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Origin and distribution of calcite concretions in Cretaceous Wall Creek Member, Wyoming: Reservoir-quality implication for shallow-marine deltaic strata

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ABSTRACT

Calcite concretions reduce reservoir quality, but there are limited studies that examine 3D distribution and consequences for reservoir quality in outcrop analogs. We integrate petrography, diagenesis, and geochemistry with 3D ground penetrating radar and borehole data to investigate the timing, 3D distribution and origin of concretion growth within a mixed fluvial, tide influenced shallow-marine deltaic reservoir analog in Cretaceous outcrops in Wyoming.

Calcite concretions, varying in size and shape from 70 cm to 5.5 m in length and from 20 cm to 60 cm in height, fill up to 15% of the sandstone volume. Concretions range from almond shape, long, thin ellipsoids, associated with tidal bar facies, to short, thick ellipsoids, within more fluvial-dominated distributary-channel facies. 3D mapping shows concretions are moderate to highly connected forming an aggregate pattern with irregularly shaped branches.

Several concretions have clear nucleation sites that include carbonaceous muds, calcareous muds, marine shell material, and/or organic matter. Carbon-isotope values suggest carbon sources that include in-situ marine skeletal-fragments and organic carbon. Rather than reflecting an early or late origin, these concretions are much more complex and show a long-lived history of growth.

Cements are confined to the middle parts of the sandstone body, suggesting that initial preferential flow paths become sites for later cementation and reduction of porosity. This will potentially reduce overall reservoir volumes and may impede fluid flow in both horizontal and vertical directions. The 3D distribution of concretion must be taken into account in reservoir modeling and fluid flow simulations to avoid overestimation in recovery factors.

1. Introduction

Calcite concretions change fluid flow dynamics and reduce reservoir quality in many subsurface shallow-marine reservoirs (Kantorowicz et al., 1987; Saigal and Bjørlykke, 1987; Bjørkum and Walderhaug 1990; McBride et al., 1995; Morad and DeRos, 1994; Dutton et al., 2000; Dutton et al., 2002; White et al., 2003) but are not well understood. Although many studies document the 2D distribution of concretions, there are no studies, to the best of our knowledge, that examine the 3D distribution in outcrop analogs and the consequences for reservoir production.

The purpose of this study is to document the 3D distribution of cements in continuously-exposed cliff faces of a mixed-influenced deltafront, augmented with shallow borehole and 3D ground penetrating radar (GPR) data taken adjacent to the outcrop cliff face. This study forms part of a broader research program aimed at a full 3D reservoir characterization of a shallow-marine deltaic reservoir analog that includes sedimentology (Gani and Bhattacharya, 2007), GPR imaging (Lee et al., 2007a,b) and fluid flow modeling (Tang, 2003).

This paper focuses on the petrography, diagenesis, and geochemistry of calcite concretions in the Cretaceous Wall Creek Member in superb outcrops adjacent to the Powder River basin. Particularly, we aim to investigate the constraints on the timing and origin of concretion growth and their relationship to porosity, permeability and fluid flow dynamics. This data are used to determine the relationship and influences of the calcite concretions on 3D

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GPR signals that have been collected in order to produce a 3D model of reservoir heterogeneity in an ancient shallow-marine delta. These results have major implications for reservoir characterization relative to porosity and permeability predictions and fluid flow pathways, particularly for Cretaceous reservoirs of onshore USA.

2. Geological setting

2.1. Basin framework

The Powder River Basin is a compressional foreland basin that formed during the Sevier Orogeny (Merewether, 1996) and is asymmetric with a synclinal axis east of the Bighorn Mountains and Casper Arch (Fig. 1). The basin formed due to localized tectonic movements before Late Cretaceous (Markert and Al-Shaieb, 1984). The basin development became prominent during Late Cretaceous and Paleogene in the early stages of the Laramide Orogeny and the rise of the Bighorn Mountains and Black Hills (Fig. 1). Folding and faulting occurred during early Eocene westward tilting, caused by uplift of the Black Hills during the late Eocene, with continued downwarping and regional tilting through the Miocene (Markert and Al-Shaieb, 1984).

2.2. Stratigraphy and burial history

The Frontier Formation consists of the Cenomanian Belle Fourche Member, the middle Turonian Emigrant Gap Member, and the upper Turonian Wall Creek Member (Fig. 2) (Tillman and Almon, 1979). The Frontier forms a thick succession of non-marine strata which thins to marine sandstones interbedded with shale in the study area. Main source areas for the Frontier are believed to have been areas uplifted from movement along the Paris Thrust fault (Wiltschko and Door, 1983). Volcanic activity to the west of the depositional basin was high, and is shown both by the abundant volcanic rock fragments within the Wall Creek and older Frontier members (McBride et al., 2003), and numerous bentonite horizons in the Frontier, many up to several meters thick (Bhattacharya and Willis, 2001). Abundant bentonites and bentonitic shales indicate that this volcanic detritus was intermingled with other clastic detritus. Frontier successions were deposited into the western border of the north-south trending Cretaceous North American Interior Seaway.

The Wall Creek Member forms the top of a regional sandy to conglomeratic clastic wedge, which prograded eastward from the Sevier mountain belt. Below the Wall Creek, a regional unconformity marks the boundary with the Emigrant Gap member (Fig. 2). The Wall Creek is capped by a marine ravinement surface separating the uppermost sandstone body from the younger Sage Breaks member of the Cody Shale (Willis et al., 1999). The Wall Creek outcrops are located on the southeastern border of the Bighorn Mountains in Wyoming (Figs. 1, 3). The Wall Creek sandstone is interpreted to consist of several delta lobes, indicated by seven different sandstone bodies (Fig. 2; Gani and Bhattacharya, 2007; Sadeque et al., 2008). By factoring in both quality and accessibility of outcrop, the most southerly outcropping of sandstone body #6 at Raptor Ridge (Figs. 2, 3) was chosen for this study.

The stratigraphic thickness from surface to the bottom of the Shannon sandstone of the Steele Member of the overlying Cody Shale is 763 m (Hansley and Nuccio, 1992). The thickness of strata (Niobrara Member and Sage Breaks Member of the Cody Shale) from the bottom of the Shannon sandstone to the top of Frontier Formation and Wall Creek sandstone in eastern Natrona County and the western border of the Powder River Basin is approximately 570 m (Merewether, 1996) (Fig. 2). Therefore the ultimate burial depth of the Wall Creek sandstone was at least 1.35 km. This is a minimal approximation as any additional erosion and compaction could not be quantified.

Using an average geothermal gradient of 29 °C/km, (Hansley and Nuccio, 1992; Dutton et al., 2000) and a surface temperature of 10 °C–15 °C, (Spencer, 1987; McBride et al., 2003), the maximum burial temperature of the Wall Creek sandstone likely reached approximately 50 °C–55 °C.

2.3. Outcrop sedimentology and cement mapping

At Raptor Ridge, Sandstone #6 is the uppermost parasequence of the Wall Creek Member. Sandstone #6 shows a coarsening and thickening-upward facies succession and a lobate geometry with a

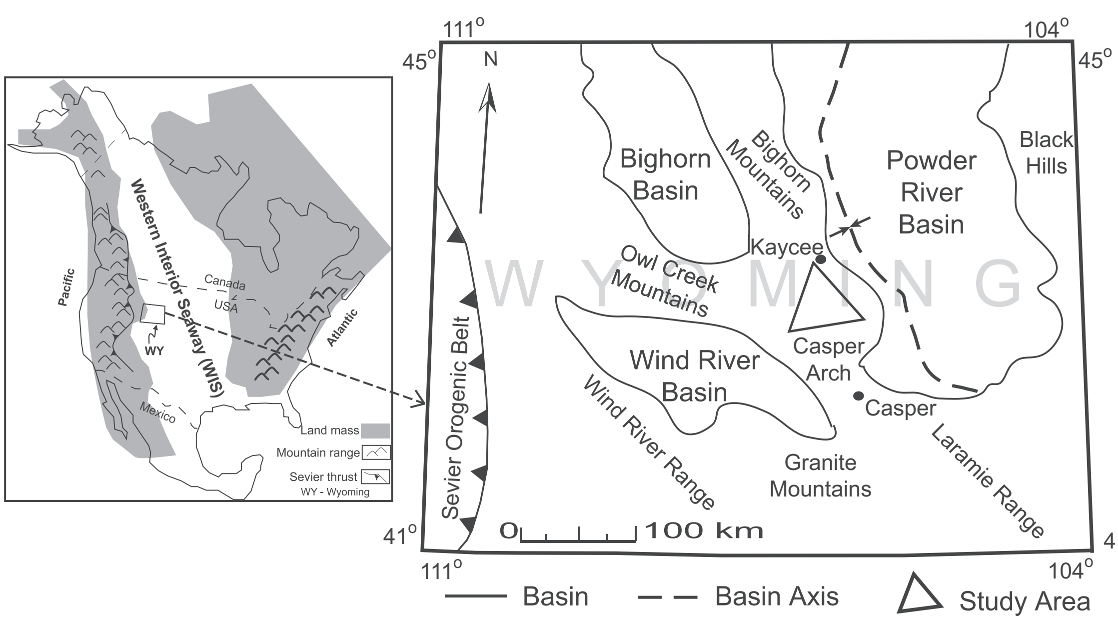

Fig. 1. Cretaceous paleogeography of the Western Interior Seaway during the middle Turonian, and Wyoming map with location of the Powder River Basin, study area, and tectonic features.