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# Simulation of Brine Reflux and Geothermal Circulation in Large Carbonate Platforms: An Attempt to Predict Dolomite Geo-Bodies

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**Abstract:** Significant volumes of the worlds proved reserves are in dolostone reservoirs. Scope for recover and success of new exploration plays depend on the chances of encountering dolostone reservoirs with good reservoir properties.

Although dolostones make excellent reservoirs in favorable cases, the prediction of its location, geometry and rock properties has not yet been achieved fully. Two mechanisms that have been put forward recurrently to explain pervasive dolomitization of extensive carbonate platforms are: 1) Brine reflux due to fluid density gradient, 2.) Brine flow generated by geothermal convection process during burial. This paper will discuss the results obtained by using COMSOL to model brine reflux and geothermal convection processes for dolomitization of large carbonate platforms. This paper will attempt to demonstrate the benefits of using COMSOL to generate models for quicker prediction of the shapes of dolostone geo-bodies.

COMSOL is chosen to model this process as it provides a multi-physics framework for solving coupled systems as in the case of brine reflux and geothermal convection.

Since Dolomitization processes sometimes also alters the underlying porosity and thereby permeability of the porous medium. In this paper the porosity and permeability changes resulting from dolomitization process will also be discussed.

**Keywords:** Dolostone, Carbonate platforms, Brine reflux, Geothermal convection, Dolomitization, Density gradient and COMSOL.

## 1. Introduction

A significant proportion of world hydrocarbon reserves are located in dolostone reservoirs. From the exploration point of view the prediction of location, geometry and rock properties of these dolostone geo-bodies in the hydrocarbon reservoirs is an important and challenging endeavor.

Dolostone reservoirs form due to the diagenetic alteration of carbonate rocks, namely dolomitization.

A number of dolomitization models exist in literature, but a significant number of dolostone reservoirs are interpreted as formed during early diagenesis occurring due to brine reflux [1]. Brine reflux model was first proposed by Adam and Rhodes in 1960 [2] to explain dolomitization of Permian reefs in West Texas. Since then reflux circulation is widely acknowledged to explain dolomitization of carbonate platforms in the geological record [3, 4, 5].

The two most common brine reflux mechanisms that have been put forward recurrently to explain pervasive dolomitization of carbonate platforms are, 1.) Gravity driven brine reflux due to density gradient, and 2.) Brine circulation due to geothermal heating. Evaporation of restricted bodies of seawater can result in the generation of high density brines that subsequently flow downward under the influence of gravity; this process is commonly known as brine reflux due to density gradient. Geothermal heat flux causes heating of the underground waters, which create geothermal convection forcing heated ground waters to move upward forming convection cells.

The driving force for brine reflux is the density gradient between platform top brines and underlying platform ground water for brine reflux and vice-versa for geothermal brine circulation. These transient convection problems have been identified for flows in porous media and were first looked at by Elder's in 1960's [6, 7]. In this paper we will revisit the problem of transient convection in porous media flows and we will employ the capabilities of COMSOL Multiphysics to model this problem. Using the capabilities of COMSOL we will try to predict the shapes of dolomite geo-bodies formed due to geothermal and brine reflux circulation. We will present a comparison of predicted geo-bodies shapes with conceptual and geological outcrop analogues. We will also attempt to predict the

changes in rock properties e.g., porosity and permeability due to brine reflux circulation.

This paper is organized as follows: Section 2 presents a brief description of dolomitization process. Mathematical model for brine and geothermal circulation is presented in section 3. Section 4 outlines the parameters used in construction of geological model. Boundary conditions and model setting for COMSOL simulations are presented in section 5. Numerical simulation results are presented in section 6. Conclusions follow in section 7.

## 2. Dolomitization

Physico-chemical changes that occur in sediments after depositions, known as diagenesis, can significantly alter the chemical and petrophysical properties of rocks. The knowledge of diagenetic processes is crucial to understand and predict the rock property distribution of rocks hosting mineral deposits, hydrocarbon and/or aquifers. Dolomitization is a diagenetic process and is referred to the replacement of calcite ($CaCO_3$) by dolomite ($CaMg\ (CO_3)_2$). Although the exact form of the reaction and the associated volume change is uncertain, dolomitization is commonly described by stoichiometric equation

$$\underset{\text{(Calcite)}}{2CaCO_3} + Mg^{2+} \leftrightarrow \underset{\text{(Dolomite)}}{CaMg\ (CO_3)_2} + 2Ca^{2+} \quad (1)$$

where one mole of calcium is replaced by one mole of dolomite. In this case of mole to mole replacement porosity is created as a result of the reaction. As indicated by this reaction 1, dolomitization require substantial mass transport of magnesium and may contribute to formation of calcium-rich, magnesium depleted basinal brines. Conceptual and numerical models that have been used to explain dolomitization of carbonate platforms center primarily on variations of the mixing-zone, reflux, and geothermal convection models. Mixing-zone models rely on the fact that some mixtures of fresh groundwater and seawater are supersaturated with respect to dolomite but unsaturated with respect to calcite. Other models for dolomitization require hyper saline brines. In terrestrial sabkha environments, evaporation from water table and precipitation of aragonite and anhydrite create hyper saline, magnesium rich brines that are supersaturated with respect to dolomite. Saline brines play an important role in the reflux model for dolomitization. During reflux, denser brine form by evaporation in restricted flow shallow platform environment, and these brines sink and flow downward due to gravity. Refluxing fluids may reach depths in excess of 1km and appear capable of delivering substantial supply of magnesium for dolomitization. This process is further discussed in detail in [8].

## 3. Mathematical Model

Density variations between two fluids can initiate flow even in a still fluid. In earth, density variations can arise from naturally occurring salts, subsurface temperature changes, migrating pollutants or migration of fluids due to subsurface compaction. This buoyant or density driven flow factors influences the fluid movement in salt-lake systems, saline-disposal basins, dense contaminants and leachate plumes, geothermal reservoirs etc.

Elder [6, 7] was first to study thermal convection in a laboratory experiment. Voss and Souza [9] re-casted the Elder's problem for salt concentration and this became the benchmark for many researchers to test variable-density driven flow models. In this paper we will use the formulation from Voss and Souza to model the brine reflux problem and Elder's formulation to model the geothermal reflux circulation.

### 3.1 Equations Governing Brine Reflux Circulation

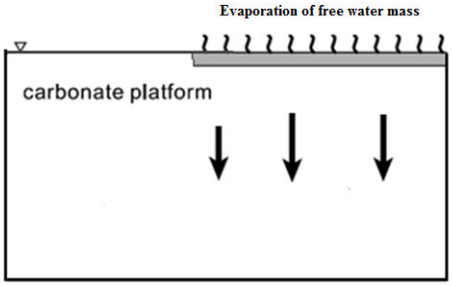


**Figure 1**. Conceptual model of reflux circulation of magnesium rich basinal brine.

The brine reflux circulation model for dolomitization, which is essentially movement of magnesium rich brine through a costal sabkha, salt-lake system or saline-disposal basin (Figure 1) causing replacement of calcium carbonate to calcium magnesium carbonate, can be created by examining the

Elder's problem for magnesium-rich brines via a two way coupling between Darcy's law for fluid flow in porous media and solute transport equation. We can define the fluid flow part of the brine reflux circulation problem using the Darcy's law with an extra term:

$$\rho S(\partial p/\partial t) + \Phi(\partial \rho/\partial c)(\partial c/\partial t) + \text{Div}\,(-\rho\,(K/\eta)\,\text{Grad}\,(p+\rho g D) = 0 \quad (1)$$

where the pressure, $p$ (in units of $kg/s^2m$), and the concentration, $c$ ($kg/m^3$), are dependent variables. In this equation $\rho$ is the density ($kg/m^3$); $S$ is the storage coefficient ($s^2m^2/kg$); $t$ is the time; and $\Phi$ is the porosity. The divergence operator has a velocity multiplied by a fluid density where $K$ is the permeability ($m^2$) of the porous medium, $\eta$ is the viscosity (kg/s m), $g$ is gravity ($m/s^2$); and D is the vertical coordinate, y.

Now we define density as function of concentration according to:

$$\rho = \rho_0 + \gamma\,(c-c_0) = \rho_0 + ((\rho_s - \rho_0)/(c_s-c_0))(c-c_0) \quad (3)$$

Multiplying the time-rate change in concentration by $\gamma$ gives the change in mass stored per time as a function of concentration. The density, $\rho$, appears as a multiplier to the time-rate change in pressure and also as a scalar multiplier of the velocity

$$\mathbf{u} = -\,(K/\eta)\,\text{Grad}\,(p+\rho g D) \quad (4)$$

where $\mathbf{u}$ is the vector of direction seepage rates also known as Darcy velocity. Storage is negligible in the Elder problem, and storage changes come from variation in density as a function of concentration.

The governing equation for solute transport is given as:

$$\theta_s \partial c/\partial t + \text{Div}\,[-\theta_s D_L\,\text{Grad}(c) + \mathbf{u}c] = 0 \quad (5)$$

where $D_L$ is the hydrodynamic dispersion tensor ($m^2/s$); $\theta_s$ is the fluid volume fraction; c is dissolved concentration ($kg/m^3$); $\mathbf{u}$ is the Darcy velocity (m/s); and $S_c$ is the quantity of solute added per unit volume of porous medium per unit time ($kg/m^3d$). In Elder's problem, the contaminant spread only by advection and molecular diffusion. With a typical transport problem, the hydrodynamic dispersion tensor, $D_L$, also contain mechanical mixing owing to variation in velocity. The diagonal component, $D_{Lii}$, of the tensor is given as:

$$\theta D_{Lii} = \alpha_1\,(u_i^2/|\mathbf{u}|) + \alpha_2(u_j^2/|\mathbf{u}|) + \tau D_m \quad (6)$$

where $\alpha$ is the dispersivity (m); the subscripts "1" and "2" denote longitudinal and transverse flow directions respectively; $\tau$ is tortuosity; and $D_m$ is the coefficient of molecular diffusion ($m^2/s$). The contaminant source i.e. magnesium rich brine in the model is the saline disposal basin or salt-lake system.

### 3.2 Equation Governing Geothermal Reflux Circulation

In order to model the geo-thermal reflux circulation process as shown in the conceptual model, Figure 2, we need to solve the coupled partial-differential equations representing advection and convection of fluid flow in porous medium. This is achieved by coupling of heat and solute transport in porous media through Darcy's law and equation for heat and solute transport, respectively. The Darcy's law for fluid flow and solute transport is already covered in previous section via equation 1-6; the equations governing heat transport are presented in this section.

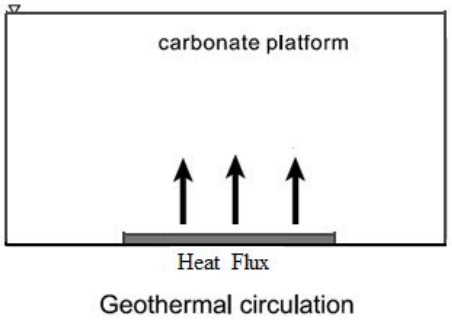


**Figure 2.** Conceptual model of geothermal circulation under the influence of heat flux.

$$\partial/\partial t(\rho_b\, c_{p,b} T) = -\text{Div}\,(\lambda\,\text{Grad}(T)) + \text{Div}\,(\rho_w\, c_{p,w} T\mathbf{u}) + Q \quad (7)$$

$$\partial/\partial t(\theta \rho_w) = \text{Div}\,(\rho_w\,\mathbf{u}) \quad (8)$$

where, $T$ is the temperature ($^oC$), $\lambda$ is the thermal conductivity (W/mK), $\rho_b\ c_{p,b}$ is the bulk thermal capacity per unit volume of saturated porous medium, i.e.,

$$\rho_b\, c_{p,b} = \Phi \rho_w c_{p,w} + (1-\Phi)\,\rho_s c_{p,s} \quad (9)$$

where Φ is the porosity of the porous medium, $\rho_w$, $\rho_s$ and $c_{p,w}$, $c_{p,s}$ are the densities (kg/m$^3$) and thermal capacities (J/K) of ground/seawater and solid phase. Q is the geothermal heat flux (W/m$^2$) and **u** is the Darcy velocity (m/s). Equation 7 stands for the conservation of heat as it is transported by the flowing ground/seawater and conduction. Equation 8 describes the conservation of mass.

The fluid density is specified to be a nonlinear function of temperature by the following relation:

$$\rho_w = 1025.6 - 0.06742T - 0.00374T^2 \qquad (10)$$

where the fluid density is in kg/m$^3$ and temperature is in $^o$C. The fluid viscosity is also allowed to vary with temperature and is given as:

$$\mu = 239.4\ e\text{-}7 * 10^{248.37/T+133.15} \qquad (11)$$

where μ is in units of (kg/ms) and T is in $^o$C.

### 3.3 Dimensionless Parameters and Instabilities in Brine and Geothermal Reflux Circulation

Brine and geothermal reflux circulation instabilities may form due to significantly large difference in density between the basinal fluids and groundwater. These instabilities cause lobes of dense/light fluid to move downward/upward (reflux/geothermal), counterbalanced by less dense/heavier fluid moving upwards/downwards. The onset of these instabilities is governed by the value of dimensionless numbers, the Rayleigh number $R_a$, defined as the ratio between the buoyancy forces trying to cause flow to other forces trying to resist flow, and the Peclet number $P_e$, defined as the relative rates of advection and diffusion/dispersion. Another dimensionless parameter that is important with respect to the Dolomitization process is the Damkohler number $D_a$, defined as the rate of reaction relative to rate of advection. The Peclet number and Damkohler numbers are important as they help in getting an estimate of the range of applicability of macroscopic equations for the advection-reaction-diffusion systems as shown in Figure 3. Figure 3; help us in identifying the regimes for applicability of reactive transport in porous media for modelling Dolomitization.

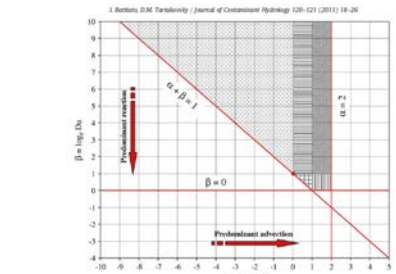


**Figure 3**. Figure showing a phase diagram indicating range of applicability of macroscopic equations for the advection-reaction-diffusion systems based on $D_a$ and $P_e$, modified from [9].

### 4. Geological Model: Static Parameters

In this study we have used realistic models of varying porosity with depth for all simulations. We have used a homogeneous media modified only by a *Φ-K* decreasing trend vs. depth relationship for carbonate rocks developed by Schmoker and Halley [11] as shown in Figure 4. The porosity versus depth relationship as inferred from Figure 4 is given as:

$$\Phi = 0.4173e^{-z/2498} \qquad (12)$$

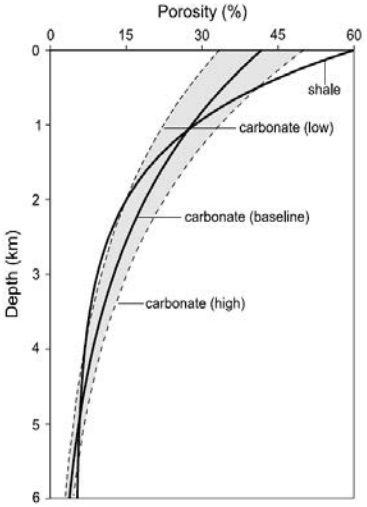


**Figure 4**. Porosity versus depth relationship for carbonates and basinal shale.

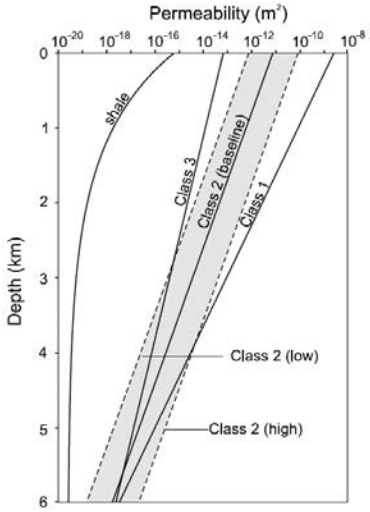


**Figure 5**. Permeability calculated from porosity as a function of depth for carbonate grainstones (Class 1), pack stones (Class 2) and mudstones (Class 3).

Permeability is calculated as a function of porosity using the empirical relationships of Lucia [12] for carbonates as shown in Figure 5. The porosity and permeability transforms according to the Lucia classification (shown in Figure 5) are given as follows:

$$\text{Class 1: } k = (45.35e^{8})*\Phi^{8.537} \quad (13)$$

$$\text{Class 2: } k = (2.040e^{6})*\Phi^{6.380} \quad (14)$$

$$\text{Class 3: } k = (2.884e^{3})*\Phi^{4.275} \quad (15)$$

The resulting permeabilities may vary over four orders of magnitude for a rock fabric class over the simulated depth range. The porosity and permeability variation for one of the static geological model used in reflux simulation is shown in Figure 6, 7.

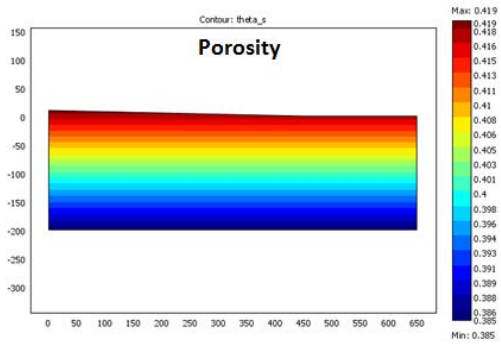


**Figure 6**. Porosity versus depth variation for the Carbonate platform used in reflux dolomitization model in presence of hydraulic gradient.

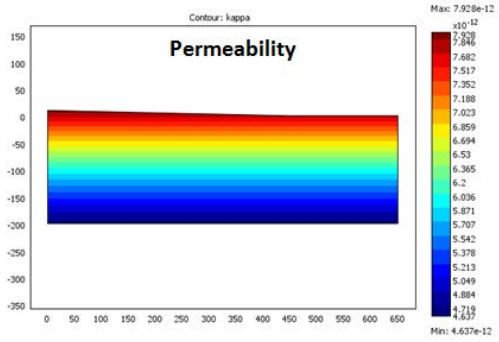


**Figure 7**. Permeability versus depth variation for the Carbonate platform used in reflux dolomitization model in presence of hydraulic gradient.

## 5. Model Setting and Boundary Conditions

To analyze the brine and geothermal reflux circulation models we solve the PDE's presented in section 3.1 and 3.2. For brine reflux circulation we use two different types of models which are shown in Figure 8, 9. These two models correspond to reflux circulation in shallow marine evaporitic basin with and without hydraulic gradient.

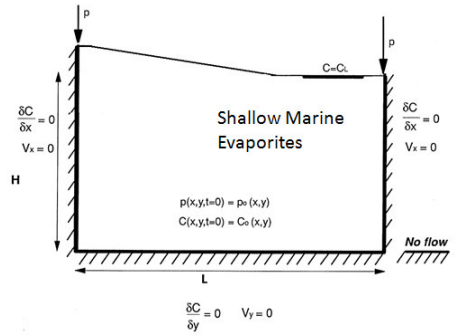


**Figure 8**. Model setting with boundary conditions for brine reflux circulation in presence of a hydraulic gradient.

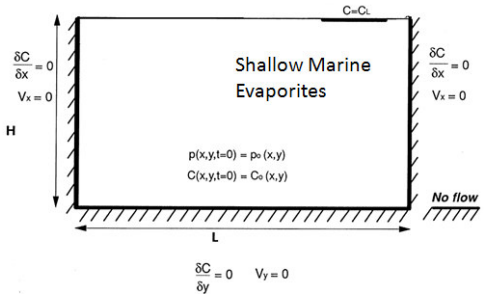


**Figure 9**. Model setting with boundary conditions for brine reflux circulation in absence of a hydraulic gradient.

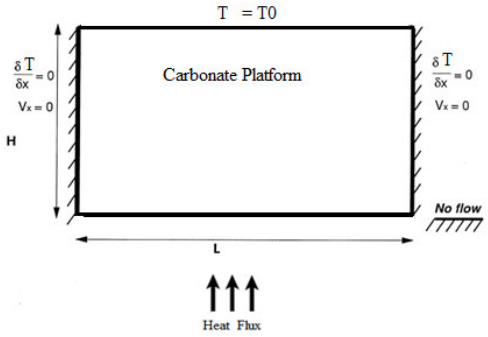


**Figure 10**. Model setting with boundary conditions for geothermal circulation in a Carbonate platform.

The model used for simulating geothermal reflux circulation in a Carbonate platform is shown in Figure 10 along with the boundary conditions used for simulation.

## 6. Simulation Results

In this section we present simulation results for the brine reflux and geothermal circulation. The simulation parameters used to initialize the simulation models for brine reflux and geothermal circulation are shown in Table 1. The simulations are performed on 2D domains. In-order to reduce computational costs of the simulations, in this paper we have used scaled-up geometries to create models of brine reflux and geothermal dolomitization of Carbonate platform.

We first present the simulation results for dolomitization process due to brine reflux circulation followed by results for geothermal reflux circulation.

**Table 1:** Parameters used for model initialization

| **Parameters** | **Values** |
|---|---|
| Water Density (distilled water) | 1000 [Kg/ $m^3$] |
| Salt Water Density Range | 1005 – 1290 [Kg/ $m^3$] |
| Dynamic Viscosity | 0.001 [Kg/ms] |
| Molecular Diffusion | 3.56e-6 [$m^2$/s] |
| Salt Water Concentration | 287.7 [Kg/ $m^3$] |
| Temperature | 298.15 [K] |
| Aquifer Recharge/Hydraulic Gradient | 3.215e-9 [m/s] |
| Longitudinal Dispersivity | 0.5 [mm] |
| Transverse Dispersivity | 5 [mm] |
| Geothermal Heat Flux Range | 0.06 – 2 [W/ $m^2$] |

### 6.1 Simulation Results: Brine Reflux Circulation

Here we present simulation results for two different types of brine reflux circulation models; model with and without the presence of hydraulic gradient. Model setting and boundary conditions are shown in Figure 8 and 9. The model geometry is about 600m in length and about 150m in depth. Initial porosity and permeability of the models are based on the geological parameters presented in section 4. Initial porosity and permeability for the model with hydraulic gradient are shown in Figure 6 and 7. Porosity and permeability for the model without hydraulic gradient are shown in Figure 11 and 12.

The reflux circulation model ran for a total period of 200 years. In these simulations it was assumed that as the denser fluid (magnesium-rich) moves downward it causes complete dolomitization by replacement of calcite (CaCO3) with dolomite (CaMg (CO3)2). This way we can predict the dolomitize rock fraction due to brine reflux processes. The dolomitize rock fraction for the two models after 1, 10, 100 and 200 years of brine reflux dolomitization are shown in Figure 13 and 14, respectively.

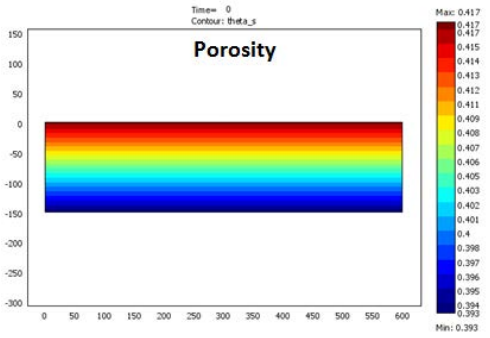


**Figure 11**. Porosity versus depth variation for the Carbonate platform used in reflux dolomitization model in presence of hydraulic gradient.

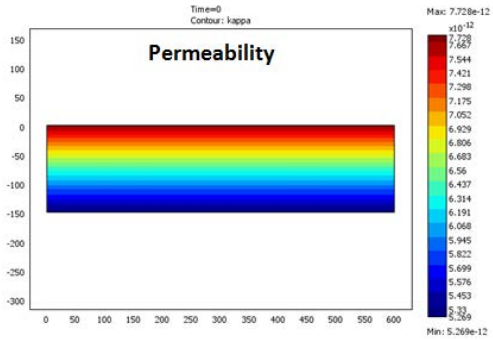


**Figure 12**. Permeability versus depth variation for the Carbonate platform used in reflux dolomitization model without hydraulic gradient.

It can be seen from the Figure 13 that in the model without hydraulic gradient dolomite fingering takes place resulting in particular shapes of dolomite geobodies. These shapes are sometime observed in outcrop analogues. The fingering effects are particularly attributed to the contrast in the density of saline fluid rich in magnesium moving downward to the underground water. In order to verify this effect of density differences simulations were performed with varying density difference between the saline fluid and underground water, results for which are shown in Figure 15. It can be seen from the Figure that as the density difference decreases the fingering effect vanishes all together.

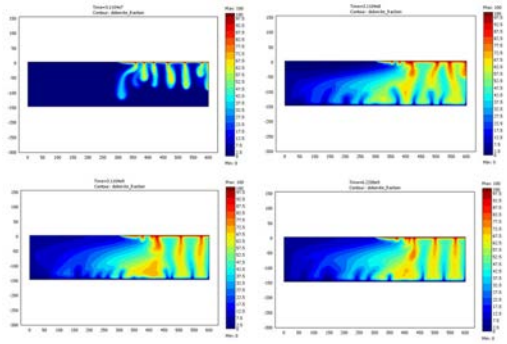

**Figure 13**. Dolomitized rock fraction after 1, 10, 100 and 200 years of brine reflux simulation respectively without hydraulic gradient.

In the model with hydraulic gradient this fingering effect is not seen, as the presence of hydraulic gradient dictates the direction of the fluid flow and therefore the geometry and distribution of dolomite geobodies, Figure 14.

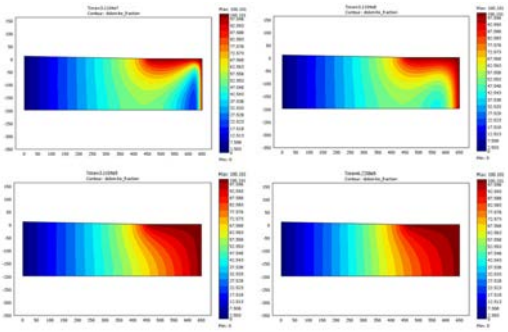

**Figure 14**. Dolomitized rock fraction after 1, 10, 100 and 200 years of brine reflux simulation respectively with hydraulic gradient.

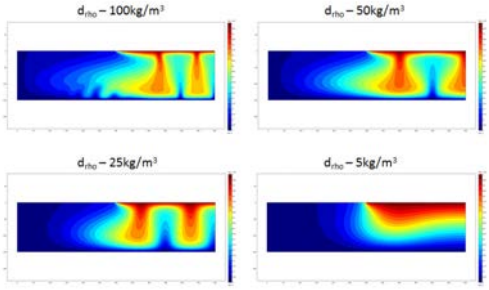


**Figure 15**. Dolomitized rock fraction with varying density difference between the magnesium rich basinal fluid and underground water, from 100 $Kg/m^3$ to $5kg/m^3$.

### 6.2 Simulation Results: Geothermal Circulation of Brine

In this section we present the results for dolomitization patterns resulting from the geothermal brine circulation process. The model dimensions are 6km in width and about 1km in depth. The model setting and boundary conditions are shown in Figure 10. The model is simulated for a total period of about 200 years. The dolomite fraction after 100 and 200 years are shown in Figure 16. We also ran sensitivity on the effects of geothermal heat flux on dolomite patterns and we found that similar to the brine reflux dolomitization cases dolomite patterns are very much linked to the magnitude of geothermal heat flux. Figure 17 shows the effect of varying geothermal heat flux on dolomite patterns.

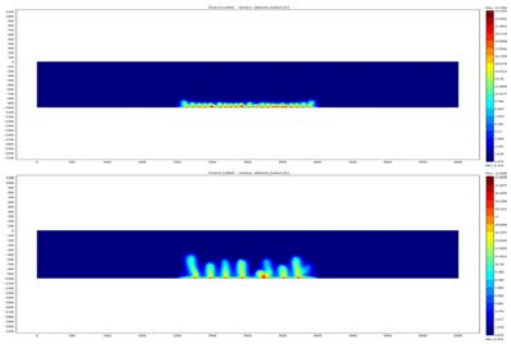

**Figure 16**. Dolomitized rock fraction after 100 and 200 years of geothermal brine circulation.

Heat flows constantly from its sources within the Earth to the surface. Mean heat flow is in a range of 65mW/m$^2$ to 101 mW/ m$^2$ from continental to oceanic crusts [13]. Our simulations are within these ranges of geothermal heat fluxes. It can be seen from the Figure 17 that for lower values of geothermal heat flux more layered dolomite bodies are predicted compared to the irregular finger like bodies predicted at higher values of geothermal heat flux.

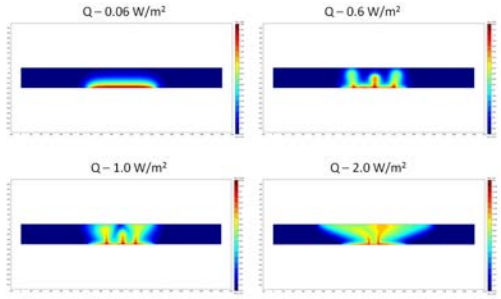


**Figure 17**. Different dolomite pattern generated due to varying degree of geothermal heat flux.

### 6.3 Porosity/Permeability Changes: Geothermal and Brine Reflux Circulation

Dolomitization is a mass transferring process, where Calcite is replaced by Dolomite. Therefore, if there is a net mass transfer either to or from a fluid phase, the porosity of the rock may change. We will use this theory presented by Wood in [14] to model the changes in porosity during dolomitization process. The porosity, Φ, is the fraction of total volume *V* occupied by void space $v_f$, i.e., $\Phi = v_f / V$, then the volume occupied by solids is given as:

$$1- \Phi = \sum m^i/\rho_i \qquad (16)$$

where $\rho_i$ is the density of the *i*th solid phase. The rate of change of porosity with time is then given as:

$$\partial\Phi/\partial t = \rho_f \{\sum \alpha_{T(i)}/ \rho_i\} \mathbf{u} * \text{grad } (\mathbf{T}) \qquad (17)$$

This equation is the fundamental equation for diagenesis involving fluid flow through a temperature field. It relates the change in porosity to a chemical term, $\sum \alpha_{T(i)}/ \rho_i$, and a term which is proportional to the component of the fluid flow field perpendicular to the temperature field. The expression also assumes that the changes in $\alpha_T$ and the temperature field can be neglected with respect to the rate of pore fluid flow.

For a system which consists of the two minerals Calcite and Dolomite plus an aqueous pore fluid, this expression can be expanded to

$$\partial\Phi/\partial t = \rho_f\{\alpha_{T(c)}/\rho_c + \alpha_{T(d)}/\rho_d\}\mathbf{u}*\text{grad } (\mathbf{T}) \qquad (18)$$

where the subscript *c* refers to Calcite and the subscript *d* refers to Dolomite. The **u***grad (**T**) term is independent of the actual phases involved in the diagenetic (dissolution/precipitation) reactions. For a given flow field and temperature gradient, it will give the spatial distribution of the rock alteration regardless of the minerals involved. The diagenetic or chemical terms, which do depend on mineralogy, modulate the intensity of the diagenetic field but they do not change the alteration pattern.

Once the changes in porosity are estimated we can use the Carmen-Kozeny equation, given as:

$$k_j = k_i((1- \mathbf{\Phi_i})^2/(1- \mathbf{\Phi_j})^2)( \mathbf{\Phi_j}/ \mathbf{\Phi_i})^3 \qquad (19)$$

to modify the permeability. *k* is permeability (m$^2$), ***Φ***, is porosity, and *i* and *j* are the previous and subsequent time steps. This equation ignores the changes in grain size, tortuosity, and specific surface area.

We have used the equation shown above for modelling changes in porosity and permeability for the brine and geothermal reflux circulation models. The results for changes in porosity are permeability for brine reflux (with and without the hydraulic gradients) and geothermal brine circulation models are shown in Figure 16, 17, 18, 19, 20 and 21 respectively. It can be seen from the results that in both models the porosity/permeability changes follow the

dolomitization pattern. These results are very intuitive.

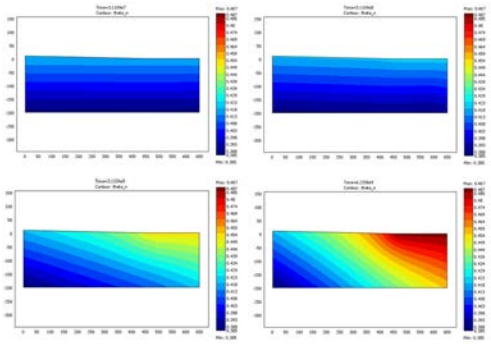

**Figure 16**. Porosity changes after 1, 10, 100 and 200 years for the brine reflux circulation model with hydraulic gradient.

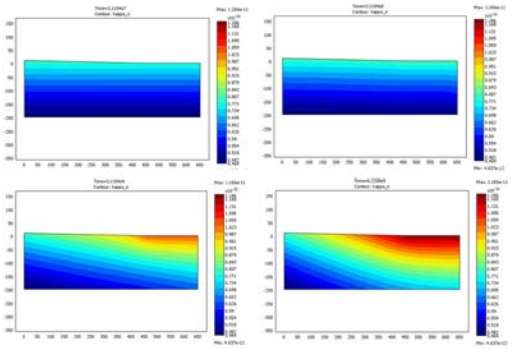

**Figure 17**. Permeability changes based on porosity changes after 1, 10, 100 and 200 years for the brine reflux circulation model with hydraulic gradient.

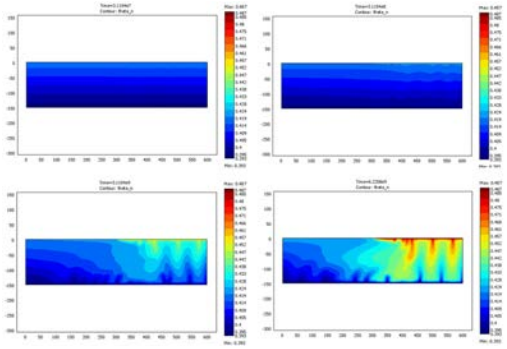

**Figure 18**. Porosity changes after 1, 10, 100 and 200 years for the brine reflux circulation model without any hydraulic gradient.

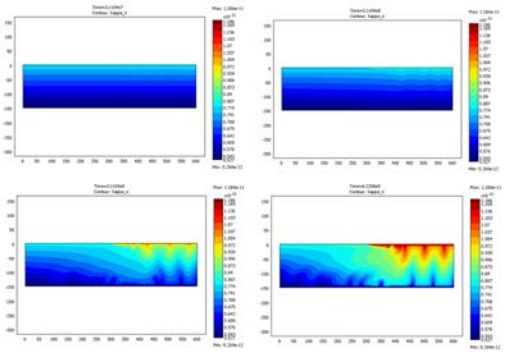

**Figure 19**. Permeability changes based on porosity changes after 1, 10, 100 and 200 years for the brine reflux circulation model without any hydraulic gradient.

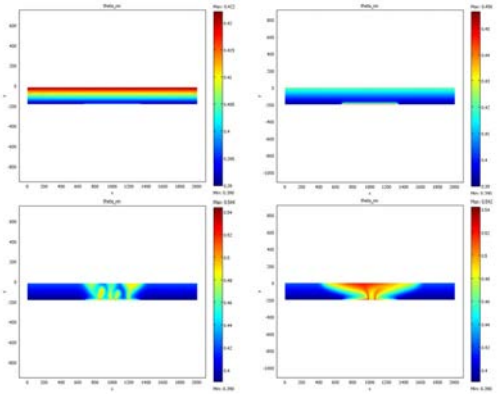

**Figure 20**. Porosity changes after 1, 10, 100 and 200 years for the geo-thermal brine circulation model.

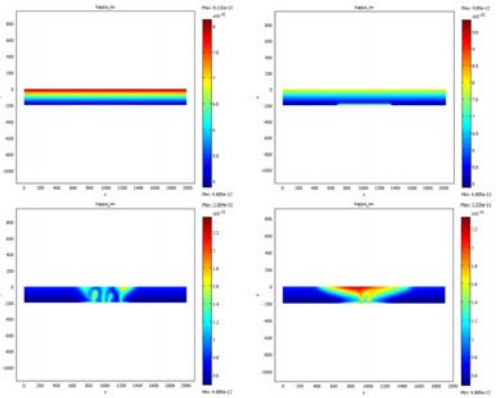

**Figure 21**. Permeability changes based on porosity changes after 1, 10, 100 and 200 years for the geo-thermal brine circulation model.

It is also possible to couple COMSOL with reactive transport modelling software Phreeqc [15] to model the reactive transport processes involved with in dolomitization due to brine and geothermal reflux. Coupled COMSOL and Phreeqc framework can then be used to model dissolution and precipitation reactions

involved in dolomitization processes to correctly model the changes in porosity and permeability. Authors intend to work on this in future.

### 6.4 Comparisons of Numerical Results with Outcrop Analogues

In this section we present a brief comparison of dolomitization patterns predicted from numerical simulation using COMSOL with observed dolostone geometries in the outcrop analogues.

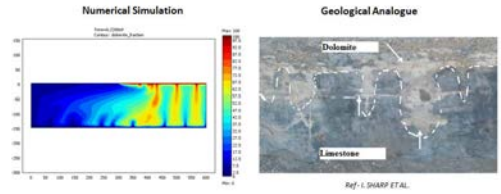


**Figure 22**. Figure showing dolomite pattern generated by simulation of brine reflux on left and similar pattern observed in nature in an outcrop on the right (50m in length). Figure (right) modified from [16].

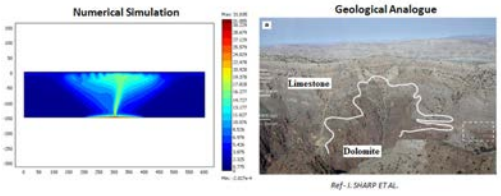


**Figure 23**. Figure showing dolomite pattern generated by simulation of geothermal brine circulation on left and similar pattern observed in nature in an outcrop on the right (250m in length). Figure (right) modified from [16].

Figure 22 and 23 shows a comparison of dolostone patterns generated by simulation of brine and geothermal reflux circulation with real dolostone pattern observed in an outcrop [16], respectively. The outcrop geometries look very similar to the ones predicted by numerical simulations. In order to exactly quantify the geometric patterns observed in outcrops with the patterns produced by numerical simulations further data need to be collected, so that realistic data corresponding to outcrop geology, mineral composition, fluid density and geothermal heat flux can be used to constraint the numerical simulations.

### 7. Conclusions

Results presented in this paper reproduce geometries resulting from two of the relevant processes that cause dolomitization in nature; mainly brine and geothermal reflux circulation. Dolomitization is a key to alteration of porosity and permeability and therefore an important geological process for formation of good quality reservoirs.

In this paper we have presented a numerical study to predict the dolomite geobodies/patterns formed due to brine and geothermal reflux circulations. Numerical modelling of dolomitization process allows us to identify key controls for diagenetic alterations of carbonate platform geometry/shape and distribution of dolostone geobodies. These numerical simulations can be applied to reservoir characterization to help constrain and develop scenarios for subsurface correlation of dolomite bodies and their connectivity and producibility.

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