Research paper

Observations on the origin of micrite crystals

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ABSTRACT

The transformation of depositional lime mud to microporous micrite has been the subject of several important papers recently in response to the recognition that micropores are important to the production of carbonate hydrocarbon reservoirs. The origin of micrite has generally been described as a micro dissolution and reprecipitation process (often referred to as Ostwald ripening), with nanometer-sized depositional particles being dissolved and larger crystals (micrite) averaging 2 μm in diameter being precipitated. These conclusions were tested by detailed scanning electron microscope (SEM) observations of micrite and minimicrite crystals found in the mid-Pliocene to upper Miocene section of the Clino core taken on the western edge of the Bahama Bank. Minimicrite in this data set is shown to be composed of both aragonite and calcite with calcite being the dominate mineral. In addition, micrite crystals are composed of cemented nanometer-sized calcite crystals and are not individually precipitated calcite crystals. As a result, the faces of the micrite are anhedral and knobby in appearance rather than being smooth, euhedral crystal faces. Extensive size measurements could find no size selectivity in the dissolution of the calcite minimicrite, indicating that the Ostwald ripening process is not active. Aragonite and calcite crystals are dissolved and some calcite crystals act as nuclei for the precipitation of the dissolved carbonate. The origin of the micropores is also debated. Some authors call upon a dissolution event to increase porosity of a partially cemented micrite, based largely on the anhedral nature of the micrite. Others conclude that porosity is originally inherited from the deposition lime mud and that porosity is lost by overgrowth cementation, which results in euhedral micrite crystals. The observations presented here show that anhedral crystals are due to the inclusion of nanometer calcite crystals rather than to dissolution of euhedral crystals. Lastly, these micrite crystals are formed by calcite and aragonitic sediment precipitated from an aragonitic sea, disproving the assertion of some authors that porous micrite only forms from sediments deposited in calcitic seas.

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1. Introduction

One of the most poorly understood processes in carbonate diagenesis, and until recently the least interesting in my opinion, is the diagenesis of lime mud. The recent interest results from the large hydrocarbon reservoirs in the Middle East that produce from micropores in muddy carbonate fabrics. Kaczmarek et al. (2015) described numerous microporous reservoirs. They concluded that micropores are located between micro calcite crystals ranging in size from 1 to 5 μm and averaging around 2 μm (). Porosity is generally quite high, ranging up to 35%, and permeability is generally quite low, in the 1–10 md range. Pore-throat size is generally in the micropore to mesopore size range. The porosity–permeability data plots in or below the petrophysical class 3 field of Lucia (Lucia, 1995; Lucia and Loucks, 2013).

In the ongoing debate on the origin of these highly porous, mud-dominated fabrics, it is generally agreed that the fabric results from a transformation of depositional carbonate lime mud into micro calcite crystals by a process of dissolving unstable aragonite and Mg-calcite and precipitating micro calcite crystals (Dickson and Kenter, 2014; Volery et al., 2010). However, the exact process by which this transformation occurs is debatable. Folk (1965) published an extensive review of the problem and a detailed discussion of possible mechanisms. He divided the problem into the formation of crystals less than 4 μm in size, referred to as micrite, and crystals between 4 and 30 μm in size, referred to as microspar. Folk envisioned that aragonitic mud (carbonate mud from the Bahama Platform was the model) transformed to calcite micrite by a solution-reprecipitation process. Smaller crystals are preferentially dissolved and the carbonate precipitated as overgrowths on larger calcite crystals. This process would continue until all pore space was filled, which requires that carbonate be transported in from a

distant source. Folk (1965) concluded that microspar formation was a separate process, occurring after micrite formation. He proposed that microspar forms by aggrading neomorphism of a low porosity micrite by some type of grain-growth mechanism.

Several recent studies, however, have shown that microspar does not form by aggrading neomorphism of a low porosity micrite. Steinen (1982) described 5—15 μm calcite crystals growing in aragonitic mud on the Bahama Platform, concluding that aragonite was dissolved to provide carbonate for the calcite crystals and that the calcite embedded some aragonite needles. This observation suggests that microspar can form directly from a porous mud. Lasemi and Sandberg (1984) studied Pleistocene lime muds and concluded that the aragonitic muds transformed into microspar by some combination of transformation and cementation of a mud similar to modern Bahaman aragonitic mud and not by aggrading neomorphism.

In 1990, the Comparative Sedimentology Laboratory of the University of Miami drilled and cored two wells on the western edge of the Bahaman Bank: the Unda and the Clino (Ginsburg, 2001). The Clino core has been the source of data for studying the transformation of aragonitic mud to microspar within a marine diagenetic environment (Munnecke et al., 1997; Westphal et al., 2000; Melim et al., 2001, 2002). These authors conclude that microspar forms by cementing an aragonitic lime mud and later dissolving the aragonite crystals. Westphal et al. (2000) suggest that aragonite is dissolved from some layers and transported by diffusion to other layers and used as carbonate to cement the porous aragonitic mud. Lucia and Loucks (2013) collected data from the Clino core and also concluded that the conversion of aragonitic mud to microspar was a dissolution and reprecipitation process. However, based on the fact that porosity did not significantly change during the process, they concluded that dissolution and precipitation was a local process, and that no dissolved carbonate was transported out and no carbonate was transported in, at least initially. Several low porosity samples suggested the introduction of a distant source of carbonate similar to the conclusion of Westphal et al. (2000)

One would expect the micrite crystals to be euhedral if cementation were a principal process in their formation. However, many of the micrite crystals in the ancient record are not euhedral microrhombic crystals but rather subhedral to anhedral (Kaczmarek et al., 2015; Regnet et al., 2015). In this paper I study the origin of the micrite crystals examining the changes in crystal morphology that occur during the transformation from nanometer-size calcite crystals to micrite. In addition, recent studies have suggested that the process of Ostwald ripening is responsible for the transformation of deposition lime mud to micrite (Volery et al., 2010; Carpentier et al., 2015). Ostwald ripening is a process of dissolving smaller crystals and precipitating larger crystals. In this paper I test for the Ostwald ripening process by documenting changes in crystal size of the calcitic minimicrite as the transformation progresses.

2. Definition of terms

Terms used to describe the microfabrics of mud-dominated fabrics vary. In this paper, I will strive to use terms as defined by Folk (1965). Micrite is used for crystals between 1 and 4 μm in size. Microspar, also referred to as spar in this paper, is used for crystals larger than 4 μm. In addition, the term minimicrite is used for crystals that are smaller than 1 μm, as defined by Lucia and Loucks (2013). These are not rigid boundaries because often the range of a population of minimicrite or micrite crystals extends outside of the defined boundaries. A further complication is that the term micrite as used in thin-section descriptions may not conform to a ridged

definition because crystals smaller than 7—10 μm cannot be readily distinguished with a light microscope. The term micrite used in thin-section descriptions often includes considerable minimicrite, as well as a considerable volume of micropores. In addition, the term crystal is very loosely applied in this manuscript. As I will show, the "crystals" are often composed of several smaller "crystals."

Crystal morphology is difficult to describe in this data set. Aside from aragonite needles and rods, most of the crystals have no recognizable faces and are called anhedral. Some crystals have a few well-defined faces and are referred to as subhedral. Only a few crystals were observed that could be described as euhedral and these crystals are commonly filling pore space. The anhedral crystal faces have been described as lumpy or rough and will be described as knobby in this paper, for lack of a better term. The term rounded was introduced by Lambert et al. (2006) to describe an anhedral crystal form, but that is a generic term interpreted to imply dissolution of the crystal faces and will not be used here. When viewed in backscatter SEM images, micrite crystals have rough outlines and are described as irregular.

Recently, several authors have attempted to relate texture to porosity and permeability by using terms such as granular, clustered, fitted, fused, and punctic (Deville de Periere et al., 2011; Kaczmarek et al., 2015; Regnet et al., 2015). These terms will not be used here because porosity and permeability are not the subject of this report (see Lucia and Loucks, 2013, for a discussion of porosity, permeability, and crystal size). Describing the nanometer-sized crystal shapes found in minimicrites presents a somewhat different problem. The nanometer-sized crystals are mostly described as anhedral, but others are described as needles, rods, and slabs to be more descriptive.

3. Methods

Seventeen 1-inch core plugs were collected from the Bahama Clino core drilled on the western Great Bahama Bank (Ginsburg, 2001) (Fig. 1). Polished thin sections impregnated with fluorescent blue dye were prepared for microscopic examination with a Zeiss polarizing petrographic microscope. Fabric percentages for thin sections were obtained using a point counting stage and counting 300 points. The polished thin sections were coated with carbon and viewed on a field-emission FEI Nova NanoSEM 430 having a Bruker energy-dispersive spectroscopy system. Both secondary and backscatter (Bsc) images were prepared and used for point counts and for crystal size analysis. The computer program JMicroVision 1.2.7 was used to make point counts and for measuring crystal sizes from the SEM images. The number of points counted was 300. The number of crystal size measurements varied from 16 to 136 with an average of 54 measurements per sample depending upon the SEM image and magnification. Mineralogy was determined using XRD by Dr. Necip Guven at The University of Texas at San Antonio using a Rigaku-Ultima IV (2007) defractometer. The 17 samples were analyzed for porosity and permeability by Weatherford Labs in Midland, Texas. Porosity was measured using a Boyles's Law Porosimeter and permeability was measured using a Hassler Permeameter.

4. Observations

The seventeen core plugs were collected from between 992 and 2093 ft. (Fig. 1). The upper four samples have between 12 and 30 percent aragonite. Calcite composes 88 to 70 percent of the minerals. The lower 13 samples are mainly calcite with a minimum amount of aragonite and several intervals with considerable dolomite (Fig. 1). The following observations are based on polarizing