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Self-limiting geothermal convection in marine carbonate platforms

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Abstract. Large scale inward and upward density-driven convective circulations occur in the porous structure of many marine carbonate platforms. Their geochemical implications are of prime importance for a variety of problems where a substantial transport of chemical species is required. In the present study we show, using simple thermal and hydraulic arguments, that there is a negative feedback between convective flow and heat transfer. This results in an upper limit on geothermally-driven vertical fluxes, irrespective of the hydraulic conductivity of the medium. This concept is potentially applicable to a variety of problems. Taking the example of two on-going debated questions in the reef scientific community, i.e., diagenesis and nutrient cycling, we show unambiguously that whereas convective circulations in coral reefs are compatible with dolomitization models, they are too low by at least one to two orders of magnitude to be a significant process in the nutrient budget of coral reefs.

Introduction

It is now well established that large scale convective circulations can occur in oceanic carbonate platforms (Rougerie et al., 1991; Henry et al., 1996; Leclerc et al., 1999), driven by density gradients. For a given hydraulic gradient ∇h (a dimensionless measure of the density disequilibrium across the system), these circulations increase linearly with the hydraulic conductivity K (in m/s) of the medium following Darcy's law:

$$V = K \times \nabla h \quad (1)$$

The Darcy velocity V (in m/s) is an average velocity and represents a water flow (in m³/s) per unit area (in m²). Actually, flow takes place only through part of the cross-sectional area. It can be shown (Bear and Verruijt, 1987) that the Darcy velocity is linked to the real velocity U of the fluid in the interconnected porosity (pore velocity) by $U = V/n$, where n is the volumetric porosity of the medium.

From (1), for sufficiently large values of the hydraulic conductivity K , the convective circulations may be able to quantitatively transport significant amounts of chemical species in and out of the system. Such a transport mechanism has actually been invoked to account for various biogeochemical processes in marine carbonate platforms including diagenesis (Simms, 1984; Buddemeier and Oberdorfer, 1986) and nutrient supply to coral reefs in oligotrophic waters (Rougerie et al., 1992; Rougerie and Wauthy, 1993). However, we show here that there is a negative feedback between the hydraulic and thermal regimes so that an upper limit can be placed on the water flux brought

upwards by these circulations. The existence of such a physical limitation on water flow, irrespective of the value of K , is all the more important because large scale hydraulic conductivities are extremely difficult to assess experimentally, even within a factor of a hundred. This is due to the fact that carbonate platforms such as coral reefs are complex porous media with both horizontal and vertical heterogeneity over a wide range of distance scales, including cracks, karsts and strata of composite materials with different permeabilities. In the first part of this study, we demonstrate the reality of such self-limiting fluxes. Then, as an example of the potential of this concept, we briefly examine their implication for dolomitization models and for the nutrient budget of coral reefs, two important problems that are still open to question.

Physics of large scale convective flow

The hydraulic system can be approximated to the first order by a simple U tube, one branch of which represents the ocean while the other branch is filled with the porous carbonate medium of the platform framework (figure 1). In this second branch, the interstitial water is warmed by the residual geothermal flux from the bedrock on which the platform is built and also, from the top, by the warm surface waters.

Figure 1. Marine carbonate platform 1-D representation used in the present study (U-shape).

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These thermal boundary conditions make the second branch lighter than the oceanic branch so that inward and upward convective circulations can develop in the system. In the present study, the examples used are of tropical settings, because of the strong association of carbonate platforms with low-latitudes. Nevertheless, the conclusions potentially apply to a large variety of environments. Using the very simple physical representation described above, we show in the following that, if the Darcy velocity V is increased, the residence time of the interstitial waters will decrease so that they will have less time to warm up and they will become denser. Hence the weight difference between the two branches of the U tube will be reduced and V will tend to decrease. Because of this negative feedback between V and ΔH , the Darcy velocity will be limited to a maximum value $V_{\max}$ that will be reached when the weights of the two branches are equal. One interesting consequence of this asymptotic behavior of the system is that an order of magnitude of the upper limit of the upward flow can be estimated for any marine platform without any assumption as to the hydraulic conductivity. The «order of magnitude» term is deliberately used, because the U tube approximation is a crude description of the real geometry of the system that neglects in particular the inward horizontal component of the real flow. However, it has been shown that large horizontal karstified layers are common features in coral reefs (Buddemeier and Holladay, 1977; Henry et al., 1996; Andrié et al., 1998; Leclerc et al., 1999) as a result of dissolution by meteoric waters during sea level low stands. They act as high hydraulic conductivity conduits connecting the inner part of the structure to the ocean. Hence, as the circulating fluids preferentially enter the karst before moving upwards, the 1-D approximation is reasonable. As will be shown further in the text, this is confirmed by the fairly good agreement between the Darcy velocities calculated with the 1-D approximation and those derived from more sophisticated finite-elements models (Henry et al., 1996; Leclerc et al., 1999).

Because oceanic conditions are almost identical for most coral reefs in the intertropical belt, the water flow will depend only, to a good approximation, on the thickness H of the platform (thicker platforms will tap deeper and denser levels) and on the geothermal flux Φ beneath the platform. We have computed the asymptotic value of the Darcy velocities, $V_{\max}$, for a reasonable range of Φ and H by solving the thermal equation (2):

$$\rho_w C_w V (\partial T / \partial z) = \lambda (\partial^2 T / \partial z^2) \quad (2)$$

where $\rho_w C_w$ represents the water heat capacity in $J/m^3/^\circ C$, λ the thermal conductivity of the saturated medium in $J/s/m/^\circ C$ and V the Darcy velocity in m/s . The surface temperature is that of the surrounding ocean waters ($T=25^\circ C$) and the temperature T_{in} of the incoming recharge water at the base of the structure is given by (3):

$$T_{in} = T_{ocean}(H) + \Phi / \rho_w C_w V \quad (3)$$

where $T_{ocean}(H)$ is the temperature of the ocean at depth H and the term $\Phi / \rho_w C_w V$ represents the temperature increase during the initial horizontal inward transit of the water (see figure 1).

With equations 2 and 3, for any given value of Φ and H , we derive the vertical temperature profile in the platform for increasing values of the Darcy velocity V , then calculate the weight of the interstitial water column, H_{int} , from the equation

Figure 2. Variation of the hydraulic head $\Delta H = H_{ext} - H_{int}$ (expressed in meter of water equivalent) in an oceanic porous platform 1000m thick, as a function of the Darcy velocity V (m/s) for various geothermal heat flows Φ between 0 and 100 mW/m^2 . In the top right inset, the solid line shows the corresponding maximum Darcy velocity $V_{\max}$ sustainable by a given heat flow Φ . For comparison, the dotted line corresponds to the case $T_{in} = T_{ocean}(H)$, i.e., when one neglects the warming of the recharge water during its initial horizontal transit.

of state for seawater and compare it to its oceanic counterpart, H_{ext} . The oceanic vertical temperature profile used in this simulation is a typical tropical thermal profile (Bainbridge, 1982). The effect of salinity on density is neglected. This is correct to the first order since Leclerc et al. (1999) have shown that the maximum salinity effect on interstitial waters' velocities is about 35%.

The results in figure 2 show that as expected, the weight difference between the two branches of the U tube, $\Delta H = H_{ext} - H_{int}$ (expressed in meter of water equivalent), decreases with increasing velocities. The maximum Darcy velocity $V_{\max}$ that a given thermal flux Φ can sustain, is an increasing function of Φ (figure 2 inset, solid line). Figure 3 (solid line) shows the variation of $V_{\max}$ as a function of the platform thickness H . The curve displays a characteristic minimum for recharge depths within the oceanic thermocline. This feature, already observed by Leclerc et al. (1999) using a 2-D finite-element model, is linked to the oceanic thermal vertical structure. Below the thermocline, $V_{\max}$ increases monotonically. For deeper recharge depths ($H > 1500m$), maximum Darcy velocities are almost constant, due to the quasi-constancy of the deep ocean temperature.

In every case, $V_{\max}$ always remains relatively low ($V_{\max} < 1.5 \times 10^{-8} m/s$) for heat flows spanning the whole range of possible values (Moore et al., 1989) from 0 to 100 mW/m^2 . As shown in Table 1, these velocities are consistent with those found for Mururoa atoll by Henry et al. (1996) and by Leclerc et al. (1999) using two independent 2-D finite-element models.

Table 1. Comparison of the present 1-D hydraulic model (asymptotic regime), applied to the case of Mururoa atoll ($\Phi=50\text{mW/m}^2$ and H between 600m and 800m) with average Darcy velocity computed by two independent 2-D finite element thermo-hydraulic models. (N.B. The Henry et al.'s value is deduced from a total water flux of $300\text{m}^3/\text{yr}$ through their modeled platform section).

Model	Mean flow (m/s)	Reference
METIS	2.8×10^{-9}	Henry et al., 1996
CASTEM-2000	2.5×10^{-9}	Leclerc et al., 1999
Present 1-D model		
- for $H=600\text{m}$	5.4×10^{-9}	this work
- for $H=800\text{m}$	6.5×10^{-9}	

Geochemical implications

Dolomitization models

A number of studies have dealt with the understanding of diagenetic processes in carbonate platforms. One of the most studied problems is that of dolomitization, i.e., the transformation of calcite to dolomite following the reaction: $2\text{CaCO}_3 + \text{Mg}^{2+} \rightarrow \text{CaMg}(\text{CO}_3)_2 + \text{Ca}^{2+}$. This phenomenon requires the supply of vast amounts of magnesium from seawater. Different circulation schemes can be envisaged for the delivery of this magnesium (Simms, 1984), including reflux, freshwater lens flows and thermal convection (a review of forces producing head gradients capable of generating such flows and mixing of interstitial water can be found in Buddemeier and Oberdorfer, 1988).

For a typical carbonate platform (with a thickness $H=1000\text{m}$ and a geothermal flux $\Phi=50\text{mW/m}^2$), the thermal convection flow is $7 \times 10^{-9}\text{ m/s}$. The corresponding amount of magnesium transported by the water flux is then $3.7 \times 10^{-7}\text{ mol/m}^2/\text{s}$ (for an oceanic magnesium concentration $[\text{Mg}]=53\text{ mmol/kg}$). Using a dolomitization factor of 10% (Simms, 1984), the above value is sufficient to account for the complete dolomitization of a 100-m thick carbonate platform in 0.9 million years (using a typical porosity of 30%). Although this does not constitute a proof that such large scale convective circulations are actually the right explanation for dolomitization, the above calculation indicates that they are compatible with the dolomitization process.

Nutrient fluxes

Gross primary production in coral reefs is remarkably high, between 4 and $12\text{ gC/m}^2/\text{d}$ (Smith and Kinsey, 1981; Lewis, 1981) when compared to the low productivity of the oligotrophic tropical waters ($0.1\text{--}1\text{ gC/m}^2/\text{d}$). This apparent paradox has raised questions as to how this high metabolism is maintained. Although it was demonstrated that net productivity is rather low (Smith, 1988; Crossland et al., 1991), implying that nutrients are efficiently recycled within the system, the fact remains that most lagoonal waters are significantly enriched in nutrients and organic matter that are eventually exported at a rate depending on the lagoonal waters residence time (Webb et al., 1975; Rougerie et al., 1992). Several studies have unambiguously shown that reefs communities are net exporters of nitrogen in the form of dissolved species (NO_2 , NO_3 , NH_4) and organic matter at a rate up to several thousands micromoles per day and per

square meter of the whole reef area (Charpy-Roubaud et al., 1990; Furnas et al., 1990). Challenging the nitrogen fixation hypothesis, which has gained the widest support in the reef scientific community (Wiebe et al., 1975; Webb et al., 1975), several workers (Rougerie et al., 1992; Rougerie and Wauthy, 1993) have advanced the idea that the missing source comes from deep ocean waters that are brought to the surface through the carbonate framework by geothermal convective circulations (the so-called « endo-upwelling » theory).

For an upper limit of the geothermal heat flux $\Phi=100\text{mW/m}^2$ and a recharge depth of $H=2000\text{m}$, corresponding to high nitrate and phosphate concentrations of 40mmol/m^3 and 2.5mmol/m^3 respectively (Bainbridge, 1982), the maximum possible value for the water flow is $V_{\text{max}}=1.5 \times 10^{-8}\text{ m/s}$. Even in this highly favourable case, nutrient fluxes do not exceed $6 \times 10^{-10}\text{ molN/m}^2/\text{s}$ ($52\text{ }\mu\text{molN/m}^2/\text{d}$) for nitrate and $0.37 \times 10^{-10}\text{ molP/m}^2/\text{s}$ ($3.2\text{ }\mu\text{molP/m}^2/\text{d}$) for phosphate, with the most probable value lower by at least a factor of 2, corresponding to a typical heat flow of around 50mW/m^2 (figure 3). These figures are extremely modest compared to the order of magnitude of export fluxes (N.B. the nitrogen export figures cited above represent an exportation per meter square of the whole platform area and can therefore directly be compared to the nutrient fluxes calculated with the 1-D model). The present study shows that the order of magnitude of the endo-upwelled nutrient fluxes is low and actually falls in the range of the nutrient supply by atmospheric fallout (Schlesinger, 1991; Jaffe, 1992; Jahnke, 1992). Therefore, the importance of endo-upwelling to reefs, which had already been challenged by Tribble et al. (1994) on the basis of nutrient budgets, again can be discounted on hydrologic grounds.

Conclusion

Large scale convective circulations do occur in marine carbonate platforms. Their existence is supported both by

Figure 3. Maximum Darcy velocity V_{max} vs platform thickness (solid line) for a typical geothermal heat flow $\Phi=50\text{ mW/m}^2$ and corresponding endo-upwelled nitrate flux.

borehole thermal and tracer data and by numerical modeling. However, we point out here with very simple hydraulic and thermal arguments that there is a negative feedback between the convective flow and the heat transfer which leads to an asymptotic flow regime, irrespective of the hydraulic conductivity of the medium. This places an upper limit on geothermally-driven fluxes and puts strong constraints on their ability to transport geochemical species in and out of the system. In rather simple hydraulic cases such as coral reef platforms where the system can be described to a reasonably good approximation by a 1-D vertical model, we show that water fluxes do not exceed a few $10^{-8} \text{ m}^3/\text{m}^2/\text{s}$ at most. This value is sufficient to transport the amount of magnesium required by dolomitization models. On the other hand, it is too low by at least one to two orders of magnitude to significantly affect the nutrient budget of coral reefs.

For more complicated porous media geometry, such as continental systems, simplifying 1-D approximations may not always be appropriate and the asymptotic regime should be derived from more sophisticated thermohydraulic models.

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