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Controls on reflux dolomitisation of epeiric-scale ramps: Insights from reactive transport simulations of the Mississippian Madison Formation (Montana and Wyoming)

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ABSTRACT

Prediction of the geometry and petrophysical properties of dolomite geobodies depends on understanding both the hydrological system supplying reactive fluids and the chemistry of these fluids. However, patterns are complicated by the non-linear response of the diagenetic system to depositional texture, which controls both fluid flux *via* permeability architecture and reaction rate *via* effective surface area. This study explores interactions between extrinsic controls (spatial distribution of brine composition and temperature) and intrinsic controls (permeability and reactivity) using local and regional scale reactive transport models of sequential episodes of brine reflux that resulted in partial dolomitisation of the Mississippian Madison ramp.

Inter-well scale models show preferential early dolomitisation of fine grained, more reactive beds. Pervasive dolomitisation can occur most readily beneath the brine pool where flow is perpendicular to bedding, and is most rapid at high brine fluxes. Down-dip of the brine pool, bedding-parallel flow is focused in relatively permeable coarse grained beds, providing reactants for strongly preferential alteration of intervening more reactive fine grained beds. In contrast, thicker sequences of fine grained beds dolomitise more slowly, limited by the rate of supply of magnesium. Regional-scale models, with injection of brines of increasing salinity towards the ramp interior, reproduce the observed pattern of dolomitisation. However, more realistic simulations in which reflux is driven by lateral density contrasts, generate flow rates orders of magnitude too low for significant dolomitisation. Simulations suggest pervasive dolomitisation of epeiric-scale ramps by a platform-wide reflux circulation, as often invoked, is not feasible. Rather, dolomitisation of such extensive systems critically requires local-scale flow systems, such as may result from topographically-controlled variations in restriction of platform-top seawater circulation.

1. Introduction

Dolomite formed by replacement of calcite can be mimetic, but in many cases fundamentally modifies the geometry of the pore network (Wardlaw, 1976; Lucia, 1995; Woody et al., 1996). Mud-dominated carbonates can be replaced by coarser sucrosic dolomite crystals with a resulting increase in pore size and also permeability up to three orders of magnitude (Lucia, 1995). Thus defining the geometry and characteristic of dolomite geobodies is important in assessing the distribution of reservoir quality. The chemical composition and flux of Mg-rich diagenetic fluids are key controls and vary with the hydrological system driving dolomitisation (Morrow, 1982; Land, 1985; Warren, 2000; Machel, 2004).

In many important conventional carbonate reservoirs hydrocarbons are hosted in dolomites associated with reflux of platform-top evaporative brines (Sun, 1995). Within these systems primary porosity is commonly occluded by dolomite cement proximal to the brine source, whilst higher porosity and permeability are expected in more distal parts of the flow system where the brines are less dolomite-supersaturated (Lucia and Major, 1994; Saller and Henderson, 1998; Wahlman, 2010). However, such simple conceptual models predicting dolomite distribution and its effect on reservoir quality ignore both dependence on depositional texture and feedbacks during diagenesis, both of which have positive and negative influences on reservoir properties. Spatial variations in depositional texture control both fluid flux *via* permeability architecture and reactivity *via* the effective reactive surface area. Dolomitisation and associated diagenetic reactions modify the permeability, altering the distribution of fluid flux, and

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also modify reactivity, resulting in systematic changes in the distribution of water–rock interaction over time irrespective of changes in boundary conditions such as climate and relative sea-level.

Numerical simulations coupling fluid flow and diagenetic reactions have provided new insights into dolomitisation and associated diagenetic modifications. Small-scale one-dimensional reactive transport model (RTM) simulations of shallow reflux systems (Gabellone and Whitaker, 2016), for example, evaluated the sensitivity of dolomitisation to a range of extrinsic and intrinsic factors, suggesting a major control by brine composition, effective surface area of precursor sediments and temperature. Only in systems where fluid flux is very low do reactions become limited by supply of reactants rather than reaction rate. Two-dimensional RTM simulations have also been used to investigate reflux dolomitisation, and specifically the spatial and temporal distribution of dolomite bodies and associated porosity modifications at a range of scales in generic carbonate platforms (Jones and Xiao, 2005; Al-Helal et al., 2012a). At the inter-well scale three-dimensional RTM simulations explored the effect of permeability and spatial distribution of platform-top brines (Xiao et al., 2013), showing that reflux associated with local brine ponds has the potential to generate complex distributions of dolomite with 'finger' orientations that reflect multi directional fluid flow with respect to depositional dip and strike.

These 2D and 3D models are capable to replicate processes observed in natural systems, and predict diagenetic patterns which in some cases differ from those of simple conceptual models. The introduction of even very simple horizontal layering of sediment texture or vertical fracturing produces spatially complex diagenetic patterns (Whitaker and Xiao, 2010; Al-Helal et al., 2012a). Jones and Xiao (2005) introduced a randomly distributed heterogeneous initial permeability which resulted in pronounced perturbations in the geometry of the simulated dolomite front (dolomite fingers). However, none of these previous studies considered the links between platform geometry and distribution of depositional facies. In natural systems, sequence stratigraphy exerts a strong systematic control on depositional texture. Previous RTM simulations (Gabellone and Whitaker, 2016) suggest that depositional texture should affect the pattern of dolomitisation through the combined control of fluid flux and effective reactive surface area. Resulting feedbacks are likely quite complex and their operation in carbonate systems with systematic spatial variations in the distribution of depositional facies are difficult to predict from first principles.

RTM simulations constrained by case studies provide an important advance on simple generic simulations, allowing both the use of a more realistic spatial facies distribution and the possibility to compare the model results with observations from real fields. Garcia-Fresca et al. (2009) simulated the impact of successive episodes of reflux during accumulation of a column of sediments to explain vertical variations in dolomite abundance and relationships to discontinuity surfaces in the Albian Glen Rose Formation in central Texas. In more recent 2D simulations Lu and Cantrell (2016) suggested that the lateral migration of an evaporative pond over time following deposition of the Jurassic Arab-D reservoir in the Ghawar field could explain the occurrence of non-stratigraphic (non-stratabound) dolomite bodies. Here we combine these two concepts, to investigate the diagenetic overprinting resulting from the interaction of syndepositional dolomitisation during deposition of an extensive prograding ramp with lateral and vertical facies contrasts, and changes in the position, extent and degree of evaporation in the brine pool developed at successive sequence boundaries.

We present numerical exploration of dolomitisation of the Mississippian Madison Formation ramp, which extended 700 km from the transcontinental arch in SE Wyoming into the Central Montana Trough. Previous detailed studies characterised the partially dolomitised ramp system and provided important constraints to help unravel key controls on reflux flow and resultant diagenesis (Elrick and Read, 1991; Sonnenfeld, 1996a, 1996b; Smith et al., 2004; Buoniconti, 2008; Katz, 2008). Geochemical and fluid inclusion data from finely to medium crystalline dolomites of the mid-to-upper ramp indicate dolomitisation by Mississippian marine-derived fluids characterized by increasingly high salinity and alkalinity landwards (Katz, 2008). RTMs at the inter-well scale within an individual bed of the Madison Formation explored lateral heterogeneities in porosity developed during early dolomitisation, which were interpreted to be the result of geochemical self-organisation (Budd and Park, 2011).

In this study, RTM simulations at the outcrop (inter-well) and regional scales are used to explore operation of and interaction between intrinsic facies-dependent controls and extrinsic factors such as spatial distribution and composition of brines and temperature, during sequential episodes of brine reflux during deposition of three 3rd-order cycles. Specifically we aim to address the following questions:

Can large scale reflux be driven by laterally extensive brine pools developed over epeiric platforms or broad ramps such as the Madison?

Does pervasive dolomitisation of such systems require overprinting by sequential reflux episodes generated during progradation of the ramp system?

Is dolomitisation always favoured in fine grained highly reactive sediments, or can also less reactive but more permeable coarse grained sediments be preferentially dolomitised in systems where reaction rates are limited by fluid flux?

2. Geological setting

The Madison Formation comprises an epeiric carbonate ramp deposited in water depths of 0–>40 m in the Early Mississippian when the north-western part of modern North America was some 0–10° north of the paleoequator (Fig. 1). The ramp prograded north-west from the Transcontinental Arch and was bounded to the west by the deeper water Antler Foredeep, to the north by the Central Montana Trough and to the north-east by the Williston Basin (Gutschick and Sandberg, 1983; Sonnenfeld, 1996b). The Madison varies in thickness from *ca.* 15 m at Hartville Canyon in Wyoming to *ca.* 330 m at Livingstone in Montana (Fig. 1; Sonnenfeld, 1996b). These carbonates were deposited unconformably, directly overlying the Precambrian basement in the updip area, and extending over the Cambrian Gallatin Formations and Ordovician Bighorn Dolomite to the south-east and the Devonian Jefferson and Three Forks Formations in the downdip sections to the north-west (Fig. 2A).

The Early Mississippian was a period of calcitic sea (greenhouse condition), characterised by low amplitude (<10 m) high frequency sea-level cycles superimposed on low frequency 3rd-order cycles (duration up to 6 My) with amplitudes from a few tens of meters up to *ca.* 120 m (Haq and Schutter, 2008). According to the sequence stratigraphic framework of Sonnenfeld (1996b; Fig. 2A), the Madison evolved from a ramp (Sequences I and II) to a flat-topped rimmed shelf (Sequence III). Each of these 3rd-order sequences represents about 2 My and comprises a series of higher frequency cycles (0.1–1 My).

Sequences I to III were deposited in an arid climate and large parts of the platform were affected by early marine derived dolomitisation, with evidence for brine reflux (associated with evaporite deposition), as well much more localised hydrothermal calcite cementation and dolomitisation, with associated minor-to-trace amounts of both replacive and cementing quartz and fluorite minerals (Sonnenfeld, 1996b; Moore, 2001; Katz et al., 2006). In contrast the overlying Sequences IV to VI (not shown), which lack dolomite, were deposited under a more humid climate (Sonnenfeld, 1996b). Within Sequences I to III dolomitisation is pervasive in the inner ramp and is not fabric selective (Fig. 2B), whereas in the mid-ramp mud-dominated carbonate sediments are preferentially dolomitised and grainier units are partially dolomitised to limestone (Katz, 2008). There is no significant dolomitisation at the margin or basin (Fig. 2B). Two regional solution collapse breccias were recognised at the base of Sequences III and IV. These breccias formed by the dissolution of massive evaporite beds