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Flow Patterns of Dolomitizing Solutions in a Buried Carbonate Ramp - The Benicassim Case Study (Maestrat Basin, NE Spain)

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SUMMARY

Geometric, petrographic, and geochemical observations suggest that sub-stratiform dolomitization in a Lower Cretaceous Benicassim ramp (Maestrat Basin, E Spain) was due to the circulation of high temperature brines through faults and high permeability layers. In this study, fluid and heat flow numerical simulations are applied to investigate the controls on hydrothermal flow in this area, depending on the tectonic activity at the time of dolomitization. The results indicate that flow caused by rapid release of overpressured fluids below seals in recurrent pulses through large-scale faults may drive enough fluid for dolomitization, but not enough heat. Thermal conduction dominates advection over large-time scale. However, long-term fluid circulation, due to differences in pressure and temperature within the basin, can pump dolomitizing fluids at high temperature during long periods of time if the system is open. Moreover, a permeability contrast of two orders of magnitude is required to have lateral flow preferentially in some layers and to form relatively sharp, sub-stratiform dolomitization fronts.

Introduction

The controls on fluid flow in dolomitized carbonate reservoirs are not well understood due to the complex relationships between processes that enhance and decrease porosity and permeability. Dissolution and/or precipitation of minerals, caused by diagenetic or hydrothermal processes, and fault-zone properties (e.g fault-zone permeability, fault connectivity and segmentation, etc.) are features that have major impact on fluid circulation in carbonate reservoirs. Detailed case studies integrating the results from a variety of techniques may contribute to our understanding of these features. With this aim, our study focuses on fluid flow patterns through the formerly buried ramp of Benicassim, a well-exposed dolomitized carbonate system in the Maestrat basin (Iberian Chain, E. Spain).

Benicassim is located in the eastern part of the Maestrat Basin, which is a Mesozoic extensional basin bounded by normal faults (Salas *et al.*, 2001). During the Early Cretaceous (mainly Aptian), extensional faults accommodated thick sequences of shallow marine limestone, which appear partially dolomitized along preferential beds (Fig. 1). The geometric, geochemical, and petrographic characteristics of dolomites, limestone host rocks, and vein fillings are described by Martín-Martín *et al.* (2009) and Gomez-Rivas *et al.* (2009). These studies indicate that dolomite distribution conforms to a sub-stratiform pattern, where dolomite layers extend over several kilometres away from large faults, following former high permeability layers. Mississippi Valley-Type (MVT) ore deposits, of Paleocene age, have been documented in the area and are spatially related to the dolomitized bodies close to fault zones. Large-scale extensional faults most likely served as conduits for the circulation of reactive fluids, causing dolomitization, as well as MVT deposition. According to our geochemical data and the results of Grandia (2002), the dolomitizing fluid was concentrated seawater that interacted with basement rocks. This saline solution circulated at a temperature of 80ºC-120ºC. The dolomitized layers at Benicassim were buried to depths of 200 to 1100 m during the dolomitization stage, which occurred some time between the Albian (~112 Ma) and the Early Paleocene (~62.5 Ma).

Realistic driving mechanisms for dolomitizing fluids are necessary to understand when and how dolomitization takes place (Whitaker *et al.*, 2004, and references therein). We have developed basic 2D numerical simulations of fluid and heat flow to gain insight into the driving mechanisms that operated in the Benicassim area, taking into account the tectonic setting of the Benicassim half graben at the time of fluid circulation. The models address the role of fault activity/inactivity during dolomitization and aim to serve as a benchmark for further 3D simulations.

Figure 1 *Panoramic view of the field study area near Benicassim (NE Spain). Light grey layers are limestone and brownish layers are sub-stratiform dolomite. The lateral field of view is ~ 4 km.*

Conceptual models of fluid flow in Benicassim

Based on our field and geochemical observations, two possible geodynamic settings are proposed for the dolomitization that occurred in Benicassim: (1) a rift/extensional environment during the Albian or the Early Paleocene or (2) a quiescence/post-rift period during the Late Cretaceous (see Salas *et al.*, 2001). We developed two end-member models of dolomitizing fluid flow to represent these two end-member scenarios.

For the first case (syn-rift dolomitization), we assumed that fluid flow was caused by the rapid release through faults of overpressured solutions sealed below impermeable layers (marls). In this model, episodic fault movements, related to active rifting, released confined fluids in recurrent pulses over several thousands to a few million years. During inter-pulse stages, fluids became geopressured again.

This model is similar to the seismic pumping concept of Sibson *et al.* (1975). For modelling purposes, inner fault zones are assumed to act as conduits during fault movement stages and as barriers during non-deformation periods. The permeabilities assigned to fault zones (cores and damage zones) have been estimated from Agosta (2008) and Boutareaud *et al.* (2008); values are summarized in Table 1.

For the second case (fluid circulation in a quiescent/post-rift tectonic setting) fault zones were modelled as deformationally inactive. Therefore, fluid circulation is driven by differences in pressure or temperature gradients within the basin, which may be maintained through long periods of time. The Earth's crust below the Iberian Peninsula was heterogeneously thinned during the Late Cretaceous as a consequence of rifting, a process that likely enhanced differences in pressure and/or temperature within the Maestrat basin and the Benicassim half graben.

Table 1. Estimated fault zone permeabilities (in m^2) depending on their activity

Tectonic	Fault cores		Damage zones	
activity	k_h	k_v	k_h	k_v
Active faults	10^{-13}	10^{-12}	10^{-14}	10^{-13}
Inactive faults	10^{-18}	10^{-18}	10^{-15}	10^{-16}

Two different homogenous meshes were built for the two simulation scenarios, where the stratigraphic succession was simplified in 100 m thick blocks with homogeneous properties (Fig. 2). Fault core and damage zone widths were 1 m and 10 m wide, respectively. The top of the model, located at 400 m depth during Albian times, was sealed by a 100 m thick layer of clay (Fm. Escucha; Salas *et al.*, 2001). Horizontal and vertical permeabilities for sedimentary facies were estimated from log porosity-log permeability regression curves calculated from ExxonMobil field data, taking into account depositional and diagenetic/compaction properties. According to the distribution of early diagenetic calcite cements and the original deposition textures, we assigned considerably higher permeabilities (on the order of 10^{-13} m^2) to the two main groups of layers that are currently dolomitized. Permeabilities assigned for the rest of the succession ranged between 10^{-15} and 10^{-17} m^2. Rock porosities were calculated using the equation of Schmoker and Haley (1982). A constant density of 2650 kg/m^3, a thermal conductivity of 2.2 W/m·ºC and a specific heat of 1000 J/kg·ºC was assigned to the whole succession. Using the calculations of Caja *et al.* (2009), the initial temperature gradient was estimated to be 30ºC/km.

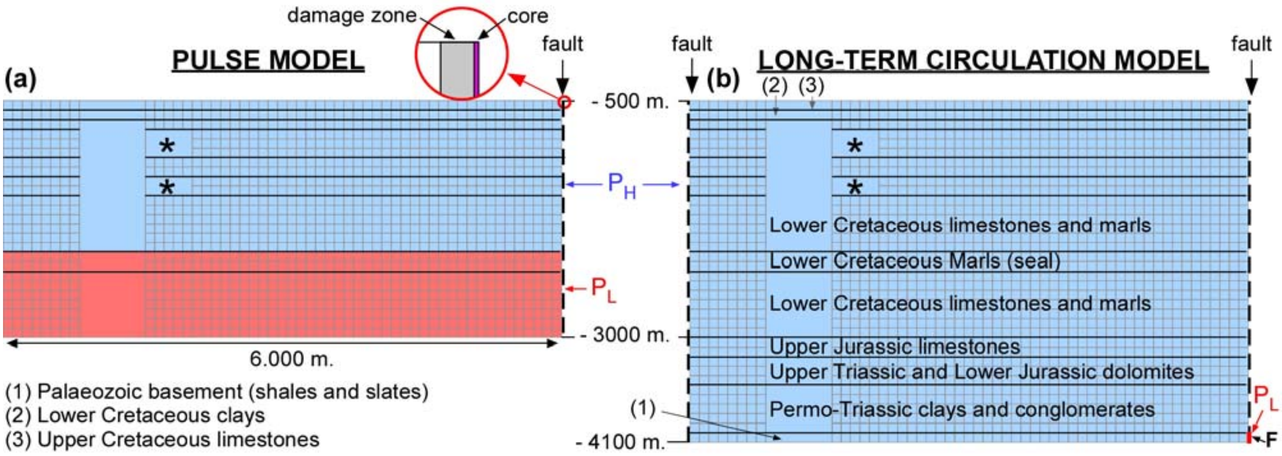

Figure 2 *Grid and design of (a) pulse simulations and (b) long-term fluid circulation simulations. Asterisks indicate high permeable layers (i.e. the ones that have been dolomitized).* P_H *and* P_L *indicate initial hydrostatic (blue) and lithostatic (red) pressure gradients. The two right lowermost fault cells on the long-term fluid circulation simulations (coloured in red) have fixed properties (F).*

For the syn-rift pulsating model, we modelled a 6000 m long and 2500 m thick section of the basin, with a vertical fault located at the right boundary (Fig. 2a). We only included Lower Cretaceous sediments in this model. In order to simulate one fluid flow pulse during a fault movement event, we used a hydrostatic pressure gradient above the uppermost marl layers (200 m thick seal) and lithostatic pressure below it. A fast fluid flow pulse was simulated by assigning high permeability to the fault zone (Table 1) and by letting overpressure drive the compressed fluid upwards. All mesh cells in the system had a volume factor of 1 and non-fixed conditions (i.e. they do not keep their initial properties over time). The individual pulse simulations were run for 10 years.

For the post-rift model, two vertical faults were added, one at each lateral boundaries of the grid (Fig. 2b), which was 6000 m long and 3600 m thick to include underlying rocks (Palaeozoic basement, Triassic and Jurassic rocks). The pressure gradient in the whole system was assumed to be hydrostatic, but, in order to sustain long-term fluid circulation, lithostatic pressure was assigned to the two lowermost right cells of the fault zone (core and damage zone). Additionally, these two cells were fixed; therefore, they had an infinite volume and kept their initial pressure and temperature during the entire simulation time. These long-term fluid circulation runs were simulated for 100,000 years. All the runs were carried out with the software Tough2 (Pruess, 1991).

Results and discussion

The results of pulse simulations are presented in Fig. 3. The fluid velocity plots of the pulse model (Fig. 3a,b) indicate that overpressured fluids stored below seals can be driven upwards very rapidly when fault permeability is suddenly increased due to fault movement episodes. Fluid also flows laterally through the most permeable layers with velocities on the order of meters/year for a few years. Consequently, many recurrent pulses would be required to carry enough reactive solutions to dolomitize the permeable layers. Recurrent fault movement events associated with earthquakes are likely to happen periodically in a rift setting. Therefore, in terms of fluid volume circulating through the affected layers, this model could match the requirements for a pervasive stratiform dolomitization. Nevertheless, to match the field observations of preferential fluid flow in certain layers, these must be an initial permeability variation of two orders of magnitude between the dolomitized and undolomitized rocks. Fig. 3c shows that fluids released from geopressured zones loose their temperature very rapidly because thermal conduction is more important than advection. This implies that although solution fluxes are high through the permeable layers, the solutions do not keep their high temperature (120-130 ºC) when they are released upwards.

The results from the long-term fluid circulation simulations (Fig. 3d,e) indicate that lateral flow rates of the order of meters/year or tens of meters/year can be maintained over long periods of time, as long as there is a pressure and/or temperature gradient difference in the half-graben. Moreover, as the temperature contour plot depicts (Fig. 3e), shallow rocks can be heated up due to the heat flow. The model of quiescence/post-rift fluid circulation easily meets the requirements of a dolomitizing solution in the Benicassim area, according to isotope data. However, this conceptual model only works when the system is open. Otherwise flow rates are too low.

Conclusions

Numerical modelling results confirm that faults may play a critical role in controlling selective hydrothermal fluid flow through high permeable layers. A dolomitizing solution driven by fracture activity in the form of pulses of fluid, as would be expected during syn-rift activity, is able to carry enough volume of fluid to the permeable layers, but cannot account for the temperature inferred in the Benicasim platform. Instead, a long-term fluid circulation system in a post-rift environment can better provide enough warm solution reacting and heating up shallow rocks, although it requires an open system and a high pressure and/or temperature gradient to be maintained over a long time period.

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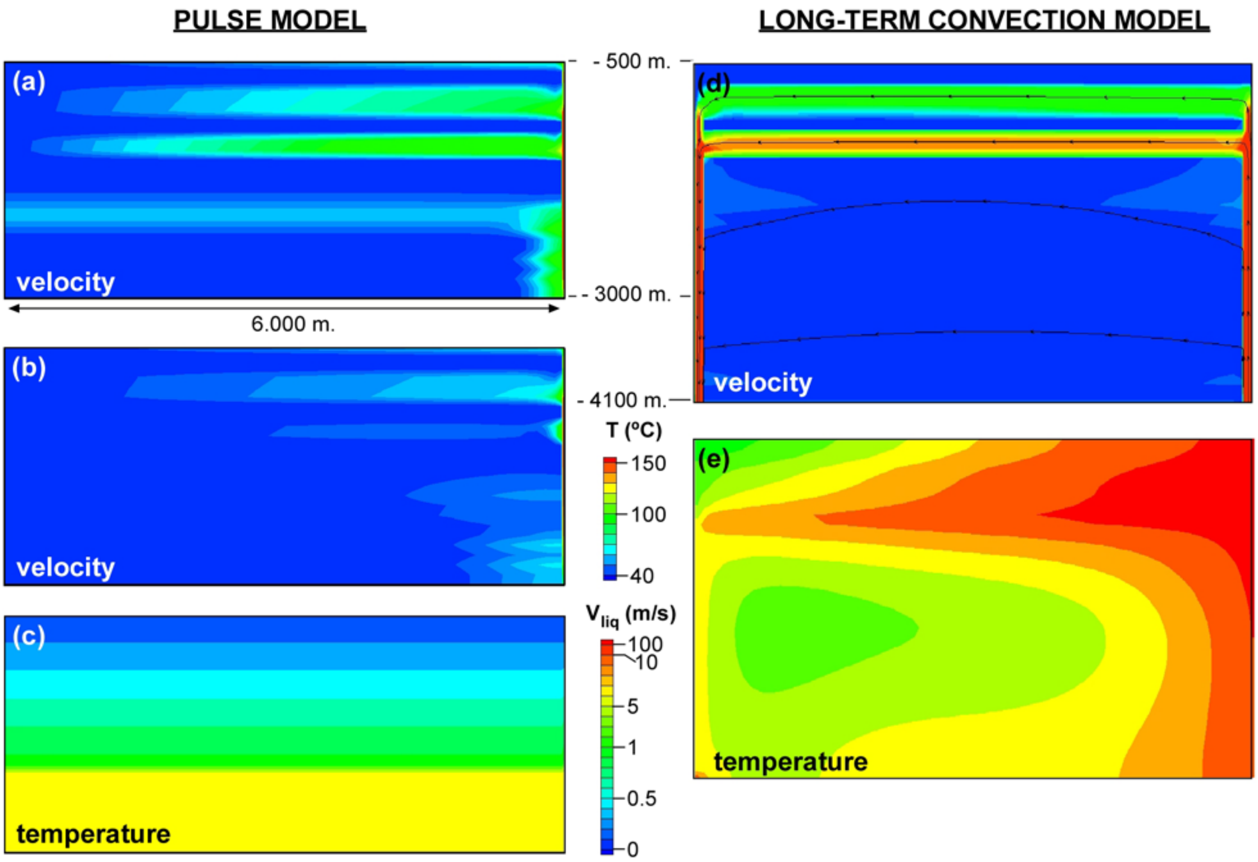

Figure 3 *Simulation results: (a) fluid velocity vector module after 1 year; (b) fluid velocity vector module after 10 years; (c) temperature after 1 year; (d) fluid velocity vector module after 20.000 years in an open system; (d) temperature after 20.000 years in an open system. Figures (a) to (c) show results of pulse simulations, while figures (d) and (e) display outputs from long-term fluid*

circulation simulations. Black arrow lines in figure (d) are streamtraces. The scale is the same in all diagrams.