precisely described by Szmant-Froelich (1985).

> Cave water concentrations are 13 times higher in NO_3, 2 times higher in NH_4 and 3 times higher in organic N than offshore waters. These enrichments in the caves represent a significant increase in nutrients for any primary producers that might have access to them. Dye injections into caves showed that there was rapid outwelling of cave waters onto the reef and, importantly, that these cave waters flowed within 1 m of the bottom for 10–15 min or longer before mixing upwards.

The present authors interpret these observations as possible indications of endo-upwelled water impregnating both the limestone substrates and its living cover. By ionic continuity, the centers of coral heads are thus soaked with sufficient nutrients to satisfy zooxanthellae requirements and locally spike the surrounding waters. It is recalled that, although reef ecosystems are important gross primary producers, they can thrive with a rather low net primary production, essentially because of their high efficiency in recycling and remineralizing inside their complex network. However, as noted by Szmant-Froelich (1983) "It is important to point out that nutrient recycling mechanisms, even when 100% efficient, cannot supply nutrients for a positive net production; furthermore, if recycling mechanisms are inefficient it will take an input of new nutrients to maintain a steady state biomass."

One may note that if a reef, with a yearly loss of only 1%, cannot balance its nutrient budget (Smith and Kinsey 1988), half of its calcified bulk will disappear in 70 years. Because atolls endure for millions of years, new nutrients possibly supplied by endo-upwelling might be the process necessary for balancing coral ecosystems.

Reef zonation and generalization of the model

An important implication of this hypothesis is that a coral ecosystem represents the biological signal of endo-upwelled waters. In photic, warm tropical oligotrophic water, nothing may prevent the community from assimilating nutrients and CO_2-rich water from seeping through its porous basement. Coral larvae, or planulae, have a decisive advantage when they settle in these particular locations, where they can develop in close proximity to nutrient sources without being dislodged by oceanic currents and wave action. We have already emphasized the important role of oceanic waves in cleaning the reef crest, avoiding "clogging" by fine sediment and thus, in the long term, facilitating easy seepage of the endo-upwelled water.

It is not surprising, as a direct implication of this model, that coral species are rather scarce in lagoons. Although colonies do occur as patch-reefs, most are situated on scattered pinnacles lacking any evident order; these pinnacles, whose tops are often at sea level, constitute small oases colonized by benthic species and surrounded by fish that feed on them. It is not impossible that these pillar-shaped structures are located above secondary endo-upwelled seeps, as suggested in Fig. 11. Kohout and Kolipinski (1967) formulated a similar conclusion in a paper devoted to biological zonation related to groundwater discharge along the shore of Biscayne Bay, Florida. "The distribution of the organisms correlates so

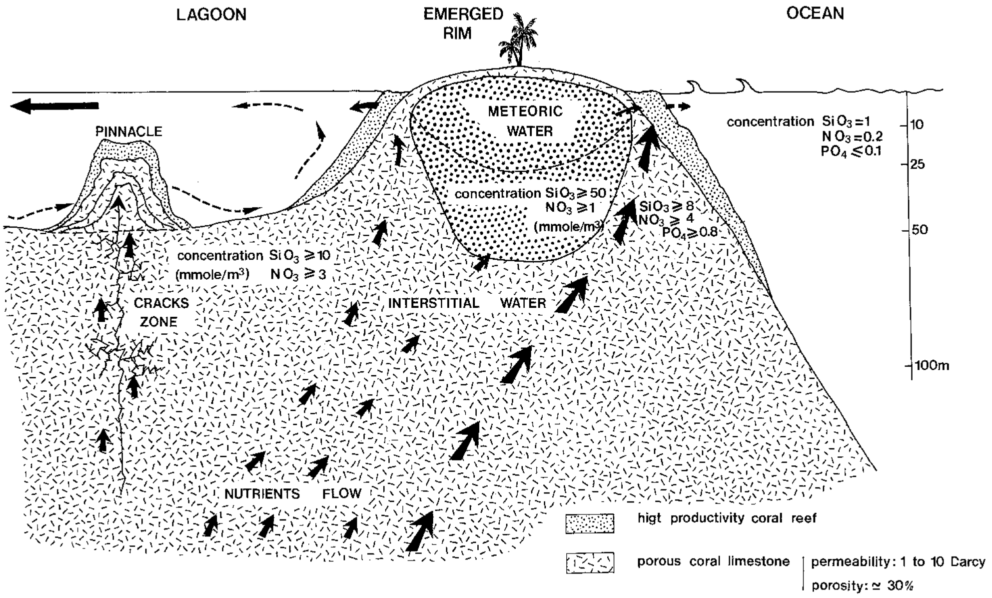

Fig. 11. Interstitial, nutrient-rich water moving up and seeping through an atoll outer rim and the sublagoonal zone along fissures and cavities

closely with the underlying hydrological factors that a conclusion appears justified: the distribution of the organisms is primarily a function of salinity related to groundwater discharge." This low-salinity spring probably has kept a fraction of the high nutrient content present at depth where seawater penetrates the plateau. Another possible confirmation has been made by Gittings et al. (1984) at "East Flower Garden Bank" (northwest Gulf of Mexico) where a sulfurous brine discharges at 72 m depth on a coral slope. They describe this brine as "a surface manifestation of an underlying salt diapir, and seawater percolating through the porous carbonate bank to the level of the salt domes produced brine seepage at several locations on the bank." The brine is diluted by seawater as it flows down a 96-m-long canyon such that salinity and sulfide concentrations are close to those of normal seawater at the canyon's mouth. The authors emphasize that "there is a significant increase in the number of hard bottom invertebrates as one approaches the undiluted brine of the lake or the diluted brine of the canyon... This brine seep system is a significant exporter of organic carbon for the normal hard bank community which is food limited." Although these authors do not discuss the driving force required to move this high-density brine through the basement, geothermal convective circulation must again be considered.

Generalization of our endo-upwelling model to barrier reefs or other types of biotherms (Fig. 2), viewed as oases relative to tropical oceanic oligotrophy, implies the conjuncture of three basic conditions:

- A permeable substratum
- A heat-generating basement
- A contiguous deep ocean.

These factors may occur at numerous locations along steep coasts or at the edges of continental shelves, on banks and shoals in the open sea where sediments or sedimentary rocks, saturated with seawater, overlie lower permeability layers through which terrestrial geothermal heat flows. Upwelled water discharged by submarine springs or seeps would add nutrients of deep oceanic origin and thus enhance organic production in surface waters. This contribution should be most significant in the intertropical zone where oceanic surface waters are usually poor in nutrients, especially where land run-off is low. Operating conditions of nutrient supply by endo-upwelling could account for settlement, sustained growth or demise of coral reef building ecosystems particularly in the oligotrophic Coral Sea where a great variety of coral reefs are known to occur (Queensland Plateau reefs, Chesterfield group with reefs, banks and guyots, etc.). Organic binding and early cementation within the framework, as reviewed by Fagerstrom (1987), can be strongly enhanced by the endo-upwelled fluid, due to the physico-chemical modifications it endures during its upward migration. A series of cementation and inorganic precipitations can result from decrease in $CaCO_3$ solubility, CO_2 degasing and temperature increases during the endo-upwelling process. In a synthesis of global coral reef geomorphology, Guilcher (1988) emphasizes the roles played by water circulation at depth through the atolls.

Logically, we must assume that what is true for an atoll barrier reef must also apply to the barrier reef surrounding a high island, particularly when the presence of a large lagoon prevents any noticeable terrestrial contribution to enter the nutrient balance of the outer barrier reef which is surrounded by oligotrophic oceanic water. In vast system such as the west lagoon in New Caledonia (Fig. 12a), geomorphology is characterised by submerged barriers, inner barriers and islets surrounded by fringing reefs, which attests to the importance of local tectonic controls (Coudray et al. 1985). The network of inner faults linked to these coral buildups may possibly facilitate seepage of endo-upwelled water migrating through the sublagoonal pile (Fig. 12b).

In a paper concerning water flow and plankton patterns around Pandora Reef in the Great Barrier Reef lagoon (Australia), Hammer and Hauri (1981) note that "prior estimates of coral reef nutrition based on the assumption that nutrient-poor oceanic water crosses the

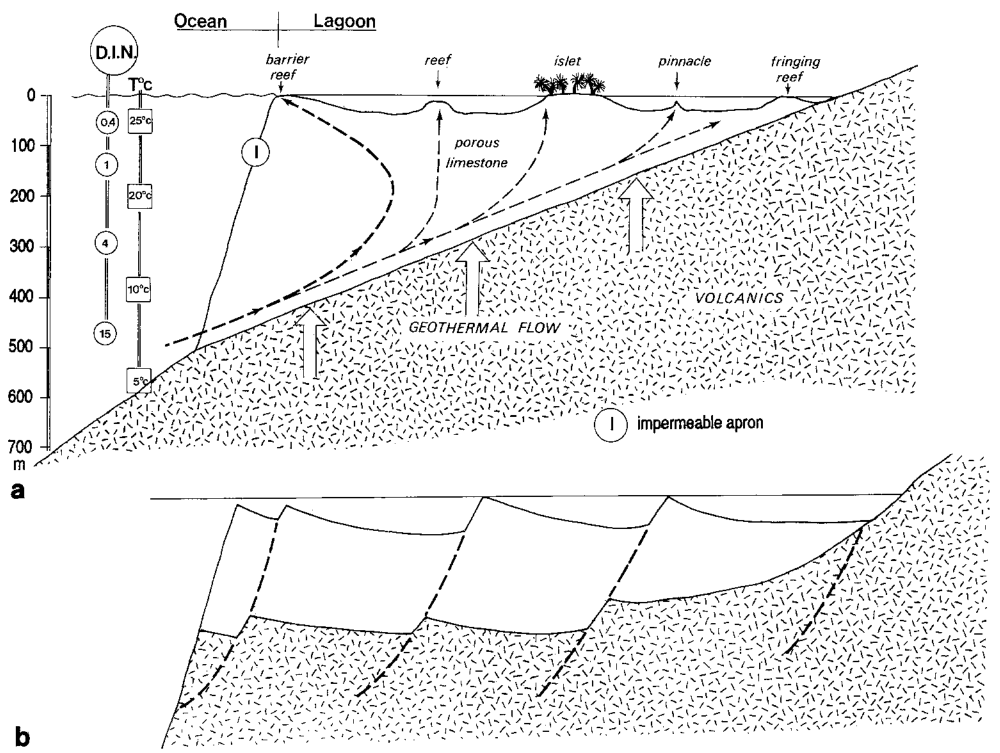

Fig. 12.a. A generalization of the endo-upwelling model with application to New-Caledonia west lagoon. **b** Relationship between local tectonic, fault network and reef buildup in the same lagoon. (From Coudray et al. 1985)

reef may be in error." For Andrews and Gentien (1982) upwelling as a source of nutrients may be the solution to Darwin's question concerning reef functioning. Recent data published by Andrews and Furnas (1986), showing several cold events related to upwelling along the slopes of the Great Barrier Reef, must be replaced in the very special and sporadic context of the very strong ENSO of austral summer 1982–1983, during which an exceptional rise of the oceanic thermocline was detected in the Coral Sea; such an intrusion of nutrient-rich waters onto the reef shelf is a relatively rare event, the significance of which, for the long-term balancing on the reef budget, can be questioned.

Endo-upwelling: an important hydrodynamic process for internal diagenesis of carbonate platform

To explain the diagenetic changes affecting coral reefs in the core of Funafuti Atoll in the Gilbert Islands where limestone has been converted to dolomite, Fairbridge (1957) proposed an internal circulation of interstitial seawater supplying magnesium; cold intermediate depth, oceanic water could be expected to penetrate the carbonate mass and, subsequent to warming by the underlying volcanic cone, to circulate upward through the calcareous material by thermal convection; it would be discharged as submarine springs or seeps in the lagoon or outer reef tract. Deep seawater is then regarded as an infinite reservoir, especially for magnesium, which is always in excess at any depth. Largely confirmed by new data and laboratory simulation, the geothermal hydrology convection of seawater in the Florida aquifer can now be considered firmly established (Kohout et al. 1977).

This thermal convection model has been applied by Simms (1984) who called it "Kohout convection": this model may explain the formation of massive dolomites. Fanning et al. (1981) have suggested that chemical differences between the meteoric waters and seawater may cause large-scale dolomitization by thermal convection in the Florida subsurface. On a smaller scale, Saller (1984) interpreted the dolomite of Eniwetak Atoll as an example of dolomitization by normal deep seawater. As indicated by Machel and Mountjoy (1986), "Additionally, thermal convection half cells which pump normal sea water through platform carbonates or atolls at considerable depth, might also accomplish extensive dolomitization."

A particularly well-documented model of reef diagenesis at Mururoa atoll has been published by Aissaoui et al. (1986). These authors describe an annular lens of dolomite which forms the lower part of the sedimentary framework and note that this dolomite develops initially as a cement within the microscopic voids of the limestone and that dissolution of $CaCO_3$ is a prerequisite for dolomitization. As emphasized by Buddemeier and Oberdorfer (1986) "dolomitization requires the passage of many volumes of pore water through the system in order to remove calcium and supply magnesium." Because deep oceanic water is unsaturated in $CaCO_3$ but oversaturated in $MgCO_3$, the propitious fluid is at hand! And finally, a further application of the hypothesis of dolomitization by sea water convection is given by Aharon et al. (1987), from Niue raised atoll (South Pacific), whose core is extensively dolomitized.

> The observed isotopic composition points to sea water as the dominant dolomitizing fluid. A model of sea water convection is proposed for atoll dolomitization on the basis of thermal gradient between the atoll and the ambient ocean water. Sea water is drawn through the atoll margin and transferred upward by convective flow

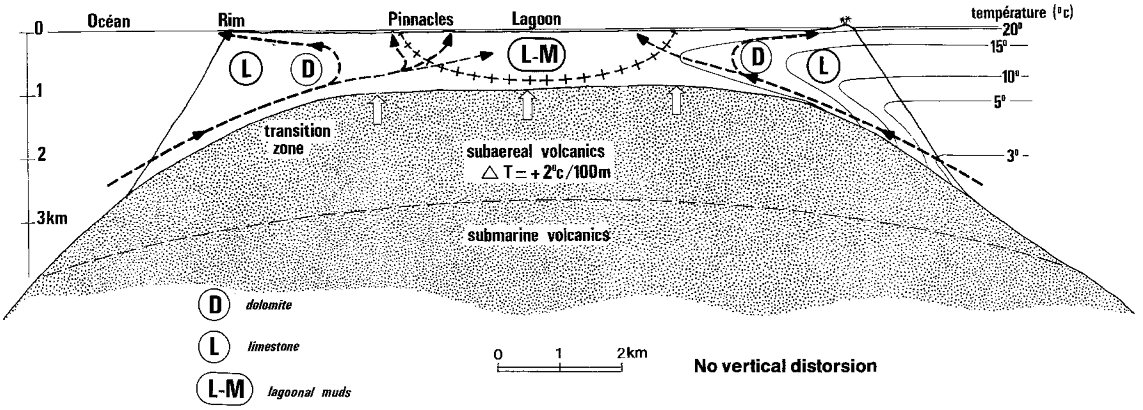

Fig. 13. Idealized section across an atoll showing the distribution of the different formations, including the lenticular dolomite body, as depicted by Aissaoui et al. (1986)

delivering Mg to the sites of dolomite precipitation. Transported with the sea water are volcanic derived metals (Fe, Cu, Zn, Mn) as evidenced by the chemical gradient in the dolomite unit.

This recent finding is in close agreement with the positive silicate anomaly we observed in atoll wells. The overall conclusion of these various studies is that internal fluid circulation favors limestone diagenesis (Purser and Schroeder 1986) as schematized in Fig. 13; deep oceanic water driven by geothermal constraint is a logical candidate.

Conclusion

The endo-upwelling concept now appears to be more convincing than was thought at the time of earlier publications (Rougerie and Wauthy 1986), thanks to progress concerning limestone diagenesis and interstitial water properties. By a simple mechanism based on a convective geothermally driven cell, it provides a satisfactory explanation for a great many observations on flow and ionic composition of interstitial waters. Thus, at any locality where the three basic conditions are respected (i.e. a porous structure, a heat-generating basement and a contiguous deep ocean) one may encounter endo-upwelling: it can then be viewed as a low-energy hydrothermal mechanism, of which reef ecosystems in the tropical zone constitute the biological signal.

The endo-upwelling concept is, then, a very fruitful paradigm, which can solve the old paradox of huge production/calcification of coral communities surrounded by clear oligotrophic waters. Being a slow but continuous process, endo-upwelling prevents nutrient limitation, or any unbalance between relative amounts of phosphate and nitrate needed for autotrophic growth of coral communities. On the long term this process can guarantee a positive net production able to compensate for any exportation of organic matter or particles through lagoon passes or on reef slopes, enabling an atoll to function as a pelagic net producer. Following our model, an atoll is a possible answer to the question by posed Isaacs (1977):

Why are there no pelagic trees in the ocean? One can easily compute the advantages such a tree would enjoy, with its canopy near the surface in the lighted levels and its trunk and roots extending down to the nutrient rich waters under the mixed layer.

Looking at their age and their marvelous species diversity it is unfortunate that reef ecosystems, like tropical forests, are in the front line of human pollution and destruction, due to the growth rate of 1 billion/decades of *Homo "sapiens"* (Ramade 1986).

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