NUMERICAL ANALYSIS OF SEAWATER CIRCULATION IN CARBONATE PLATFORMS: I. GEOTHERMAL CONVECTION

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ABSTRACT. Differences in fluid density between cold ocean water and warm ground water can drive the circulation of seawater through carbonate platforms. The circulating water can be the major source of dissolved constituents for diageneric reactions such as dolomitization. This study was undertaken to investigate the conditions under which such circulation can occur and to determine which factors control both the flux and the patterns of fluid circulation and temperature distribution, given the expected ranges of those factors in nature. Results indicate that the magnitude and distribution of permeability within a carbonate platform are the most important parameters. Depending on the values of horizontal and vertical permeability, heat transport within a platform can occur by one of three mechanisms: conduction, forced convection, or free convection. Depth-dependent relations for porosity and permeability in carbonate platforms suggest circulation may decrease rapidly with depth. The fluid properties of density and viscosity are controlled primarily by their dependency on temperature. The bulk thermal conductivity of the rocks within the platform affects the conductive regime to some extent, especially if evaporite minerals are present within the section. Platform geometry has only a second-order effect on circulation. The relative position of sealevel can create surface conditions that range from exposed (with a fresh-water lens present) to shallow water (with hypersaline conditions created by evaporation in constricted flow conditions) to submerged or drowned (with free surface water circulation), but these boundary conditions and associated ocean temperature profiles have only a second-order effect on fluid circulation. Deep, convective circulation can be caused by horizontal temperature gradients and can occur even at depths below the ocean bottom. Temperature data from deep holes in the Florida and Bahama platforms suggest that geothermal circulation is actively occurring today to depths as great as several kilometers.

INTRODUCTION

Carbonate platforms are thick sequences of mostly shallow-water carbonates that can develop under a range of tectonic settings, including passive continental margins, intracratonic basins, failed rifts, back-arc basins, and foreland basins. Morphological types can fall under the broad categories of ramp, rimmed shelf, epeiric, isolated, and drowned (Tucker and Wright, 1990). Carbonate platforms are of particular interest to geologists because their generally high permeability and porosity make them excellent conduits for fluid movement and reservoirs for fluid storage. Carbonate rocks contain 60 percent of the world’s known hydrocarbons (Roehl and Choquette, 1985), are host to extensive Pb-Zn ore deposits (Garven and others, 1993), and supply water to an estimated 40 percent of the world’s population (Ford and Williams, 1989). Permeability and porosity in carbonate platforms, however, are quite variable, due both to depositional facies and subsequent diagenesis (Moore, 1989). Although metastable sediments are highly susceptible to early diagenesis by meteoric water, modeling studies have suggested that, because of continued subsidence, carbonate rocks spend most of their history exposed to seawater (Mathews and Frohlich, 1987; Whitaker and others, 1997). Molecular diffusion alone cannot supply the reactants and remove the products of diagenesis, thus a large advective flux is required.

Various mechanisms have been proposed to drive seawater through carbonate platforms (Whitaker and Smart, 1990), including differentials in sea-surface elevation,
evaporative reflux, mixing-zone entrainment, and geothermal convection (fig. 1). A mean sealevel differential of only a few centimeters can create a significant flow of seawater in the shallow subsurface, given the presence of high karstic permeabilities (Whitaker and Smart, 1993). Such differentials can be wind-driven across small islands.
(Atkinson, Smith, and Stroup, 1981; Humphrey, 1988) or caused by regional ocean circulation across large platforms (Marshall, 1986; Maul, 1986). Evaporation of seawater in restricted shallow-water environments can raise salinity to the extent that the associated increase in fluid density causes continuous sinking and circulation of water through the shallow platform (Simms, 1984). When the surface of a carbonate platform becomes emergent, coastward discharge of freshwater creates a compensatory flow of seawater beneath the transition zone (Kohout, 1960). Finally, lateral contrasts in temperature between cold ocean waters and geothermally heated groundwaters create buoyancy-driven convection.

Of the mechanisms listed above, only the last, geothermal convection has the potential to circulate seawater on a regional scale under conditions that occur in nearly all carbonate platforms independent of relative sealevel. Moreover, geothermal convection produces significant changes in temperature along flow paths, changes that in turn affect the thermodynamic equilibria controlling diagenesis. For these reasons, this paper will focus on the mechanism of geothermal convection. We recognize that fluid density can be affected by salinity as well as temperature and that geochemical potential for diagenesis may also be enhanced from the evaporative concentration of seawater. However, this occurs only when a particular combination of sealevel and platform-surface elevations required for reflux exist. This mechanism is considered in detail in a second, companion paper. In this first paper we assume that fluid density is a function solely of temperature. Shallow fresh water is treated as an upper boundary to the saline flow system, and although evaporites are present in some modern carbonate platforms, no direct evidence exists to suggest that related brines migrate significantly beyond the relatively impermeable evaporite layers.

Active geothermal convection has been inferred from temperature profiles in a number of different carbonate platforms. Large scale geothermal convection of seawater was first proposed by Kohout (1965) and Henry and Kohout (1972) on the basis of vertical temperature profiles through the Floridan Aquifer. Inland from the Atlantic Ocean, temperatures decrease with depth to near the bottom of the Floridan Aquifer, where they begin to increase again at rates consistent with the estimated regional heat flux. Ground water at the base of the Floridan aquifer is chemically nearly equivalent to seawater, and the only source of cold seawater is at subsea outcrops along the Straits of Florida. Geothermal convection on a smaller scale has more recently been recognized in Pacific atolls (Saller, 1984; Rougerie and Fagerstrom, 1994; Rougerie, Fichez and Dejardin, 1997) where thermal upwelling has been identified to carry critical nutrients for coral reef growth. The energy for this convective flow is derived ultimately from the normal geothermal heat that warms the platform and the solar energy that causes the oceans to circulate cold waters to great depths. Evidence also exists for geothermal convection in carbonate platforms in the geologic past. The Latemar platform contains a dolomite section which, due to its geometry and isotope content, has been shown to have most likely formed as the result of upwelling geothermally heated waters (Wilson, Hardie and Phillips, 1990). Field investigations have demonstrated that geothermal convection occurs, however, detailed hydrological investigations are impossible as logistical and financial difficulties in accessing the deep subsurface have resulted in an extreme paucity of data for modern platform configurations. Our alternative approach is to conduct an numerical analysis using parameter values that best represent field conditions, and thus to test potential system behavior under a wide range of platform conditions.

Theoretical analyses of fluid convection caused by geothermal heat flux have been undertaken previously (Elder, 1967; Wood and Hewett, 1982). An analysis by Henry and Hilleke (1972) demonstrated that the difference in density between the cold ocean water and the warm platform water would create pressure differences that could drive
seawater through the platform and alter the temperature field. A theoretical and dimensional analysis of geothermal convection in carbonate platforms was derived by Phillips (1991), but the analysis did not extend beyond a homogeneous, rectangular domain. The numerical analyses described here go beyond previous work by specifically investigating the conditions under which geothermal convection is likely to occur. This is done by including heterogeneous permeability configurations, more realistic geometries, and a range of parameter values typical of carbonate platforms.

Understanding fluid circulation in carbonate platforms has wide ranging implications for understanding diagenesis. Seawater circulation through carbonate platforms may be an important control on marine calcite cementation (Harris, Kendall, and Lerche, 1985), deep calcite dissolution (Saller, 1984), and the flushing out of hydrocarbons (Tator and Hatfield, 1975). However, the impetus for many recent studies of seawater circulation (Wilson, Hardie, and Phillips, 1990; Whitaker, Sanford, and Smart, 1993) has been to understand large-scale replacement dolomitization, which is still an area of active debate (Machel and Mountjoy, 1986; Hardie, 1987; Budd, 1997). Results from this study may also benefit our understanding of other environments affected by geothermal convection, such as cooling plutons (Hayba and Ingebritsen, 1997), mid-ocean ridges (Lowell, Rona, and Von Herzen, 1995), or siliciclastic strata (Wood and Hewett, 1982). A comprehensive analysis of any diagenetic process may ultimately require the additional consideration of geological transients and dynamics and coupled reactive transport. Such an analysis is beyond the scope of this paper, in which we have presented only the first step—a more thorough understanding of the fluid flow systematics.

MATHEMATICAL MODEL

Governing equations.—To analyze seawater circulation through carbonate platforms, we solve the partial-differential equations representing fluid flow and heat transport in a porous medium. Although carbonate platforms are composed of significant volumes of fractured limestones and dolomites, our analysis is at a spatial scale sufficiently large enough so that we can assume that fluid behavior within the rock is nearly identical to that within a porous medium. The representative elemental volumes in our numerical model are of sizes that are consistent with the scale at which regional-scale hydraulic conductivity values are appropriate for the representation of karstic limestones (Whitaker and Smart, 1997). Fluid velocities are small enough that the kinetic energy of the water can be neglected, and, thus, Darcy’s law is valid. Under these assumptions we use Darcy’s law written for a fluid of variable density in cartesian tensor notation:

$$q_i = -\frac{k_{ij}}{\mu} \left( \frac{\partial P}{\partial x_j} + \rho g \frac{\partial z^*}{\partial x_j} \right),$$

where \(q_i\) is the specific discharge, \([LT^{-1}]\), \(k_{ij}\) is the intrinsic permeability, a second order tensor, \([L^2]\), \(\mu\) is the dynamic viscosity of the fluid, \([ML^{-1}T^{-1}]\), \(P\) is the fluid pressure, \([ML^{-1}T^{-2}]\), \(\rho\) is the fluid density, \([ML^{-3}]\), \(g\) is the acceleration due to gravity, \([LT^{-2}]\), \(z^*\) is the elevation of the reference point above a standard datum, \([L]\), and \(x_j\) is the coordinate direction.

By substituting Darcy’s law into a mass balance equation, one can obtain the ground-water flow equation. In our analysis, we assume that fluid pressures in the system change quickly over time relative to changes in boundary conditions or physical rock properties. Thus a reasonable assumption is that the system is in steady state with respect to fluid pressure. There are also no sources or sinks of water other than flow through the
boundaries under constant pressure conditions. The steady-state flow equation under these conditions can be written as:

$$
\frac{\partial}{\partial x_i} \left[ \rho k_{ij} \left( \frac{\partial P}{\partial x_j} + \rho g \frac{\partial z^*}{\partial x_j} \right) \right] = 0.
$$  \hfill (2)

Development of the heat-transport equation is analogous to that for fluid flow, except that Fourier’s law is substituted into an energy balance equation. As with fluid mass, internal temperatures are assumed to change quickly in time relative to changes in boundary conditions or changes in physical rock properties. Thus we solve the steady-state form of the energy equation as well. Other assumptions are that the effect of hydrodynamic dispersion on the heat transport is small relative to conductive heat transport and that there are no internal sources of heat within the platform. Under these assumptions, the heat transport can be written as:

$$
\frac{\partial}{\partial x_i} \left( K_i \frac{\partial T}{\partial x_j} \right) - \frac{\partial}{\partial x_i} \left( \rho c_w q_i T \right) + Q_v = 0,
$$  \hfill (3)

where $K_i$ is the bulk thermal conductivity of the porous medium, [EL$^{-1}$t$^{-1}$T$^{-1}$], $T$ is temperature, [T], $c_w$ is the heat capacity of sea water at 25°C, [EM$^{-1}$T$^{-1}$], $Q_v$ is the geothermal heat flux, [EL$^{-3}$t$^{-1}$], $E$ is energy, [ML$^2$T$^{-2}$], and $t$ is time [t].

We assume that the bulk thermal conductivity of the porous medium is a volumetric average of the thermal conductivities of the water and the rock. The bulk thermal conductivity can be expressed as:

$$
K_i = \epsilon K_w + (1 - \epsilon) K_s,
$$  \hfill (4)

where $\epsilon$ is the porosity, [dimensionless], $K_w$ is the thermal conductivity of the water, [EL$^{-1}$t$^{-1}$T$^{-1}$], and $K_s$ is the thermal conductivity of the rock.

While certain theories suggest that a geometric mean is a better representation of the bulk thermal conductivity (Ingebritsen and Sanford, 1998), others have invoked a volumetric average (Voss, 1984). The difference between these two representations for carbonate rocks can be as much as 25 percent, and we address the effect of this magnitude of variation in the sensitivity analysis.

Fluid (seawater) density is specified to be a nonlinear function of temperature by the relation:

$$
\rho = 1025.6 - 0.067417 \cdot T - 0.0037385 \cdot T^2,
$$  \hfill (5)

where the fluid density is in kg/m$^3$ and the temperature is in °C. This equation is based on the data of Keenan and others (1969) and Bolz and Tuve (1973). The sensitivity of the flow and transport to this approximation is addressed later in this paper. Fluid viscosity is also allowed to vary with temperature according to the relation after Meyer and others (1967):

$$
\mu = 239.4 \times 10^{-7} \cdot 10^{2.4837T + 133.15},
$$  \hfill (6)

where $\mu$ is in units of kg/(m · sec) and T is in °C. Although this relation is valid for pure water, the viscosity of seawater is only about 5 percent greater than pure water and standard temperature and pressures. The effect of the viscosity relation on simulation results is addressed later in the sensitivity analysis. Variations in $c_w$, $K_w$, and $K_s$ are assumed to be small over the temperature ranges considered and are thus treated as constants with respect to temperature in this study.

NUMERICAL MODEL

To solve eq (2) and (3) numerically, we used the finite-element ground-water flow and transport model developed by Voss (1984), as modified by substitution of the
temperature-density relation of eq (5). A standard case simulation was created to represent average platform conditions; parameters were then varied in other simulations and compared to the standard case. In order to reduce the computational workload, we simulated a half-platform with a symmetry boundary at the left-hand side (fig. 2A). An ocean depth of 3 km and a half-platform width of 100 km were assigned to the standard case. Side boundary conditions were specified to be no-flow and insulated (no heat flux). The no-flow boundary on the right-hand side of the domain represents the line of symmetry down the center of the platform and does not reflect a physical barrier. The left boundary was extended far enough away from the platform ramp that the boundary condition would not significantly affect circulation near the ramp. In natural systems permeability is heterogeneous and tends to decline with depth, but for initial simplicity permeability was held constant to 5 km depth. A geothermal heat flux of 60 mW/m²,

Fig. 2. Principal features of the simulation domain used for the sensitivity analysis including (A) boundary conditions, (B) finite-element mesh, and (C) isotherms for a heat-conduction-only simulation.
based on data from Griffen, Reel, and Pratt (1977), was assigned at the bottom boundary. In order to buffer the base of the flow zone from this thermal boundary condition, a 2-km section of lower permeability was added to the base of the system. This allows fluid flow to cool the platform beneath the flow zone and divert some of the heat flux before it reaches the base of the flow zone. The permeability of this lower section was specified to be 4 orders of magnitude lower than the upper section. This range of values for permeability of the lower section is consistent with those reported for the oceanic crust (Fisher, 1998). The heat flux was specified at its base at 7 km depth. The finite element grid was constructed using 100 elements horizontally and 70 elements vertically (fig. 2B).

Temperatures in the ocean were specified to decrease as a function of depth by the relation \( T = 25 \exp(-z) \), where \( T \) is in °C, and \( z \) is in kilometers. For the standard case, this simple function creates an ocean bottom temperature of 1.24 degrees and a temperature gradient similar to (though not exactly like) those observed in today’s oceans. This representation is tested later in the sensitivity analysis and shown to be adequate. Temperatures along the ocean/platform interface were specified according to this depth relation, and temperatures along the top of the platform were all specified to be 25°C. Simulation results demonstrate that the temperature gradient in the ocean can create significant horizontal temperature gradients at the edge of a platform, even when heat transfer by advection is negligible (fig. 2C). This temperature gradient is the fundamental basis for geothermal circulation in these platforms. Pressures along the ocean/platform interface were specified to be constant in time and consistent with the temperature-density relation of eq (5) as well as the temperature-depth relation. Pressures were calculated downward in a step-wise fashion using these temperature and density relations. The pressures at the platform top were specified to be zero to represent a relatively shallow water depth and to allow seawater to either enter or exit the platform.

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>( c_w ) – fluid heat capacity</td>
<td>4,182 J/kg ⋅ °K</td>
</tr>
<tr>
<td>( d ) – ocean depth</td>
<td>3 km</td>
</tr>
<tr>
<td>( K_s ) – solid thermal conductivity</td>
<td>4.5 W/m ⋅ °K</td>
</tr>
<tr>
<td>( K_w ) – fluid thermal conductivity</td>
<td>0.6 W/m ⋅ °K</td>
</tr>
<tr>
<td>( k_{xx} ) – horizontal permeability</td>
<td>( 1 \times 10^{-13} ) m²</td>
</tr>
<tr>
<td>( k_{zz} ) – vertical permeability</td>
<td>( 1 \times 10^{-16} ) m²</td>
</tr>
<tr>
<td>( Q_h ) – heat flux</td>
<td>60 mW/m²</td>
</tr>
<tr>
<td>( R ) – ramp width</td>
<td>30 km</td>
</tr>
<tr>
<td>( T_r ) – reference temperature</td>
<td>25°C</td>
</tr>
<tr>
<td>( w ) – platform half-width</td>
<td>100 km</td>
</tr>
<tr>
<td>( \epsilon ) – porosity</td>
<td>0.30</td>
</tr>
<tr>
<td>( \mu_r ) – reference fluid viscosity</td>
<td>0.001 kg/m ⋅ s</td>
</tr>
<tr>
<td>( \rho_r ) – reference fluid density</td>
<td>1,025.6 kg/m³</td>
</tr>
</tbody>
</table>

Parameters for the standard case are listed in table 1. This standard case is the simulation to which all other simulations are compared by varying one parameter at a time. Parameters in the standard case are intended to be representative of an average platform—for example, heat flow and platform geometry are typical of the Florida-Bahamian platform (Smith and Fuller, 1977; Kohout, Henry, and Banks, 1977). Results illustrate the flow and temperature patterns that would develop for these typical platform conditions (fig. 3B). Cold dense ocean water creates fluid pressures at the base of the ramp that are significantly greater than those in the interior of the platform, where warm ground waters of lesser density exist. Seawater therefore circulates inward from the bottom of the ocean and platform ramp and exits at the top and center of the platform. Heat is transported with the water toward the center of the platform, and temperatures at
Fig. 3. Effect of rock thermal conductivity on geothermal circulation illustrated for values of (A) 2.5 W/m·°K, (B) 3.3 W/m·°K, the standard case, and (C) 4.0 W/m·°K.

the platform center are elevated accordingly. Although the permeability within the standard case is homogeneous, the flow is not evenly distributed within the platform. Higher temperatures at the base and center of the platform translate into lower viscosities by eq (6), which through Darcy's law (eq 1) has the same effect as increasing the permeability. Thus seawater circulates preferentially through areas of increased temperature, in this case in the lower and central sections of the platform.

SENSITIVITY ANALYSIS

Fluid parameters.—The fluid properties in this analysis are heat capacity, viscosity, and density. Heat capacity was assigned a constant value of 1000 cal/kg·°K. Experimental data indicate that this value is accurate to within 3 percent for the range of pressures and temperatures encountered in the simulations (Keenan and others, 1969). Viscosity was calculated as a function of temperature based on eq (6), which agrees to within 1 percent with data from Keenan and others (1969) for pure water at atmospheric pressure. Increasing pressure causes an increase in viscosity of about 5 percent for the maximum pressure encountered in the simulation; this deviation was considered small enough to neglect. Simulations were run (results not shown) where viscosity was assumed first to be
constant and then to be a linear function of temperature. Results showed a significant deviation of flow patterns from the standard case with less flow in the higher temperature regions, indicating that an accurate temperature-viscosity relation is necessary for accurate calculations of true flow conditions. This leads to the more general conclusion that in modeling platform or basin-scale circulation an accurate viscosity-temperature relation is crucial for systems with homogeneous permeability fields and likely for heterogeneous systems as well. Some such studies performed recently have assumed a constant viscosity (Matthai and Roberts, 1996; Bitzer, 1996), and others make no statement of the temperature-viscosity relation used.

Fluid density was calculated as a function of temperature only. The relation in eq (5) will predict density differences to within a few percent accuracy for pressures up to 100 bars. Pressure increases to those encountered at 5 to 7 km depth (~500 to 700 bars) can increase densities over 3 percent—a factor about one fifth as large as the density decrease due to increasing temperature. An equation of state for density that includes both temperature and pressure (Fisher and Dial, 1975; Fisher, Williams, and Dial, 1975) was used for a test simulation, and comparison of that test with the standard case showed little difference in the overall fluxes and patterns of flow. Although densities at 5 to 7 km depth were increased by a few percent, the effect is nearly the same for cold and hot water. Thus the overall density difference driving the circulation changes little. A linear temperature-density relation was invoked in another test simulation, and in this case fluxes and flow patterns did vary significantly from the standard case. We concluded that the nonlinear temperature relation of eq (5) was both necessary and adequate for this study. The nonlinear behavior of fluid density with respect to temperature is essential to include in platform or basin-scale simulations when buoyancy-driven forces are significant.

Rock parameters.—The rock parameters in this analysis are thermal conductivity, porosity, and horizontal and vertical permeability. Thermal conductivities of carbonate minerals are well-known and thus the uncertainty in the assigned value is also small. Calcite has a thermal conductivity of about 3.3 Wm⁻¹K⁻¹ at 25°C, while dolomite is slightly higher at about 4.0 Wm⁻¹K⁻¹, but both of these decrease somewhat as temperature increases (Birch and Clark, 1940). The effect on the flow field is depicted in figure 3 by comparing flow conditions under three different possible thermal conductivities. Figure 3B represents the standard case. The values of K in figure 3 represent the thermal conductivities of the solid rock only. The bulk thermal conductivities are calculated using eq (4). Figure 3A represents a simulation with the relatively low thermal conductivity typical for calcite at 150 to 200°C, whereas figure 3C represents a simulation with a typical thermal conductivity for dolomite at 25°C. The simulation in figure 3C could also represent a system with a high percentage of anhydrite, as the thermal conductivity of anhydrite is about 5.0 Wm⁻¹K⁻¹ (Herrin and Clark, 1956). All simulation results are displayed with eight streamfunction intervals, necessitating a different contour interval for each figure. The flux varies from 42 to 24 kg per day per meter of cross section—a factor of less than two.

Porosity affects the potential fluid circulation only through calculation of the bulk thermal conductivity (eq 4). Thus a change in porosity affects the results in the same manner as a change in thermal conductivity. The thermal conductivity of water in the simulations is 0.60 W/m · °K—significantly lower than that of the solid phase. An increase in porosity will result in a decrease in the bulk thermal conductivity. Porosity in natural systems is not likely to get much higher than the standard case (0.30), but significantly lower porosities (<0.10) can exist at depths of a few kilometers (Schmoker and Halley, 1982). In the extreme case, individual layers in a carbonate platform could be composed of anhydrite and have a very low porosity. This could result in a bulk thermal conductivity nearly twice that of the standard case simulation and a geothermal gradient
of less than 15 degrees per kilometer. Figure 3A and C also represent results for simulations with the standard thermal conductivity (3.3 Wm⁻¹K⁻¹) but porosities of 0.53 and 0.12, respectively.

Permeability affects fluid circulation directly through Darcy’s law and the flow equation but also indirectly through the heat transport equation, as Darcy’s law controls the advective flux of heat (eq 3), which in turn affects fluid viscosity. Permeability has a very large potential range of values in carbonate platforms (>10 orders of magnitude), and its distribution can be highly unpredictable. This wide range of potential values causes permeability to be a very sensitive parameter for controlling fluid circulation. The standard case permeabilities were set to $1 \times 10^{-13}$ and $1 \times 10^{-16}$ m² for horizontal and vertical components, respectively. The standard anisotropy is thus set at 1000 to represent the regional effects of having lower permeability fine-grained, well-cemented, or evaporite formations present within the platform. The magnitude of this permeability was increased by one and two orders of magnitude to illustrate the strong effect on the circulation system (fig. 4). Flow rates represented by the streamfunction interval increase by a factor of about 5 and 16 respectively. Temperature fields are also highly perturbed.
because of the cooling effect of the deep ocean water entering the system. Platforms with karstic limestones can have even greater permeabilities, which would cause even greater cooling of the platform interior.

The magnitude of the permeability has a significant impact on the temperature field. With increasing permeability the majority of the platform will incur a temperature decrease associated with inflow of cold ocean water (fig. 4). At the center of the platform, however, an increase in permeability can lead to a slight increase in temperature. For a given depth within the center of the platform, a maximum temperature will be realized for a certain optimum permeability (fig. 5). Permeabilities lower than optimum do not allow a significant amount of heat to be advected toward the platform center, whereas permeabilities higher than optimum circulate so much cold ocean water that the center of the platform cools along with the edges. For the platform geometry of the standard case simulation, a maximum temperature of about 210°C at 5 km depth at the platform center occurs with a horizontal permeability of $1 \times 10^{-13}$ m². At a shallower depth of 1 km, a maximum temperature occurs with a horizontal permeability of $1 \times 10^{-12}$ m². For an even shallower depth of 100 m a maximum temperature occurs with a horizontal permeability between $1 \times 10^{-12}$ and $1 \times 10^{-11}$ m². The difference in temperature relative to a pure conduction model is smaller at shallower depths because of the influence of the constant temperature boundary at the platform surface. Permeabilities greater than $1 \times 10^{-13}$ m² create a more focused thermal upwelling zone at the platform center—evidenced by the convergence of temperatures between the depths of 1 and 5 km (fig. 5).

Circulation within the platform is controlled by both horizontal and vertical permeability. Greater vertical permeabilities allow more thermally buoyant circulation to occur, whereas greater horizontal permeabilities allow circulation to penetrate further toward the center of the platform. Further investigation of the effect of permeability

![Fig. 5. Effect of permeability on the temperatures at the center of a platform.](image-url)
reveals that the flow system can be categorized into three transport regimes. Relatively high horizontal but low vertical permeability causes heat to be transported predominantly by forced convection—the boundary conditions produce an external hydraulic forcing that dominates the fluid flow and heat transport (fig. 6A). Under these conditions a core of upwelling flow at the center of the platform is fed by dominantly horizontal flow originating at the platform margin. Relatively low horizontal but high vertical permeability causes heat to be transported predominantly by free convection—where buoyancy driven flow dominates over external hydraulic forcing (fig. 6B). Under these conditions closed circulation cells dominate flow and transport within the platform. Relatively low horizontal and vertical permeability causes heat to be transported predominantly by conduction (fig. 6C). Also under these conditions, flow through the platform is minimal and isotherms reveal little deviation from an otherwise pure heat conduction system. These three types of transport are end members with gradations between them, yet lines can be drawn to separate roughly the three in two-dimensional permeability space (fig. 7).

Permeability for the standard case simulation and most other simulations in this study is assumed to be constant with depth to 5 km. Natural carbonate platforms do not

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**Fig. 6.** Effect of the heat transport mechanism on the circulation and temperature distribution showing (A) forced convection, (B) free convection, and (C) conduction.
usually display this characteristic; we assumed this in order to simplify this theoretical analysis and to better understand simple system behavior. To approximate a more realistic permeability distribution we simulated three cases in which permeability decreased with depth following relations based on the empirical data of Schmoker and Halley (1982) and Lucia (1995). The data of Schmoker and Halley (1982) reveal that primary porosity in the South Florida carbonate platform is around 40 percent near the land surface but drops off regularly to near 5 percent at a depth past 4 km (fig. 8). We ran two simulations that assumed a best-fit curve for this porosity-depth relation. The data however could also be interpreted as revealing certain depth-dependent zones, where the top zone has a decreasing porosity with depth caused by compaction, the next zone from about 1 to 3 km has a roughly constant porosity with depth as compaction is offset by diagenetic reactions, the third zone has a porosity that continues to decrease with depth, and the fourth zone (below 4 km) has a low porosity due to pressure solutioning. We ran a third simulation that uses a “custom-fit” relation that emphasizes this zonation. The data of Lucia (1995) were based on cores of carbonate rock that had a granular texture and established relations between porosity and permeability for different grain sizes (fig. 9). For our two simulations that used a best-fit porosity-depth relation, we ran the first with the class 1 (coarse-grain size) porosity-permeability relation and the second with the class 2 (medium-to-fine grain size) porosity-permeability relation.

Results for these simulations demonstrate that the vertical distribution of permeability dramatically influences where seawater flows into the platform margin (fig. 10). When permeability decreases to relatively low values at depth, inflow occurs mostly higher through the platform ramp, whereas in the homogeneous case much of the inflow occurred through the sediment on the ocean bottom. The class 1 porosity-permeability
relation yielded a system where flow was predominantly shallower than 1 km (fig. 10A). The class 2 porosity-permeability relation had lower permeability values overall and yielded a conduction-dominated system (fig. 10B). The custom-fit porosity-depth relation yielded a system where seawater entered the platform in significant amounts down to 3 km depth (fig. 10C). All three simulations, like the standard case, assumed a vertical anisotropy of 0.001, and all three were based on porosity-permeability relations estimated from primary porosity values. The presence of significant secondary porosity (fractures or karst features) would increase permeability values and complicate the flow patterns further.

**Platform geometry.**—Carbonate platforms can form on different scales and with different geometries. Ocean depth can vary greatly at the edges of platforms. The Florida-Bahama megabank is one example with water depths of 3 km in the Gulf of Mexico to 4 km in the Atlantic Ocean and only 0.5 km in the Straits of Florida. Simulations with ocean depths of 1 and 2 km were compared with the standard (3 km) case (fig. 11). Shallower ocean depths cause slightly less fluid circulation. This sensitivity analysis also demonstrates that closed convective circulation can occur to depths of many kilometers below the ocean bottom. This circulation is driven by the density differences that result from the horizontal temperature gradients caused by the presence
Fig. 9. The relation between porosity and permeability measured on cores from South Florida and based on grain size where class 1 data are coarse, class 2 are medium to fine, and class 3 are very fine to silty. Lines indicate best-fit relations used in flow and transport simulations.

of cold ocean water next to the bank (fig. 11C), in spite of the fact that the ocean water itself does not enter the closed section of the convection cell. We propose that this may be an important mechanism for driving fluid circulation in the upper crust (down to 15 km depth). Ocean water at the bottom of an oceanic trench could be 20 percent denser than much warmer ground water at similar depths, resulting in an excess hydraulic head of 2 km relative to the platform interior. Although regional permeabilities at such depths may not always be great enough to allow vigorous circulation, fault or fractures zones may provide permeable conduits along which such circulation could occur. Evidence that such circulation may be occurring near the Bahamas is presented in the discussion section.

Platforms widths can vary from several kilometers to hundreds of kilometers. To investigate the effect of platform width on fluid circulation we ran two simulations with platforms narrower than the 100 km half-width of the standard case (fig. 12). The narrowest platform had a 20 km half-width and still generated a significant amount of circulation. As the aspect ratio of the platform decreases, fluids can be driven to the center of the platform with a smaller permeability anisotropy. Changing platform width also changes the location of the outflow face. Large platforms should have an outflow area near the platform center, whereas in progressively smaller platforms the outflow area should tend to shift toward the platform margin and then downward onto the ramp, where most discharge might occur at a kilometer or so depth.
Fig. 10. Effect of the permeability-depth relation on geothermal circulation illustrated by assuming different porosity-depth and porosity-permeability relations based on data from figures 8 and 9, respectively.

A geometrical feature related to the width is flow convergence. Small carbonate platforms exist most frequently in nature as atolls, whereas large platforms tend to form rimmed shelves adjacent to continental land masses. Circulation within an atoll may be essentially radial, as flow can enter the margin around the circumference of the atoll. Simulation of an atoll would thus be more appropriate in radial rather than cartesian coordinates. Such simulations show somewhat different flow and temperature patterns than simulations in planar, cross-sectional coordinates (fig. 13). Because the cross-sectional area through which flow occurs decreases toward the platform center, little flow reaches the very center of the circular platform. This convergence of flow and advected heat, however, results in higher temperatures at the platform center than the standard case. The results shown in figures 12 and 13 illustrate the effects that would occur in a three-dimensional flow system within a platform. Linear and radial coordinates are two-dimensional endmembers, and a three-dimensional system would have flow patterns similar to these patterns. Investigations of particular three-dimensional flow patterns are not warranted for this study as we seek only to understand general controls on the flow systematics.

Carbonate platforms can form under a variety of sedimentological conditions which, in turn, can affect the geometry of the platform, most notably the angle of the
Fig. 11. Effect of ocean depth on geothermal circulation illustrated for values of (A) three, standard case, (B) two, and (C) one kilometers.

margins or ramps. On the basis of such criteria, platform margins have been classified as accretionary, erosional, or escarpment (Tucker and Wright, 1990), with respective ramp angles of approx 3 to 8 to 30 degrees. We simulated ramp angles across this range (erosional for the standard case), and results indicate that the effect of margin steepness on fluid circulation is relatively minor (fig. 14). Further investigation on the effects of variable ramp-slope configurations on convection is therefore not warranted.

Boundary conditions.—One of the most challenging aspects of creating mathematical models that represent natural geologic systems is to assign appropriate boundary conditions. The upper boundary condition of a carbonate platform is not difficult to treat mathematically. The ocean is virtually an infinite reservoir of constant composition from which fluid can be extracted, and thus it makes an ideal constant-pressure boundary. Temperatures along that boundary can also be approximated without difficulty, though small variations in temperature-depth profiles exist today around the world, and greater variations may have existed over geologic time. The standard case has a simple approximation for temperature with depth of $T = T_o \exp(-z)$, where $T_o$ is the temperature at the surface (25°C is assumed) and $z$ is the depth in kilometers. This profile differs somewhat from ocean profiles today in its exact shape but was invoked because of its
simplicity and the fact that it yields a realistic bottom temperature of between 1° and 2°C. For other simulations, conditions were hypothesized to be either colder (ice house conditions) or warmer (greenhouse conditions). These profiles were obtained by using an exponential term of \((-3z)\) and \((-0.3z)\), respectively. Results indicate the overall circulation is relatively insensitive to the ocean temperature profile (fig. 15). The effect of ocean temperature is two-fold: there is a difference in density contrast between the ocean water and platform groundwater that would alter the fluid flux, but temperature also affects viscosities, affecting the flux in an opposing manner to the density contrast. The viscosity effect is greater than the density effect, with the result being a slight increase in flux for warmer ocean conditions.

The boundary at the surface of the platform is less likely to be stable over time than the sides. Sealevel changes can result in platforms being emergent (an exposed land surface with a fresh-water lens), near-sealevel (potentially hypersaline conditions because of evaporation and restricted surface water movement), submergent, or drowned. Either of the last two conditions are deep enough for free surface water circulation. The standard case has assumed conditions being submergent or drowned. These different platform conditions were simulated to test their effect on fluid circulation. To simulate an
Fig. 13. Effect of coordinate system on geothermal circulation illustrated for (A) cartesian coordinates (standard case), (B) radial coordinates, and (C) radial coordinates and a 20-km-wide platform.

emergent platform, it was assumed that a fresh water lens had developed, acting as a barrier to seawater flow. Across the top of the platform the constant pressure-temperature boundary condition was replaced by a no-flow/constant-temperature condition. This forces seawater to circulate back toward and discharge at the top of the margin (fig. 16A). This extra travel distance results in a somewhat lower flux than that in the standard (submerged to drowned) condition. To simulate the near-sealevel condition, it was assumed that a shallow bank of elevated salinity water existed at the top boundary, increasing the pressure relative to normal hydrostatic conditions. In order to test the extreme situation, a 5-m-deep layer of brine was assumed with a density ten times that of sea water. This caused only minor changes in fluid circulation, as the excess seawater head (relative to hydrostatic seawater) at the platform’s top surface is only about 1 m, compared to about 12 m of excess head at the ocean bottom. The flux direction was reversed near the platform margin, but discharge of seawater still occurred near the platform center. Different permeability distributions in the upper platform can allow more reflux to occur, but investigation of the complete reflux phenomenon are reserved for the second paper in this series.
Heat flux is applied across the entire bottom of the domain at a constant value of 60 mW/m² in the standard case. Although this value is based on field measurements from a typical carbonate platform (Griffen, Reel, and Pratt, 1977), natural variations occur for different crustal terrains, and field measurements can often be complicated by perturbations in the temperature profiles due to ground-water flow. Thus it is important to estimate the effect of different geothermal heat fluxes on fluid circulation. The results indicate that fluid flow is somewhat sensitive to the assumed heat flux (fig. 17). A heat flux of half the standard case results in less than half the fluid flux. An increase to 100 mW/m² increases the fluid flux by more than a factor of two.

DISCUSSION

Implications for diagenesis.—The fluid flux estimates from these analyses have direct implications for diagenesis. Many diagenetic reactions rely upon ground water to transport reactants to and products away from the reaction sites. The extent of potential mineral transformations is often calculated in terms of the required water-to-rock ratio that assumes a certain reactant concentration for the inflowing water. Such a water-to-rock ratio can be calculated for the platform as a whole by dividing the total simulated
Fig. 15. Effect of ocean temperature-depth gradient on geothermal circulation illustrated for cases where (A) \( T = 25\exp(-3z) \), (B) \( T = 25\exp(-z) \) (standard case), and (C) \( T = 25\exp(-0.3z) \), where \( T \) is the temperature in \(^\circ\)C and \( z \) is the depth in kilometers.

The flux of seawater through the platform by the total mass or volume of rock in the platform (fig. 18). It is clear that relatively high permeabilities are required for a significant quantity of water to have flowed through the platform in 10 my. Dolomitization, for example, requires a volumetric water-to-rock ratio of greater than 400, even assuming local equilibrium, suggesting that dolomitization of the entire platform would be unlikely once the platform has grown to full scale (a condition we have assumed in these simulations as a starting point). On the other hand, diagenesis during platform growth would allow similar volumes of water to move through less rock, resulting in greater water-to-rock ratios. We believe this to be the likely explanation for those platforms that are nearly completely dolomitized.

Field verification.—Theoretical studies are most useful when their predictions can be corroborated by observations in nature. Results of simulations in this study have been presented as two-dimensional cross sections, but in real platforms data are available only in the form of temperature-depth profiles from drillholes. Other rock properties and their distributions within the platform are usually not sufficiently well-known to quantify regional flow and transport. The magnitude and distribution of permeability strongly
influences temperature-depth profiles within a platform. Temperature profiles at the edge of a platform can range from a linear heat-conduction profile for low permeabilities to a near-ocean-temperature profile for very high permeabilities (fig. 19A). A nearly isothermal profile would be caused by a permeability of approx $1 \times 10^{-12}$ m$^2$. Heterogeneous permeability distributions can cause temperature profiles with more curvature and/or inflection points, as is illustrated by profiles for the simulation where permeability decreased with depth based on porosity/permeability data (fig. 19B).

Areal distributions of temperatures within a platform may also prove useful for analyzing fluid circulation. We present here some areal and profile observations from carbonate platforms that we believe are evidence for the type of geothermal circulation predicted by our analyses. One feature predicted by many of the simulations is the pattern of elevated temperatures at the platform center, with relatively cool temperatures at the platform edges caused by the inflow of cold ocean water. The Florida platform has a sufficient number of wells drilled into it, at sufficient depths, such that recorded temperatures should be evidence for or against geothermal circulation. A map of such temperatures near the base of the Floridan aquifer reveals that temperatures are indeed higher at the center of the platform and cooler temperatures at the edge (fig. 20). Note
that the center of the Florida platform is near the west coast of the state—the continental shelf extending into the Gulf of Mexico represents the other half. Several warm-water springs (for example, Mud Hole spring) also exist along the western coast of Florida (Kohout, Henry, and Banks, 1977). Although most of our simulations assume that the platform is completely drowned and the Florida platform is half drowned and half emergent, both drowned and emergent platforms should produce similar temperature anomalies (fig. 16), and the temperature pattern in Florida is consistent with our simulations (fig. 4), suggesting that active geothermal circulation is occurring today. This observation was made by Kohout (1965); our quantitative analysis further supports his hypothesis. Topography-driven flow can be ruled out because there is little or no topography in Florida that could drive a regional flow system. Saline-buoyancy driven flow can be ruled out because the warm-water submergent springs have very near seawater concentrations (Kohout, Henry, and Banks, 1977).

Deeper temperature data are also available for the extended Florida-Bahama platform. These data show that nearly all deep temperatures are less than the values that would be expected from a system where only heat conduction operated (fig. 21). The Doublon-Saxon #1 well drilled near the southwestern edge of the Bahamas platform
Fig. 18. Effect of permeability on the water-to-rock ratio experienced by the standard platform over 10 my.

Fig. 19. Effect of permeability on temperature-depth profiles at the standard platform edge for cases with (A) constant permeability and (B) permeability that decreases with depth according to the relations in figures 8 and 9.
Fig. 20. Deep-hole temperature data from the Florida-Bahamian carbonate platform compiled from Kohout, Henry and Banks (1977) and Walles (1993).

(fig. 20) reveals amazingly cool temperatures (25°-50°C) at depths between 4 and 7 km. The full temperature profile reveals a temperature reversal with a local minima at 4 km (Walles, 1993). Although temperature profiles in oil test holes are often run before the rock has returned to its predrilling thermal state, these temperatures were obtained after several runs of the logging tool over several days and are good indications of, at least, relative changes in subsurface temperature with depth. The well log from this hole reveals many cavernous and diagenetically altered zones at these depths and the possible presence of two major thrust faults. The faults may create conduits for fluid flow, but relatively rapid thrust faulting can also create temperature anomalies solely through vertical displacement of rock of dissimilar temperatures (Brewer, 1981). The deep temperature information implies significant fluid circulation at depths below any nearby ocean bottom. The Puerto Rico Trench is 12 km deep but hundreds of kilometers from any of the well locations. We conclude that geothermal circulation of ocean water is occurring at these depths, with some of the water moving downward through the ocean bottom, as predicted in certain of our simulations.

CONCLUSIONS

The difference in fluid density is the major drive behind geothermal circulation in carbonate platforms. Temperature differences create the density differences that drive the fluid circulation, whereas the effect of pressure on density does not significantly affect fluid circulation. The viscosity of seawater is highly temperature dependent, such that inflowing seawater has a tendency to circulate through warmer sections of the platform—
the deeper and central sections—given an otherwise homogeneous permeability distribution. The presence of evaporite minerals within the platform can make a nontrivial difference in the bulk thermal conductivity and, thus, fluid circulation patterns or postulated conductive temperature-depth profiles.

Permeability is the major controlling factor on the magnitude of the fluid flux. Carbonate rocks can have permeabilities that are sufficiently high to allow large volumes of water to move through platforms, volumes high enough to alter the temperature field significantly. Three different heat transport mechanisms could occur within a platform: free convection, forced convection, or conduction. The dominant mechanism is controlled by the values of the vertical and horizontal permeability. An anisotropy of at least 100 is required for seawater to penetrate significant distances into the interior of most platforms. Simulations that invoke porosity-depth relations and porosity-permeability relations from field samples suggest that circulation may drop off dramatically with depth, though the presence of secondary permeability could maintain circulation.

Neither platform geometry nor natural variations in the ocean temperature profile are major controls on the magnitude of the convective fluid flux. Platforms juxtaposed to deep ocean basins, however, can have large horizontal temperature gradients that could, given an adequate permeability, generate convective circulation many kilometers below the ocean bottom. The fluid flow and temperature patterns in the simulations in this study are similar to those observed in or inferred from the Floridan platform. Tempera-
tures within the Florida nd Bahamas platforms are consistently elevated toward the platform center and lower near the platform margins, a trend that is repeatedly predicted in the theoretical analysis. The relative position of sealevel affects the flow pattern to some extent, and shallow water conditions at the platform top may generate saline waters that can reflux into the platform, but the amount and patterns of circulation induced by such reflux conditions are not addressed here but will be the subject of the second paper in this series.

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