THE ENDO-UPWELLING CONCEPT : A NEW PARADIGM FOR SOLVING AN OLD PARADOX

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ABSTRACT

The geothermal endo-upwelling model allows to balance the nutrient budget of an atoll located in oligotrophic ocean : it comprises a vertical ascent of deep oceanic water driven by geothermal heat flow through the atoll's porous internal structure, and a discharge of this nutrient rich upwelled water near the surface in the reef-building biocenosis areas.

This model can be used to take into account some peculiar features in different reef-building formations as the in situ observation of low salinity "shimmering" water leaking in subsurface or nutrients rich water outwelling from caves. It can constitute a rational process for accumulation of phosphate-fluoroapatite found at the top of uplift atolls and can make clear diagenetic alteration and dolomitization inside atoll structures. It fits well with the global scheme proposed for the Floridan aquifer, characterized by a circulation of geothermally heated saline interstitial water. Generalization to barrier reef surrounding high island is a logical step, which need to be sustained by specific field data.

HIGHLIGHTS OF THE CONCEPT

In the central desertic gyre of the tropical ocean atolls constitute veritable oases and the classical model of atoll functioning based on horizontal exchanges between the lagoon and breaking oceanic surface water cannot solve the long discussed paradox of the survival of a highly productive coral ecosystem flushed by oligotrophic water. With nutrients contents as low as 0.1 mmole/m3 in phosphate and nitrate these ocean surface water are unable to balance nutrient budgets in a manner that accounts for the atoll high organic production ; a source of nutrients external to the ecosystem is needed, particularly for phosphorus and silica. French studies carried out since 1965 in the Tuamotu archipelago, concerning organic production, salt and nutrient budgets, the nature of the limestone structure built up by symbiotic biocenosis, as well as thermal field and interstitial water characteristics measurements, have made it possible for us to demonstrate the reality of vertical exchanges between lagoon and deep oceanic water through the permeable atoll basement. (ROUGERIE and WAUTHY, 1986).

This "geothermal endo-upwelling concept" has been presented for the first time in 1985 during posters session of the Fifth Coral Reef Congress in Tahiti. It comprises a vertical ascent of deep oceanic water, driven by geothermal heat flow, through the atoll's internal structure ; nutrient-rich endo-upwelled water supplies the reef-building biocenosis at the surface, enabling reef-lagoonal system to thrive and to balance losses to the ocean (Fig. 1).

According to this model three constituents are needed in conjunction :

1/ a porous and permeable material
2/ a heating basement (geothermal flux)
3/ a contiguous deep ocean (nutrient source)

Furthermore it appears that some peculiar features in different places and different reef building formations can be explained by this model.

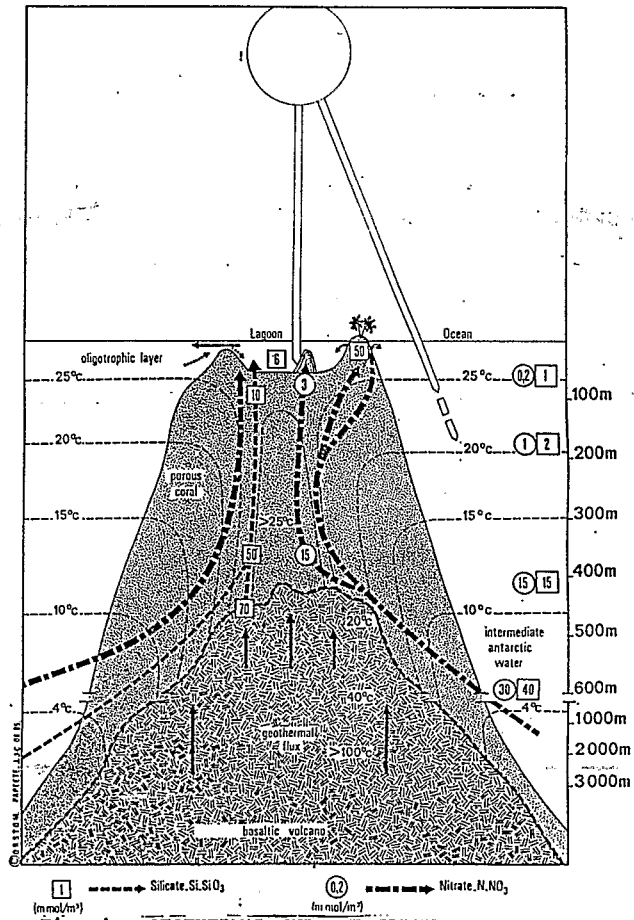

Fig. 1 : GEOTHERMAL ENDO-UPWELLING.
The geothermally driven internal ocean water circulation in an atoll and the relations between nutrient-rich upwelled water, high organic production and coral reef building localization.

Outlets of "endo-upwelled" water and calcification

Endo-upwelled water may be anticipated to flow along the easiest paths, that is to say in places where permeability is maximum ; most probable outlet spots should thus be in areas of low sedimentation and/or high porosity ; nutrients supplied in these privileged places should enhance building activity of the symbiotic communities of algae and corals, largely dependent on primary production by photosynthesis. Endo-upwelling thus brings forth a direct causal explanation to the restricted localization of active reef-construction :

- on the upper part of the seaward slope, from the algal ridge to 30-40 m, where sedimentation is prevented by waves action (figure 2).

- in some places of the lagoon where, in spite of heavy sedimentation, there may be cracks, fissures, faults ("megaporosity") in the bottom around which patch reefs, pinnacles, and other bioconstructions have developed (figure 2).

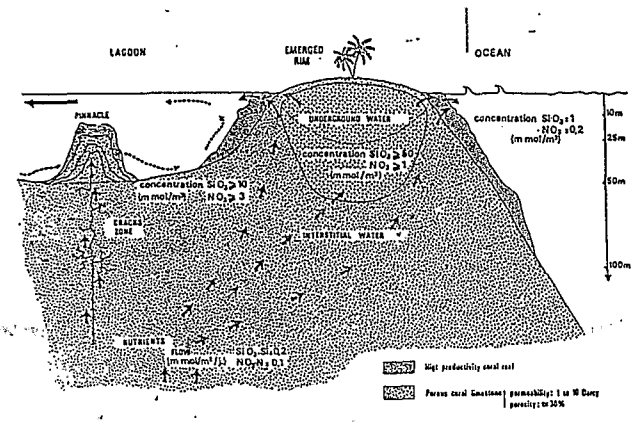

Figure 2. Interstitial nutrients-rich water moving and seeping along fissures and cavities zones.

Endo-upwelling and production level

Nutrients needed to sustain high production level of atoll-oasis in the oceanic desert are thus pumped through the basement from the deeper water oceanic reserve ; the basis of the ecosystem is the large biomass of autotrophic benthic algae thriving on and in a calcareous substratum the physical structure of which they build and control in its spatial extension ; the trophic relationships and energy transformation are thus in agreement with the scheme given by Lewis (1981) : primary benthic production ; symbiotic activity of zooxanthellae and corals to produce calcium carbonate for the skeletogenesis ; microbial production and bacteria activity in internal recycling of organic detritus ; export of a fraction of reef production to the ocean. Thus atoll-oasis can develop and survive in the desert of central oligotrophic ocean ; around the oasis, in water close to the reef slope where endo-upwelled water seeps out or in the plume of flowing-out lagoon water enriched with organic matter, there exist a volume of relative richness and life activity, able to attract pelagic nekton organisms, particularly fish.

OBSERVATIONS OF WATER OUTFLOWS AND ENDO-CIRCULATION

Shimmering waters

During submersible dives in order to examine the Johnston Island (16°45'N - 169°30'W) carbonate plateform to depths of 500 m visual observations of "shimmering water" have been reported by Keating (1985). This effect was interpreted as optical discontinuities associated with a large drop in salinity at depths of 200-250 m. The shimmering low salinity water appeared to come "from the rocks" and was actually seen "flowing from the caves" at 210 m at dive site 199. Mixing with fresh water was thought to be unlikely because neither rain water nor hydrothermal fresh water could interfere ; the other possibility left was low salinity water mass inside the porous seamount forced out through pores and caves. The 0-300 m surface layer is high salinity tropical water (higher than 35,0 ‰) ; the only low salinity water is intermediate water (34,2 ‰ near 500 m), (figure 3). The forcing thus far suggested has been internal waves and impinging currents.

We suggest to consider endo-upwelling ; moreover, lateral leakage through the caves could hamper the nutrients flow to the top of the atoll and contribute to explain the incompleteness of the reef on the windward side.

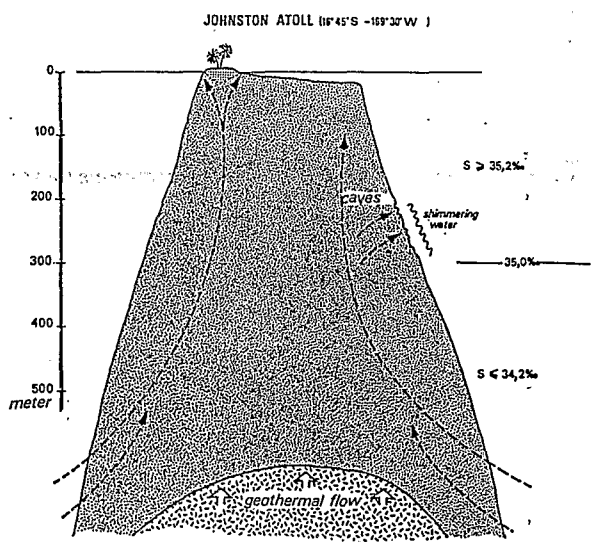

Figure 3. Optical discontinuities outside caves zones : a possible visualization of laterally leakage of endo-upwelled water.

Cave seepages

Another set of cave observations is precisely described by Szmant-Froelich (1983) in St. CROIX reefs (Carribean sea). "Cave water concentrations are 13 times higher in NO3, 2 times higher in NH4 and 3 times higher in organic N than off shore waters. These enrichments in the caves represent a significiant 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 mn or longer before mixing upwards. This indicates that there is a process that restricts vertical mixing and dilution of nutrient enriched outwelled cave waters, such that benthic primary producers would have sufficient time to strip the nutrients from these waters before they mix upwards".

We suggest that this density anomaly associated with high nutrients content constitute the signature of an outflow of endo-upwelled water.

Brine discharge

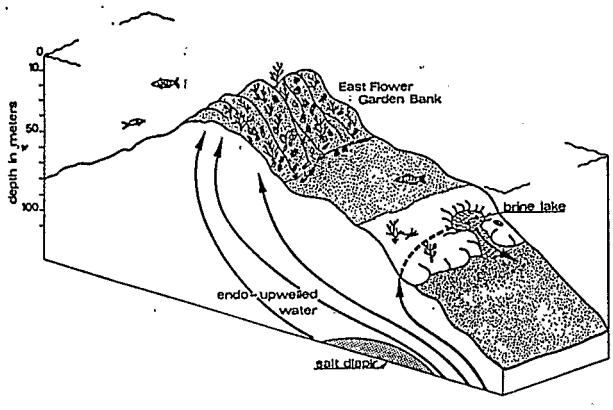

Figure 4. Diagram of the East Flower Garden Bank and assumed internal circulation.

In the northwest Gulf of Mexico Gittings, Bright and Powell (1984) report a sulfurous brine discharge at 72 m depth in the East Flower Garden Bank. This brine is "a surface manifestation of an underlying salt diapir, and seawater percolating through the porous carbonate bank to the level of the salt domes produces brine seepage at several locations on the bank". The brine is diluted by seawater as it flows down a 96 m long canyon so that salinity and sulfide are at near normal seawater concentrations at the canyon's mouth. The authors euphazize that "there is a significant increase in the number of hard bottom invertebrates as one approches 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".

We suggest endo-upwelling as the forcing of this brine discharge (figure 4) and as a nutrients source for all the banks of the Gulf.

The phosphate problem

Apatite has been found and exploited on uplifted atolls such as Nauru, Ocean, and Makatea. The rich layer which can contain more than 33 % of P205 is situated on the top of these atolls and forms pockets whose thickness can exceed several meters (Montaggioni, 1985). Traditional hypotheses put forward to explain the presence of this high grade phosphate ore are unconvincing, especially the bird guano sequence. Analyses by Bourrouilh Le Jan et al., (1985) on Clipperton phosphate deposit indicate the presence of chemical elements found neither in guano nor in limestone structure. Thus the presence of Zn, Ba, B, V and Ni, allows these authors to definitely reject the long lasting hypothesis of a genetic filiation between guano and phosphate apatite. Other hypotheses, such as alteration and maturation of drift volcanic material accumulated as soils, or alteration of marine organic matter deposited within low-oxygen shoals, seem quite unrealistic (Delesalle, 1985). We suggest that dissolved phosphate brought up continuously by endo-upwelling could accumulate in interstitial water of the lagoonal sediments in closing or closed atolls and precipitate as fluoroapatite in a manner already advocated in upwelling areas on continental margin. (Froëlich et al., 1983). This process could lead to phosphatic diagenesis of carbonated sediments and framework in situ and continue until total emergence of the atoll. (figure 5). Datings of fluorapatite from Makatea by Veeh (1985) give 800.000 years or more, in accordance with the uplift of the atoll as a result of the isostatic response of the lithosphere to the load of the nearby Tahiti-Moorea-Mehetia volcanic complex.

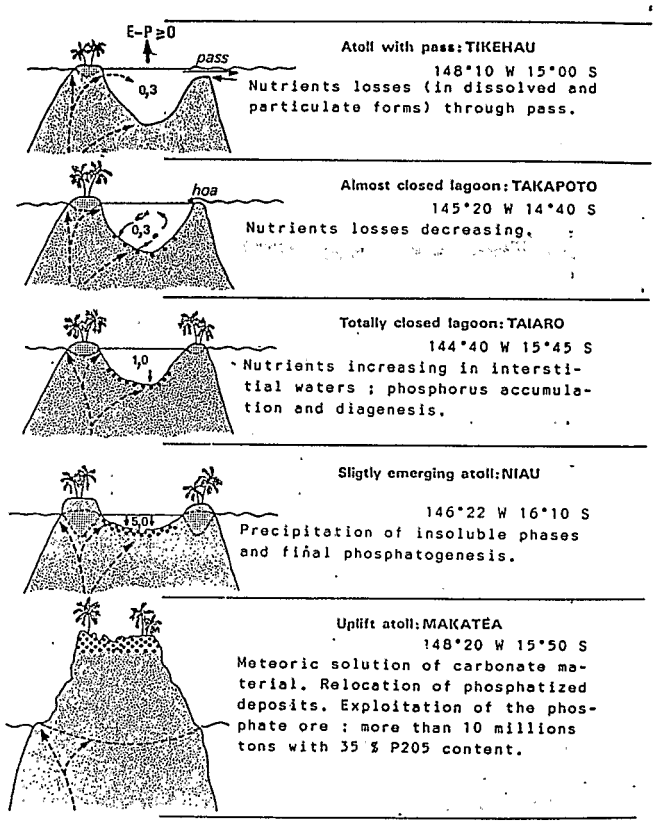

Figure 5. Formation of insoluble phosphate layer (apatite) by capitalization and precipitation of endo-upwelled phosphate.

Diagenesis and dolomitization

Numerous data obtained by core drilling at Mururoa atoll have allowed Aissaoui, Buigues and Purser (1986) to precisely describe the spatial localiza-

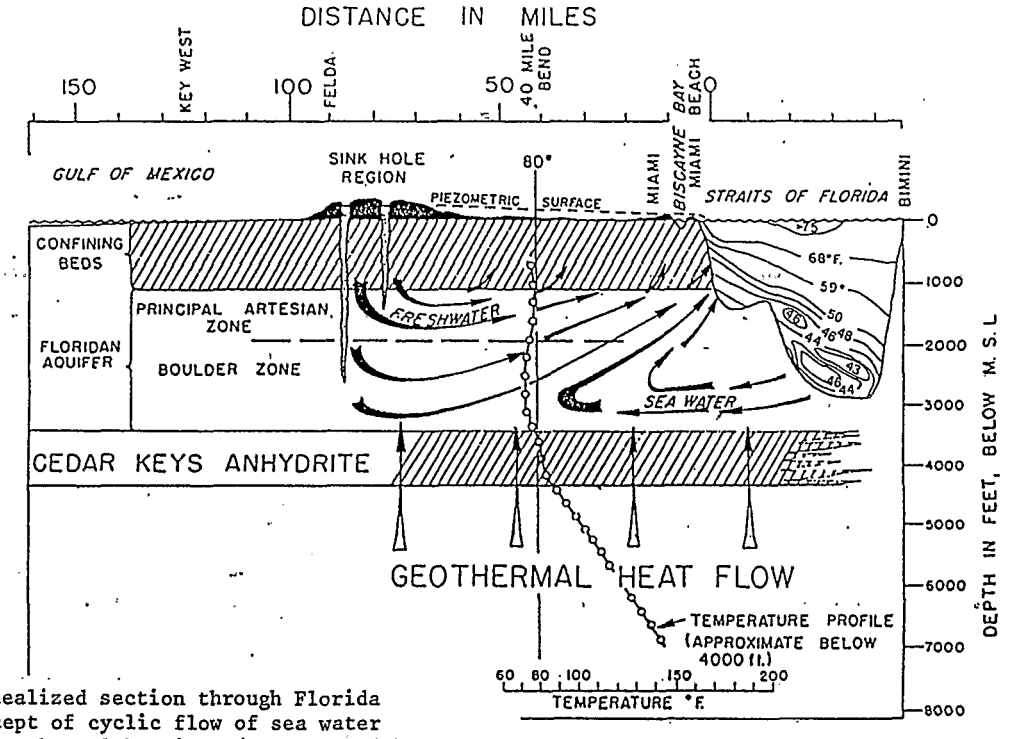

Figure 6. Idealized section through Florida showing concept of cyclic flow of sea water induced by geothermal heating. (Kohout, 1965).

tion and composition of an annular lens of dolomite between 150 and 500 meters deep. Their model of reef diagenesis and dolomitization puts forward that a centripetal hydrodynamic regime from deep oceanic water towards the axis of the mount is necessary to bring in the magnesium and fluids required for dolomitization. Cementation is always maximum at the periphery of the atoll, an important fact also noted by Marshall (1986) on Great Barrier Reef : "It would appear that some shelf-edge process, possibly upwelling ... or an as yet unexplained mechanism, caused sufficient quantities of seawater to be pumped through the outer reefs framework, which ultimately led to the formation of significant quantities of submarine cement".

Geothermal heating in the Floridan aquifer

In Kohout (1965) the hydrogeology of the thick carbonate evaporite sequence in southern Florida is presented, from land surface to the oil horizons at a depth of about 3400 meters below sea level. In the discussion evidences appear that the low-permeability anhydrite deep layer "can be compared to a hot plate. Upward geothermal heat flow raises the temperature of the aquifer water and generates a thermal convective circulation. Cold, dense sea water from the Florida straits becomes progressively warmer and less dense as it moves horizontally inland through the cavernous dolomitic limestone in the deep part of the aquifer .... Eventually, the upward component of the convective circulation brings the sea water into contact with fresh water moving seaward from the sink holes region of central Florida. After upward movement and mixing, the diluted sea water flows seaward and discharge through submarine springs and seeps on the continental shelf and slope".

Figure 6 depicts the flow pattern schematically. Although nutrients concentrations in these seeping waters are not known, their origin in the deep part of the surrounding ocean leads to admit that these figures must be high ; fringing and patch-reefs of the Floridan shelf can then be sustained by a sufficient flow of nutrients. The Floridan model is then equivalent to our atoll model, but on a much larger spatial scale.

GENERALIZATION OF THE MODEL

These examples are in our opinion convincing indices of the reality and importance of an internal circulation inside calcareous porous structure and represent different aspects of the upwelling process, according the three initial conditions already stated. Generalization is straightforward, for what is true for an atoll barrier reef must stay correct for the barrier reef surrounding an high island. It is particularly the case when the presence of a large lagoon prevents any noticeable terrestrial input to enter into the nutrient balance of the outer barrier reef and when the incoming oceanic water keeps its oligotrophic character.

The New-Caledonian barrier reef constitutes a good example to quote, its reef-lagoonal system and oceanic hydrology having been studied with enough details. Concerning the nutrients budget of the south lagoonal part previous results were inconclusive, the contribution needed from an oceanic upwelling along the outer slope having not been proven (Rougerie, 1985). There again an endo-upwelling process within this barrier reef can constitute the indispensable and sufficient condition to balance the input/output nutrients ratio

(figure 7). However, direct evidence is yet to be found, and measurements of nutrients and dissolved gases are planed in the interstitial water of this barrier reef.

Upwelling has been postulated along the Great Barrier Reef in Australia to answer the need of a nutrients source to balance the production of the reefs bathed by oligotrophic Coral Sea surface water and far away from a meagre continental run-off. Although eagerly searched for years no evidence of surface enrichment by any upwelling has been so far given. Recently several dynamic mechanisms have been suggested to explain observed thermocline uplifts and injections of richer sub-thermoclinal water over the deeper sills of the narrow passes between the reefs of the more or less continuous barrier. (Drew and Abel, 1988). The very recent confirmation of the presence of huge Halimeda bioherms on the shelf behind the reefs worsen the need of an external nutrient source. We suggest to add our continuous albeit slow geothermal endo-upwelling to the mechanisms of G.B.R. nutrient enrichment.

The island mass effect around the Marquesas islands, characterized by high chlorophyll amounts, has been discussed for a long time (Jones, 1962). A carbonated platform was first detected at 90 meters deep in 1953 by the Capricorn Expedition, but this structure was not really taken into account or discussed after this first description. The echo-soundings and dredgings performed by the french R.V. MARARA (1985-1987) have shown the importance and the identity of this platform : it is an old barrier reef which 18 000 years ago was surrounding the Marquesas islands, in the same way modern barrier reefs stand around Society islands (Tahiti or Bora-Bora). This reef has not evidently caught up with the rapid rising of the oceanic level during the last deglaciation, between 18 000 and 5 000 years B.P. as other polynesian barrier reefs have done without problem. After testing different hypotheses we assume that this barrier reef was probably killed by the arrival in this zone of an oceanic current colder than usual (Wauthy et al., 1988). At the beginning of the deglaciation a huge quantity of ice melted down all along the Chili coast and this glacial water was injected into the Humbolt Current with a northward then a westward advection toward the Central Pacific, between equator and 10° S.

From a mean temperature of 22° C, a 5° C decrease in surface water temperature in the Marquesas area could have been sufficient to kill the barrier reef at the very moment when oceanic level was rapidly rising up. Today this reef does not support living corals, the depth being too important for a new colonization by coral larvae. However, it remains an adequate site for an endo-upwelling process, according to the three criteria already stated. Thus there is a possibility that nutrient

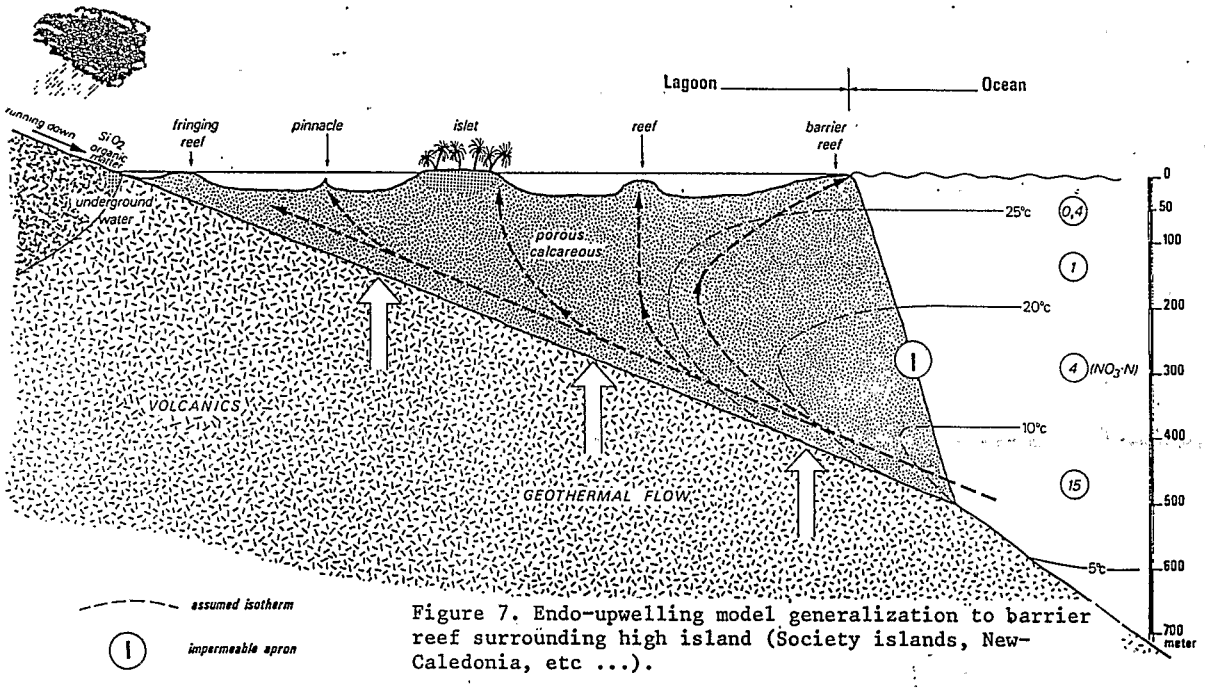

Figure 7. Endo-upwelling model generalization to barrier reef surrounding high island (Society islands, New-Caledonia, etc ...).

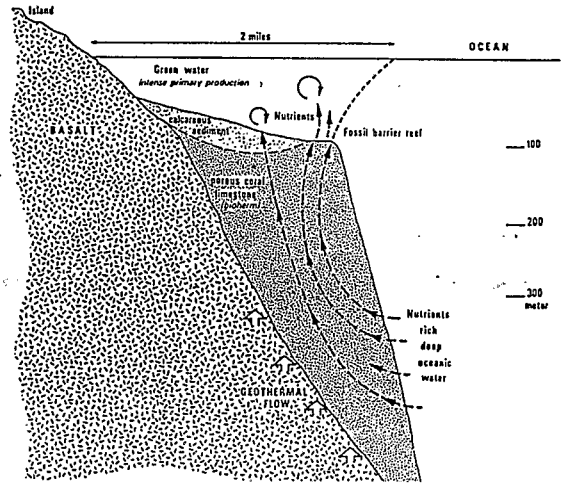

Figure 8. Specific island mass effect around Marquesas : phytoplankton blooming due to seepage of nutrients through calcareous platform (fossil reef).

rich endo-upwelled water does continue to seep through the immersed platform : nutrients being not consumed by absent zooxanthellae are available for the growing of oceanic phytoplankton, the concentration of which is high (figure 8). With this specific exogenous and permanent flow of nutrients, the food chain is particularly vigourous, which can explain the spectacular "island mass" effect around these islands.

A NEW PARADIGM FOR AN OLD PARADOX

At this stage of the discussion we are well aware that we have used a rather scattered patchwork of data and field observations not originally aimed at supporting a definite model ; but the fact that these observations and measurements fit well with our original concept and were globally unexplained by traditional hypotheses constitutes a strong incentive to continue in that direction. We think in particular to the hydrocarbures traces found in semi-lifted atolls of Tonga archipelago : there is some probability that the same kind of enrichment process already described for phosphate-apatite deposit could, in sligtly different physical environment, lead to the formation of kerogene and then to oil.

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 permanent process, endo-upwelling prevents any nutrient limitation, or any unbalance between relative amounts of phosphate and nitrate needed for autotrophic growth : coral reefs represent the biological response of reef building communities to localized nutrient rich endo-upwelled flow : applications and implications at several space-time scales go well beyond scope of this short paper.

Following our model, an atoll is a possible answer to 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".

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