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Research paper

Nature and distribution of diagenetic phases and petrophysical properties of carbonates: The Mississippian Madison Formation (Bighorn Basin, Wyoming, USA)

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ABSTRACT

The purpose of this study is to characterize factors controlling the nature and distribution of the diagenetic phases that gave rise to carbonate reservoirs. To do so, a pluridisciplinary approach was carried out, integrating sedimentologic and diagenetic studies on the Madison Formation (Lower Carboniferous, 357–340 My) which is a carbonate reservoir in subsurface.

The Madison Formation, outcropping in the Bighorn Basin (Wyoming, USA), is a 340 m thick carbonate series composed of four to seven 3rd-order depositional sequences (S1 to S7) depending of the palaeogeographic location. The first three sequences (S1 to S3) were deposited under arid and warm conditions during Tournaisian times which favoured high accumulation of carbonates leading to a morphological change from a quite flat ramp (S1 to S2) to a wide platform (S3). It also probably favoured the early calcite cementation (isopachous and syntaxial calcite cements) of the subtidal deposits and the early dolomitization (D1) of the supratidal to intertidal sabkha ones. In addition, the very flat profile occurring during S3 was also responsible for the postponed dolomitization (D2) of S1–S2 due to reflux of brines, at various degrees depending on the palaeogeographic location. The deposition of S4 to S7 under humid conditions during Visean times were associated with 1) a decrease of the carbonate accumulation and of the dolomitization; 2) dissolution processes at micro- (pores network) and macro-scales (karst, collapse breccia...) and calcite cementation (C1). The spatial distribution of all these first diagenetic phases acts as a controlling factor on the distribution of the later burial diagenetic phases. Thus, the mesogenetic calcite cements are mostly observed in the secondary porosity created by dissolution (karsts, collapse breccias) or dolomitization. The burial diagenesis of the Madison Formation was characterized by 1) a dolomitization phase (D3) in proximal parts of the platform leading to an increase of porosity and permeability and 2) calcite cementations (C2–C3) in the distal parts of the platform leading to a decrease of these properties.

The Madison Formation provides a good spatial representation of sedimentary and diagenetic heterogeneities that may occur in the carbonate reservoirs due to various palaeogeographic locations, climates, burial history and structures.

1. Introduction

The understanding of the paleohydrologic systems and of the distribution and evolution of the petrophysical properties through time is a crucial question for the management of our water and hydrocarbon resources, especially in carbonate reservoirs. The prediction of petrophysical properties in such reservoirs is difficult since the complex interplay between original depositional facies, subsequent diagenesis and fracturing pattern may modify these

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properties. The carbonate depositional facies that show a large diversity of composition and texture due to their biological origin, increase the complexity to predict the reservoir properties in space. These latter are also strongly modified during diagenesis occurring soon after the deposition through the burial (Tucker, 1993; Mazzullo, 1994; Moore, 2001; Booler and Tucker, 2002). Several factors such as temperature, pressure, brine composition, fracturing network properties contributing to the alteration of the carbonate rocks during diagenesis, can vary laterally in a reservoir and basin (Taylor and Gawthorpe, 1993; Moore, 2001). Consequently, an integrated sedimento-diagenetic approach is required to characterize and predict the spatial distribution of the reservoir properties in carbonate rocks.

The Madison Formation represents a major petroleum interest in Wyoming because it contains more than 13% (265.10^6 bbl) of the hydrocarbon reserves of this state (Stone, 1967). Previous studies have already provided a well-documented sedimentary and structural framework (Sandberg and Klapper, 1967; Sando, 1976, 1982; Poole and Sandberg, 1977; Gutschick and Sandberg, 1983; Hennier and Spang, 1983; Elrick and Read, 1991; Erslev, 1993; Reid et al., 1993; Sonnenfeld, 1996; Smith et al., 2004; Westphal et al., 2004; Bellahsen et al., 2006; Barbier et al., 2012b). Similarly, the diagenetic framework has been the topic of several researches. The first ones focused on the dolomitization and dedolomitization processes occurring in the series (Budai et al., 1984, 1987). Later, Sonnenfeld (1996) contextualized the diagenetic history into a sequence stratigraphic framework, but his study was not constrained by geochemical, microthermometric and cathodoluminescence analyses. Westphal et al. (2004) showed that the petrophysical heterogeneities of the Madison Formation were controlled by the combination of the initial facies fabric and dolomitization processes. However, this study was limited to the Wind River Basin and did not extend further to the North. In the same way, Smith et al. (2004) studied the distribution and the reservoir properties of the dolomite bodies in the Bighorn Basin. The late diagenesis of the Madison Formation was constrained by Katz et al. (2006) who studied the effect of hydrothermal calcite crystallization on reservoir properties. Recently, Barbier et al. (2012b) and Beaudoin et al. (2012) established the relationship between the deformation from the Cretaceous to the Paleocene, the distribution of different sets of fractures and the paleohydrological behaviour. Despite these previous studies, the origins of the eo- and mesogenetic phases and their spatial distribution are still a matter of debate and can be more precisely characterized for the Bighorn and Wind River Basins.

Therefore, this work aims 1) at giving a synthetic view of the sedimento-diagenetic framework of the Madison Formation from the deposition to the burial, 2) at establishing the different controlling factors on the distribution of the diagenetic phases and 3) at discussing relationships between facies, diagenesis and petrophysical properties. To do so, we proceeded in an integrated way using previously cited sedimentological studies and new investigations such as petrography, mineralogical quantification, microthermometry, and stable isotopes.

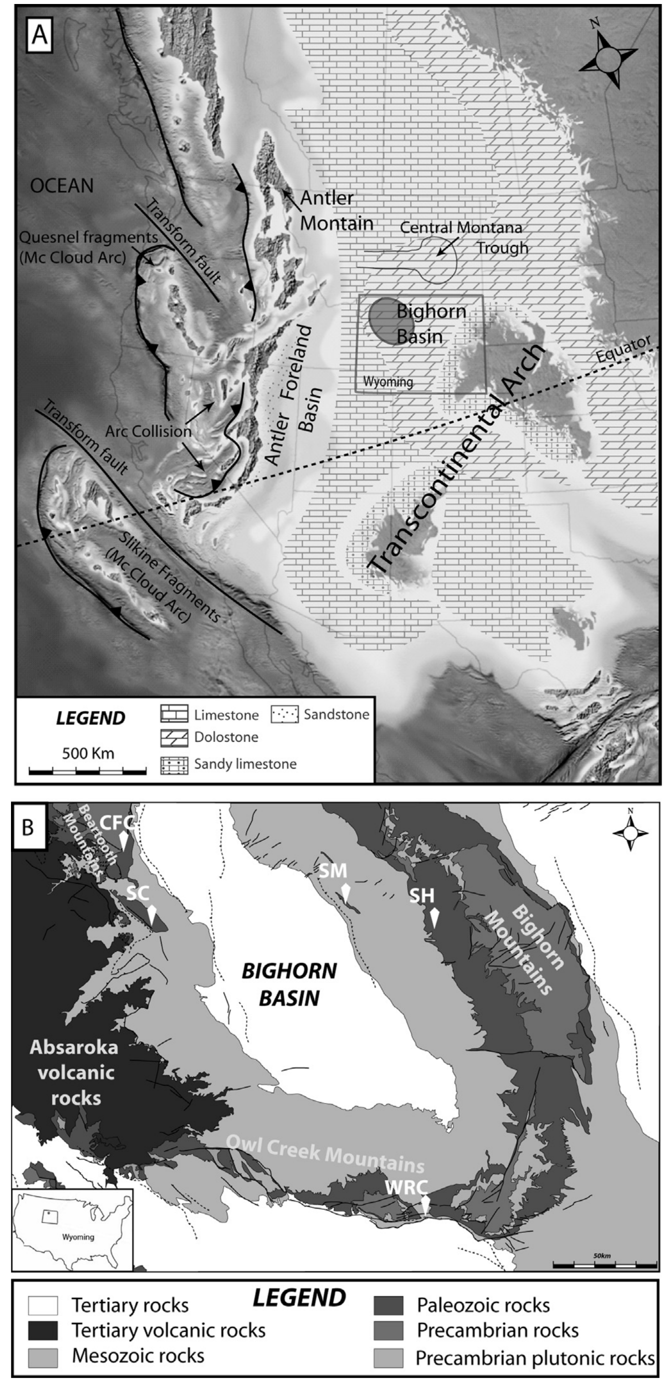

Fig. 1. A) Regional palaeogeography of the Western United States; location of the present day Wyoming State and of the Bighorn Basin (modified from Bakey, 2005). B) Simplified geological map of the Bighorn Basin and location of the studied sections (CFC = Clark's Fork Canyon, SC = Shoshone Canyon, WRC = Wind River Canyon, SH = Shell Canyon, SM = Sheep Mountain).

2. Geological setting

2.1. Palaeogeography, palaeoclimatic and stratigraphic settings

During the Early Mississippian (359–340 My.), the area of the present-day Wyoming was a shallow water carbonate platform, developed ~5°N of the paleoequator as a result of the collision between the Volcanic Antler Arch and the North America Midcontinent (Gutschick and Sandberg, 1983; Maughan, 1983; Peterson and Smith, 1986) (Fig. 1A). The platform was opened westward and northward into the Antler Foreland Basin and the Central Montana Trough respectively (Fig. 1A). Landward, the Transcontinental Arch was probably the main source of siliciclastic sediments.

The climate during the Mississippian evolved from "greenhouse" to "icehouse" conditions. This transition would be due to an increase of carbon trapping mechanisms within oceans during upper Tournaisian times, producing progressive cooling and ice formation (Berner, 1990; Saltzman, 2002).