Calcite cement in Permian deep-water sandstones, Delaware Basin, west Texas: Origin, distribution, and effect on reservoir properties

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ABSTRACT

Calcite cement is the dominant control on reservoir quality in turbidite sandstones of the Upper Permian Bell Canyon Formation, Delaware Basin. These well-sorted, very fine-grained arkoses were deposited in a basin-floor setting by channel-levee systems terminating in broad lobes. Calcite cement distribution in the East Ford and Geraldine Ford fields was mapped using core, log, and thin-section data. Calcite is concentrated in tightly cemented zones that are mostly less than 1 ft (0.3 m) thick. Areas that have high percentages of calcite-cemented sandstone (>20%) occur along the margins of the sandstone bodies, in overbank and lobe deposits, where sandstone pinches out into siltstone. Areas that have the lowest percentage of calcite-cemented sandstone (<10%) occur where the sandstone is thickest, in the channel facies.

Isotopic composition of the calcite ($\delta^{13}C = -1.8$ to $-3.0\%$ [relative to the Peedee belemnite, PDB], $\delta^{18}O = -4.6$ to $-6.3\%$ [PDB]) is consistent with the source of calcium carbonate being from dissolution of detrital carbonate rock fragments and marine skeletal debris. Because internal sources of calcite were apparently insufficient to account for the cement volume, cement components are interpreted as having been transported into the sandstones from organic-rich basinal siltstones and limestones. Feldspars buffered acidic formation waters near where they entered the sandstone, resulting in calcite concentrated near the sandstone margins. The calcite formed near maximum burial depths of 4800 ft (1.5 km) and

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temperatures of 104°F (40°C) from marine pore waters with δ^{18}O of approximately 0‰ (relative to standard mean ocean water).

Most of the calcite-cemented zones are interpreted as being concretions that extend no more than a few meters laterally. Production data and geophysical log correlations suggest that some cemented zones are laterally continuous at least 1000 ft (300 m) and cause vertical reservoir compartmentalization. Laterally extensive calcite layers may be associated with the base of turbidite deposits.

INTRODUCTION

Calcite cement exerts a strong control on sandstone reservoir properties, particularly in shallow-buried or young sandstones containing little quartz cement. Because calcite cement reduces reservoir porosity and permeability and affects fluid flow during production, an improved understanding of the controls on calcite cement distribution has economic significance. Determining the origin of calcite cement in a sandstone can improve our ability to predict its distribution. This case study of the reservoir-scale distribution of calcite cement investigated Permian deep-water turbidite sandstones of the Delaware Mountain Group to determine the (1) origin of the cement, (2) the controls on cement distribution, and (3) the effect of the cement on reservoir properties. The study focused on calcite cement distribution in the East Ford and Geraldine Ford fields in the Delaware Basin, west Texas (Figure 1).

Many previous studies have examined the origin of carbonate cement in deep-water turbidite sandstones (e.g., Boles and Ramseyer, 1987; Slatt and Hopkins, 1990; Moraes and Surdam, 1993; McBride et al., 1995; Hendry et al., 1996; Boles, 1998; Silva et al., 1998; Sombra et al., 1998; Souza and Silva, 1998; Beaubouef et al., 1999; Anjos et al., 2000; Macaulay et al., 2000; Stewart et al., 2000). In these studies, various controls on cement distribution in turbidites are identified, including contact with interbedded shales (Anjos et al., 2000), location of internal shale layers and mudclast lags (Moraes and Surdam, 1993), zones of permeabilidad at the top or bottom of beds (McBride et al., 1995), bioclast-rich beds (Hendry et al., 1996; Sombra et al., 1998) or channel lags (Beaubouef et al., 1999), zones of higher permeability and greater fluid flow (Souza and Silva, 1998; Anjos et al., 2000), faults and fractures (McBride et al., 1995), salt tectonics and associated faulting and vertical fluid movement (Stewart et al., 2000), oil migration along faults (Macaulay et al., 2000), contacts with carbonate-rich beds at the base of the reservoir (Silva et al., 1998), location of the oil-water contact (Souza and Silva, 1998), and oil biodegradation at paleo-oil-water contacts (Watson et al., 1995).

Relatively few of these studies have sufficient data to determine three-dimensional calcite cement distribution at the reservoir scale or the effect of calcite cement on reservoir flow in turbidite reservoirs. A study of two-dimensional outcrops of Permian turbidites of the Brushy Canyon Formation, west Texas, concludes that channel-lag deposits contain abundant bioclastic carbonate and have low porosity because of preferential calcite cementation (Beaubouef et al., 1999). The lags are best preserved along the margins of the channel and removed from the axes. Lags are also associated with surfaces that
define channel stories, at the base and top of massive sandstones. A halo of increased calcite cement around the channels may result from the position of channel-lag remnants (R. T. Beaubouef, 2001, personal communication).

Carbonate cement (calcite and dolomite) in Lower Cretaceous turbidite sandstones of the Upnema field, Potiguar Basin, Brazil, is more laterally continuous in lobe deposits than in channel deposits (Moraes and Surdam, 1993). Because carbonate-cemented zones in massive channel sandstones are associated with discontinuous mudclast lags, they are dispersed and of short lateral extent. In lobe facies, laterally extensive carbonate-cemented layers are associated with continuous shaly zones between turbidite depositional packages. The calcite cement enhanced permeability anisotropy inherited from depositional architecture because the cement is associated with shaly zones.

The Cretaceous Namorado Sandstone of the Campos Basin, Brazil, is composed of massive turbidite sandstones that contain calcite-cemented intervals 4 to 8 in. (10 to 20 cm) thick (Sombra et al., 1998). The cemented zones have a vertical frequency of 1/m in cores and occur in bioclast-rich layers. Horizontal cores cut concretions up to 20 ft (6 m) long, but no periodicity was observed in the horizontal distribution of concretions. Models that best fit the ratio of vertical permeability/horizontal permeability ($K_v/K_h$) from well tests were the ones constructed with small concretions 1–2 m (3–6 ft) long.

Calcite-cemented zones in massive Paleocene turbidite sandstones of the Balmoral field, North Sea, occur as strata-bound concretions in the middle of continuous sandstones (Slatt and Hopkins, 1990). Cement occurs in both lobe and channel sandstones, and average permeability is reduced by about half in both facies when cemented and uncemented samples are averaged together. Diagrams presented by Slatt and Hopkins (1990) suggest that calcite-cemented zones are somewhat more abundant in lobe facies than in channel facies and that calcite-cemented zones are more common in the lower part of the reservoir.

Miocene turbidites at the North Coles Levee field in the San Joaquin Basin, California, contain carbonate-cemented zones that average 1 ft (0.3 m) in thickness and compose 6 to 8% of the total reservoir thickness (Boles and Ramseyer, 1987). The cemented zones are not correlated with either grain size or vertical position in upward-fining cycles, and they are generally less than 300 ft (90 m) in lateral extent.

In this study of the East Ford and Geraldine Ford fields in west Texas (Figure 1), closely spaced log and core data provided reservoir-scale information on calcite cement distribution, and production data from the East Ford field revealed the influence of calcite cement on reservoir flow. The study interval was the oil-producing Ramsey sandstone in the upper Bell Canyon Formation, which is undergoing CO₂ flooding in both fields (Pittaway and Rosato, 1991; Dutton et al., 2003). This data set provides a rare opportunity to determine the three-dimensional distribution of calcite cement in subsurface reservoirs.

**GEOLOGIC SETTING**

Upper Permian (Guadalupian) Delaware Mountain Group strata compose a succession of slope and basin deposits in the Delaware Basin in west Texas and southeast New Mexico. The Delaware Basin was semirestricted, its south end partly open to the seaway and its north end surrounded by an extensive carbonate shelf-and-reef complex (Figure 1). The Bell Canyon Formation, the focus of this study, is the youngest formation in the Delaware Mountain Group, and it is composed of interbedded sandstones, siltstones, and limestones (Meissner, 1972; Fischer and Sarnthein, 1988; Gardner, 1992). During sea-level highstands, organic-rich siltstones accumulated on the basin floor by slow settling from the suspension of marine algal material and airborne silt. Associated limestone tongues within the Bell Canyon Formation were deposited by sediment gravity flows that originated by slumping of carbonate debris along the flanks of the rapidly aggrading carbonate platform (Gardner, 1992; Brown and Loucks, 1993a, b). During sea-level lowstands, siliciclastic sands were carried into the basin by turbidity currents. Clay was carried by the wind beyond.
the Delaware Basin, accounting for the scarcity of detrital clay-sized sediment in the Delaware Mountain Group deposits (Fischer and Sarnthein, 1988).

The East Ford and Geraldine Ford fields produce oil from the Ramsey sandstone, the youngest sandstone in the Bell Canyon Formation (Figure 2). Depositional models of the Geraldine Ford and East Ford fields were developed using data from Bell Canyon outcrops and subsurface data (Barton and Dutton, 1999; Dutton et al., 1999; Dutton et al., 2003). Stratigraphic relations in outcrop indicate that the Bell Canyon sandstones were deposited in a basin-floor setting by a system of leveed channels that have attached lobes and overbank splays that filled topographically low interchannel areas (Barton and Dutton, 1999, 2007). Water depths were between 1000 and 2000 ft (300 and 600 m) during deposition of the Bell Canyon Formation (Kerans et al., 1992).

Maximum burial depth of the Bell Canyon sandstones at the East Ford and Geraldine Ford fields was approximately 4800 ft (1450 m). Maximum burial was reached by the Early Jurassic, and uplift during the Jurassic and again in the late Tertiary removed about 2000 ft (600 m) of overburden in this area (Williamson, 1978), leaving the Ramsey sandstones at a depth of approximately 2755 ft (840 m) in both fields. The present geothermal gradient is 1.0°F/100 ft (18.2°C/km) (Woodruff et al., 1984). The maximum burial temperature of the Ramsey sandstones at the East Ford and Geraldine Ford fields was approximately 125°F (50°C), assuming a mean annual surface temperature of 77°F (25°C) and a geothermal gradient of 1.0°F/100 ft (18.2°C/km) in the Jurassic.

The oxygen isotopic composition (δ18O) of formation water in the Sullivan oil field, which produces from the Bell Canyon Formation 2 mi (3 km) south of the East Ford field, is −2.0‰ (relative to standard mean ocean water, SMOW) at a depth of 2700 ft (820 m) (Williamson, 1978). Formation water in the Geraldine Ford and East Ford fields is assumed to have a similar isotopic composition, but no data were available. Chloride concentration of formation water in the two fields ranges from 40,000 ppm in the southwest to 70,000 ppm in the northeast (Ruggiero, 1985; Dutton and Flanders, 2001a). A regional trend of decreasing salinity to the southwest results from late Tertiary tilting of the Delaware Basin and flow of meteoric water into Delaware sandstones in outcrop (McNeal, 1965).

METHODS

Vertical and areal distribution of calcite-cemented intervals in the Geraldine Ford field was mapped from descriptions of 3615 ft (1102 m) of Ramsey sandstone core from 70 wells in the field (Dutton et al., 1999). Calcite-cemented zones have a distinct white color in the core, and identification of cemented zones was confirmed by hydrochloric acid. These data were supplemented by core descriptions by Ruggiero (1985) from 13 additional wells. Because many wells have only a gamma-ray log, which could not be used to identify cemented intervals, calcite distribution was mapped from core data alone.

Only one core was available from the East Ford field, so calcite-cemented zones in other wells in the East Ford field were identified on interval transit time logs as prominent high-velocity deflections. Core and log descriptions were supplemented by porosity and permeability analyses in the Ramsey

Figure 2. Typical log from the 24 East Ford unit well (from Dutton et al., 2003; reprinted with premission from the AAPG). SH1 = laminated siltstone.
interval. A total of 4752 core analyses of sandstone samples from 153 cored wells from the Geraldine Ford field and 369 sandstone samples from 12 cored wells from the East Ford field identified calcite-cemented zones that have low porosity and permeability. The East Ford and Geraldine Ford fields have been unitized and named the East Ford unit (EFU) and the Ford Geraldine unit (FGU). Wells located in the units are called EFU and FGU, respectively.

The composition of Bell Canyon sandstone and siltstone from the East Ford and Geraldine Ford fields was determined by standard point-count analysis (200 points) of 68 thin sections and by cathodoluminescent petrography. Chips used to make the thin sections were end trims of core-analysis plugs so that petrographic parameters could be compared with porosity and permeability. Thin sections were stained for K-feldspar and carbonates. Authigenic minerals were categorized by location, that is, whether they filled primary pores or replaced framework grains. Framework grain size and sorting were estimated by grain-size point counts (50 points). Calcite cement was analyzed for stable isotope ratios of carbon and oxygen.

**RESULTS**

**Petrography of Ramsey Sandstones**

The Ramsey sandstones in the East Ford and Geraldine Ford fields are very fine grained and have a narrow range of grain sizes. The average grain size is 0.092 mm (3.45 φ), and the range is 0.056–0.106 mm (4.1–3.3 φ). Sorting is good to moderate, averaging 0.45 φ standard deviation and ranging from 0.33 to 0.62 φ (sorting of Folk, 1974).

The Ramsey sandstones (Figure 3) are arkoses that have an average composition of quartz = 65%, feldspar = 29%, and rock fragments = 6%. Plagioclase and potassium feldspar are approximately equal in abundance. The most common lithic grains are metamorphic, plutonic, and carbonate rock fragments. Detrital carbonate rock fragments and fossils (mostly crinoid and fusulinid fragments) together constitute 1% of the present rock volume. No detrital clay-sized matrix in these Bell Canyon sandstones is observed, reflecting the interpreted eolian sediment source (Fischer and Sarnthein, 1988).

Cements and replacive minerals constitute between 1 and 31% of the sandstone volume, calcite and chlorite being the most abundant authigenic minerals. Calcite has an average volume of 7% in the Ramsey sandstone and ranges from 0 to 30% (Figure 3A, B). Calcite is not uniformly distributed but occurs as concretions, defined by McBride et al. (1995, p. 1044) as “discrete and tightly cemented bodies embedded in weakly cemented or uncemented host sandstones.” Calcite-cemented zones range from 2 to 16 in. (5 to 40 cm) in thickness. Cemented zones contain an average of 18.5% authigenic calcite, and the “uncemented” sandstones contain an average of 3.6% authigenic calcite.

Most of the calcite fills intergranular pores, but an average of 1.5% calcite occurs as grain replacement. Some feldspar grains are only partly replaced by calcite (Figure 3C), and it is clear that partial grain replacement has occurred. In other cases, replacement has been complete, and the original detrital grain cannot be identified. These sand-grain-size areas of large, single crystals of clear calcite are interpreted to be replaced grains, probably replaced feldspars (Figure 3D). An alternate interpretation is that they are detrital grains of coarsely crystalline sparry limestone or fossils. However, it is unlikely that the limestone source area contained such large calcite crystals (R. G. Loucks, 2005, personal communication). These grains are not echinoid fragments because echinoid fragments in these sandstones can be distinguished by their granular microtexture (“small pores filled with ‘dirt’”; Scholle, 1978, p. 95). Microprobe analysis of calcite cement in the Delaware Mountain Group sandstones (mainly Bell Canyon sandstones) by Hays and Tieh (1992) indicates a mean composition of Ca\textsubscript{0.961}Mg\textsubscript{0.013}Fe\textsubscript{0.003}Mn\textsubscript{0.023}.

Chlorite (average volume = 1%) forms rims around detrital grains, extending into pores and pore throats. Other authigenic minerals include pervasive but volumetrically minor authigenic quartz and feldspar (both K-feldspar and Na-plagioclase) overgrowths (average <1%) and local anhydrite cement. Quartz generally appears to have overgrown and included chlorite.
Porosity determined by thin-section point counts averages 20% (Figure 3A), consisting of 18% primary porosity and 2% secondary porosity. Secondary pores are interpreted as forming mainly by feldspar dissolution; some partly dissolved feldspars were observed. Core-analysis porosity in the Ramsey sandstones from the Geraldine Ford and East Ford fields averages 22.0% and ranges from 2.6 to 36.1%. Sandstone permeability ranges from 0.01 to 408 md. Average permeability is 39 md, and geometric mean permeability is 17 md.

The Trap and Ford siltstones, which overlie and underlie the Ramsey sandstone, respectively (Figure 2), have an average grain size of 0.058 mm (4.1 φ) and an average composition of Q$_{68}$F$_{26}$R$_{6}$. Detrital fossils and carbonate rock fragments in the siltstones are about as abundant as in the surrounding sandstones, having a combined average volume of 1%. The average volume of authigenic calcite in the siltstones is 2.4%, ranging from 0 to 7%. The Delaware Mountain Group siltstones contain an average of 3% total organic carbon (TOC), and TOC values range from 0.5 to 12% (Hays and Tieh, 1992).

On the basis of petrographic evidence, the relative order of major events in the diagenetic history

Figure 3. Petrographic photos. (A) Porous Ramsey 1 sandstone from 41R East Ford unit well, 2766.2 ft (843.1 m). (B) Ramsey 1 sandstone completely cemented by calcite from 41R East Ford unit, 2766.8 ft (843.3 m). (C) Potassium feldspar grain partly replaced by calcite in Ramsey 1 sandstone from 94 Ford Geraldine unit, 2671 ft (814.1 m). In photos A–C, porosity is stained blue; C = calcite, K = potassium feldspar. (D) Cathodoluminescence photo of calcite cement (orange) in Ramsey 1 sandstone from 41R East Ford unit, 2766.8 ft (843.3 m). The large area of calcite cement labeled RF is interpreted to be a feldspar grain that was replaced by calcite. Photo by R. M. Reed.
of the Ramsey sandstones is interpreted to be (1) precipitation of chlorite rims, (2) formation of quartz overgrowths, and (3) precipitation of calcite cement. The same basic paragenetic sequence was observed by Williamson (1978) in the Bell Canyon sandstones in nearby fields. Calcite cement has a complex relationship with chlorite, appearing both to include and be overgrown by clay flakes; this relationship suggests that some chlorite precipitated after calcite.

Hays and Tieh (1992) emphasized the dissolution of early calcite cement as a major event in the creation and preservation of porosity in the Delaware sandstones. However, examination of samples from the East Ford and Geraldine Ford fields for this study suggests that although some calcite cement dissolution occurred, dissolution was not widespread or extensive.

**Isotopic Composition of Calcite Cement**

Isotopic composition of calcite cement in the East Ford field was measured in eight samples. All data are reported as per-mil deviation from the Peedee belemnite (PDB) standard. The $\delta^{13}C$ composition of the calcite has a very narrow range from −1.82 to −2.95‰ (PDB); $\delta^{18}O$ composition ranges from −4.55 to −6.28‰ (PDB) (Table 1). Most of the samples were taken from highly cemented sandstones (12 to 30% authigenic calcite), but one sample contained 2% detrital carbonate rock fragments and no authigenic calcite, as determined by point counts (error < 1% [Folk, 1974]). The sample without calcite cement has a $\delta^{13}C$ composition of −1.82‰ (PDB) and a $\delta^{18}O$ composition of −6.15‰ (PDB). None of the samples contained fossil fragments, as determined by point counts. Isotopic measurements of calcite cement from other nearby oil fields have a $\delta^{13}C$ composition ranging from −1.1 to −2.9‰ (PDB) and a $\delta^{18}O$ composition from −4.5 to −7.8‰ (PDB) (Williamson, 1978).

**Effect of Calcite Cement on Porosity and Permeability**

In these sandstones that have little variation in grain size and contain no detrital clay, the volume of calcite cement is the most important control on permeability. Statistically significant inverse relationships exist between the volume of calcite cement and both porosity and permeability in the Ramsey sandstone (Dutton and Flanders, 2001b) (Figure 4). In the calcite-cemented zones (defined as samples that have greater than 10% authigenic calcite), average permeability is 8.3 md, geometric

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<th>Depth (ft)</th>
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<th>Authigenic Calcite (%)</th>
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*All samples are from the 41R EFU well. Calcite and carbonate rock fragment (CRF) volume are from thin-section point counts.

**Figure 4.** Calcite cement volume is the main control on permeability in Ramsey sandstones from the 41R East Ford unit well (from Dutton and Flanders, 2001b; reprinted by permission of the AAPG Southwest Section). Permeability is unstressed permeability to air.
mean permeability is 0.9 md, and average core-analysis porosity is 13.7%. Sandstones containing less than 10% authigenic calcite have an average permeability of 54 md, a geometric mean permeability of 33 md, and an average core-analysis porosity of 22.1%.

The calcite-cemented zones have sharp margins at the top and bottom (Figure 5). Closely spaced permeability measurements were taken on the slabbed core face from the 41R EFU well at approximately 1-in. (2.5-cm) intervals above, within, and below a 5-in.-thick (13-cm-thick) cemented zone at 2757 ft (840 m) (Figures 5, 6) using a device that measures permeability by an unsteady-state pulse-decay method. The lowest permeability, and presumably the highest volume of calcite cement, occurs from 2757.5 to 2757.6 ft (840.49 to 840.52 m) (Figure 6). Permeability increases slightly in the 2 in. (5 cm) above and below this depth (Figure 6), but the absence of oil fluorescence in the entire 5-in.-thick (13-cm-thick) zone (Figure 5) suggests that most porosity is occluded.

**Figure 5.** Core of Ramsey 1 sandstone from the 41R East Ford unit well photographed in ultraviolet light. The cemented zones appear black in ultraviolet light because they have no oil-filled porosity, whereas uncemented sandstones have bright-yellow fluorescence because the pores are saturated with oil. Depths are marked in feet.

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by calcite cement. Moderate fluorescence in 1-in.-wide (2.5-cm-wide) zones above and below the completely cemented layer (Figure 5) suggests that there is a thin transition zone in which porosity is only partly filled by calcite cement. Thin sections from depths of 2757.3 ft (840.43 m) and 2757.4 ft (840.46 m) contain remnants of intergranular calcite cement that show evidence of having undergone dissolution. The gradual increase in permeability at the top of the cemented zone (Figure 6) may be caused by partial dissolution of calcite cement, and the upper boundary may have been sharper in the past. Carbonate-cemented zones at the North Coles Levee field in California have very sharp boundaries (Boles and Ramseyer, 1987); the transition from totally cemented to porous sandstone occurs within 0.5 in. (13 mm) or less.

An excellent relationship between porosity and permeability exists in sandstones from the 41R EFU well (Figure 7). Bryant et al. (1993a, b) developed a model for calculating permeability from grain size and porosity in simple granular porous media containing equal-thickness cement. To test the applicability of the model to the Ramsey sandstones, permeability values measured on core plugs from the 41R EFU well were compared with permeability calculated from the Bryant-Finney model using the modified power-law equation of Jennings and Lucia (2003):

$$\ln(k) = \ln(a) + b \ln(\phi - \phi_0) + 2 \ln(r)$$

where $a$, $b$, and $\phi_0$ are constants having values of 85.9, 3.39, and 0.0221, respectively, and $k$, $\phi$, and $r$ are given in units of millidarcys, fraction of bulk volume, and micrometers, respectively.

Measured permeability in these sandstones is about 1.5 orders of magnitude lower than predicted permeability calculated by the Bryant-Finney model (Figure 7). Actual permeability may be lower than predicted permeability because of the presence of chlorite rims around detrital grains. Although they have little effect on porosity, chlorite rims extend into pore throats and reduce permeability. In addition, calcite cement tends to completely fill pores where it occurs and be absent from other pores, so it is not an equal-thickness cement. The Bryant-Finney model correctly predicts the shape of the

![Figure 6](image_url)

**Figure 6.** Plot of permeability versus depth across a calcite-cemented layer in the 41R East Ford unit well (from Dutton and Flanders, 2001b; used with permission from the AAPG Southwest Section). Permeability was measured at 1-in. (2.5-cm) intervals directly on the slabbed core face using a device that measures permeability by an unsteady-state pulse-decay method. Permeability has been mathematically converted from air-permeability measurements to equivalent liquid-permeability values, or Klinkenberg permeability. Core interval is shown in Figure 5.

![Figure 7](image_url)

**Figure 7.** Plot of measured porosity versus permeability from core analysis data from the 41R East Ford unit well. Predicted permeability was calculated from the Bryant-Finney model (Bryant et al., 1993a, b) using the modified power-law equation of Jennings and Lucia (2003). See text for details.
porosity-permeability curve in the 41R EFU sandstones but overestimates permeability.

Calcite Cement Distribution in Geraldine Ford Field

Calcite-cemented zones can occur anywhere within the Ramsey sandstone section in the Geraldine Ford field, but they are somewhat more common near the top and base of the Ramsey interval (Figure 8) (Dutton et al., 1999). It was not possible to determine the lateral extent of the cemented intervals observed in the core or to correlate any of the cemented zones between wells with certainty. Most of these zones of calcite-cemented sandstone are assumed to be concretions that extend no more than a few meters laterally. Although concretions of this size are not barriers, they can reduce average reservoir permeability, make flow paths more tortuous, change breakthrough time and location, and modify sweep efficiency in a reservoir (Dutton et al., 2002). Cemented zones were not observed in cores of the overlying Trap siltstone or in the underlying Ford siltstone.

Median thickness of the 234 calcite-cemented zones in 70 cores in the Geraldine Ford field is 0.6 ft (0.2 m), and 75% of the cemented zones are less than 1 ft (0.3 m) thick. An average of 6% of the total reservoir interval in the Geraldine Ford field is tightly cemented by calcite (206 ft [62.8 m] of calcite-cemented sandstone/3615 ft [1101.9 m] of sandstone core). The total volume of authigenic calcite within the reservoir is estimated to be about 4.4%, assuming 18.5% calcite in the cemented zones and 3.6% in the ‘‘uncemented’’ zones.

Geographic distribution of calcite cement in the Geraldine Ford field was mapped by calculating the percentage of calcite-cemented sandstone in each cored well. Most of the areas that have a high percentage (>15%) of calcite-cemented sandstone are found along the margins of the field, where the sandstone pinches out into siltstone (Figure 9). Total thickness of calcite-cemented sandstone zones also shows a similar distribution, with the thickest cemented zones at the field margins. The trend shown in Figure 9 is thus not simply an artifact of thinning of the Ramsey sandstone toward the pinch-out into siltstone. Calcite cement is most common in what are interpreted to be overbank-splay and lobe facies at the margins of the sandstone body, and less abundant in the channel facies in the center (Figure 9).

The presence of thin layers of tightly calcite-cemented sandstone (Figure 8) results in highly variable, streaky permeability distribution throughout the Ramsey sandstone (Dutton et al., 1999). Calcite-cemented zones are common near the top of the Ramsey sandstone (~1 ft [0.3 m] below the sandstone-siltstone contact), but in some wells, unusually high-permeability zones (>100 md) occur above these calcite layers, at the top of the sandstone. Because samples were not available from these high-permeability zones, the reason for the high permeability—greater than normal feldspar dissolution, calcite cement dissolution, or grain-size variation, for example—could not be determined. As will be discussed below, extensive feldspar dissolution where acidic formation fluids entered the sandstones may explain the high-permeability zones.

Calcite Cement Distribution in East Ford Field

Distribution of calcite cement in the East Ford field was interpreted from geophysical logs taken in 20 wells that were calibrated to a core taken in the 41R EFU well (Figures 5, 10). In this core, four calcite layers in the lower part of the Ramsey 1 sandstone are spaced about 3 ft (1 m) apart. The Ramsey 2 sandstone contains one cemented layer that is 14 in. (36 cm) thick (Figure 10). Calcite-cemented zones were mapped throughout the East Ford field using core analysis data and sonic and resistivity logs to identify cemented, low-permeability intervals. This technique can be used because calcite is the predominant control on permeability in these sandstones (Figure 4). The cemented thicknesses may be somewhat overestimated because cemented zones appear thicker on the logs than they actually are (Figure 10) because of log resolution.

Vertical Distribution

In the 41R EFU well, calcite-cemented zones occur near the top and base of the sandstone body,
Figure 8. West–east cross section AA' of the north end of Geraldine Ford field (modified from Dutton et al., 1999). Calcite-cemented intervals were identified in cores. Location of cross section is shown in Figure 9. GR = gamma ray.
Figure 9. Map of the percentage of the Ramsey sandstone interval (both Ramsey 1 and Ramsey 2) that is cemented by calcite in Geraldine Ford field (modified from Dutton et al., 1999). Calcite-cemented zones were identified in cores from the 73 wells shown on this map. Sandstone pinch-out was identified using geophysical logs from 305 wells in the field (not all shown). See Dutton et al. (1999) for the interpretation of sandstone facies.
that is, at the base of the Ramsey 1 sandstone and at the top of the Ramsey 2 sandstone (Figure 10). These two zones contain ≥21% intergranular calcite cement and show greatest deflection in neutron and density curves (Figure 10). Other cemented layers in the Ramsey 1 sandstone contain lower volumes of calcite cement (8.5 to 15%) and have smaller log deflections.

Similar calcite-cemented zones are common near the top and base of the Ramsey sandstone throughout the East Ford field. A 1- to 2-ft-thick (0.3- to 0.6-m-thick) calcite-cemented zone was observed in most wells just below the top of the Ramsey 2 sandstone (labeled 1 on Figure 11), and another cemented zone occurs just above the base of the Ramsey 1 sandstone (labeled 7 on Figure 11). In most wells, including the 41R EFU well, these layers are not right at the sandstone-siltstone contact, but about 6 in. (15 cm) into the sandstone (Figure 10).

Figure 10. Gamma ray, neutron, and density logs from the Ramsey producing interval cored in the 41R East Ford unit well. Calcite-cemented sandstone intervals were identified in the core. Production and temperature logs indicated that the gas production essentially all occurred from the interval labeled “Zone of gas effect” (modified from Dutton and Flanders, 2004). SH1 = laminated siltstone.

Figure 11. West–east cross section BB’ of the south end of East Ford field (EFU) (modified from Dutton and Flanders, 2004). Four calcite-cemented layers (labeled 4, 5, 6, and 7) in the lower Ramsey 1 sandstone can be correlated in the 40, 41, and 41R EFU wells. The layer at the base of the Ramsey 1 sandstone (labeled 7) and another near the top of the Ramsey 2 sandstone (labeled 1) occur in all five wells. Location of cross section is shown in Figure 12.
Lateral Distribution and Extent
Maps of the percentage of calcite-cemented sandstone in the Ramsey 1 and Ramsey 2 intervals (Figures 12, 13, respectively) show variations in cement volume across the East Ford field. In general, the percentage of calcite-cemented sandstone is lower in the Ramsey 1 than in the Ramsey 2 sandstone. In both sandstones, areas that have higher percentages of calcite-cemented sandstone (>20%) tend to occur along the margins of the sandstone body, in overbank splay and lobe deposits. Areas that have the lowest percentage of calcite-cemented sandstone (<10%) occur where sandstone is thickest, in the interpreted channel facies.

In many field studies, the lateral extent of calcite-cemented zones cannot be determined from widely spaced subsurface well data. Cemented zones that appear to correlate between wells may not be continuous layers but instead are discontinuous, strata-bound concretions. Production data from the East Ford field, however, indicate that some calcite in the south part of the field occurs in laterally continuous layers and not as isolated concretions. The 41R EFU well was drilled 5 yr after the beginning of CO2 flooding in the EFU as an offset to the 41 EFU well (Figures 11, 12). Sonic and neutron logs from the 41R EFU well showed a gas effect in the lower 8 to 10 ft (2.4 to 3 m) of the Ramsey 1 sandstone, in the same interval where the calcite-cemented layers occur (Figure 10). When the well was first completed, it produced a high gas volume (750 mcf gas/day) that contained a high concentration of CO2 (>90%) (Dutton and Flanders, 2004). Production and temperature logs confirmed the gas effect by indicating that inflow to the well bore was essentially all occurring in the bottom 10 ft (3 m) of the Ramsey 1 sandstone. The CO2, most likely derived from the 40 EFU injector well, was trapped below the calcite layers. The CO2 was injected in the 40 EFU well both above and below the calcite-cemented layers, but producing 39 and 41 EFU wells had no perforations in the Ramsey 1 sandstone below the calcite layers. The CO2 injected below the calcite-cemented layers in the 40 EFU well became trapped, resulting in significantly higher reservoir pressure. The CO2 that was produced in the 41R EFU well probably represents banked-up energy that gave a first flush of CO2 when the well was completed (Dutton and Flanders, 2004). These data demonstrate that calcite-cemented layers can cause effective horizontal permeability barriers within a field. Calcite-cemented zones identified on logs cannot be assumed to be small, discontinuous concretions; perforations above and below calcite layers may be necessary to contact the entire reservoir volume.

The trapping of CO2 suggests that one or more of the calcite layers is laterally continuous between 40 EFU and 41R EFU. Spikes on the 41R EFU sonic log in the lower part of the Ramsey 1 sandstone appear to correlate to those on the 40 EFU and 41 EFU sonic logs (Figure 11), further evidence suggesting the lateral continuity of the cement layers. Because the distance between 40 EFU well and 41 and 41R EFU wells is about 1000 ft (300 m), the four calcite layers observed in the 41R EFU core are interpreted as having a lateral extent of at least that distance. Most of these layers apparently do not extend to the 39 EFU and 38 EFU wells (Figure 11). However, cemented zones near the base of the Ramsey 1 sandstone and near the top of the Ramsey 2 sandstone both appear to be continuous across the entire south part of the field. The 24 EFU and 28 EFU wells (Figure 12) contain three calcite-cemented layers in the bottom of the Ramsey 1 sandstone that are interpreted as correlating between the two wells, a distance of about 735 ft (225 m).

DISCUSSION
Several studies of calcite cement in shallow-marine and deep-water sandstones have concluded that the source of the calcium carbonate was internal to the sandstones, and distribution of cement reflects the original distribution of skeletal debris (see references summarized in Bjørkum and Walderhaug, 1990; Hendry et al., 1996; Morad, 1998; Walderhaug and Bjørkum, 1998). Other studies of calcite cement in fluvial, deltaic, and deep-water settings have concluded that internal calcite sources were lacking, and calcium carbonate was transported into the sandstones from outside (e.g., Sullivan and
Figure 12. Map of the percentage of the Ramsey 1 sandstone in East Ford field that is cemented by calcite. Only wells showing values for calcite percent penetrated the entire Ramsey 1 interval with sonic or resistivity logs, or both. Other wells in the field were used to map sand thickness. Cross section BB' is shown in Figure 11.
Figure 13. Map of the percentage of the Ramsey 2 sandstone in East Ford field that is cemented by calcite. Only wells showing values for calcite percent penetrated the entire Ramsey 2 interval with sonic or resistivity logs, or both. Other wells in the field were used to map sand thickness.
McBride, 1991; Moraes and Surdam, 1993; McBride et al., 1995; Anjos et al., 2000; Dutton et al., 2000; McBride and Milliken, 2006).

Calcite cement in the East Ford and Geraldine Ford fields is most abundant at the margins of the Ramsey sandstone bodies, at the top, base, and sides of the sandstones where they pinch out into siltstone, although calcite-cemented intervals occur throughout the sandstone bodies (Figures 8, 11). Distribution of calcite cement in the Ramsey sandstone bodies probably reflects the source of calcium carbonate, but two different hypotheses could explain this cementation pattern: (1) the cement distribution reflects the original distribution of detrital carbonates and skeletal material within the sandstone, which acted as the source of calcium carbonate, or (2) calcium carbonate was imported from outside the sandstone, and calcite preferentially precipitated near the margins of the sand bodies, particularly in zones of higher permeability.

**Internal Versus External Source of Calcite Cement**

Isotopic data suggest that biogenic carbonate was the source of calcite cement. The δ^{13}C composition of the calcite cement in the East Ford field, \(-1.82\) to \(2.95\%\)e (PDB) (Table 1), indicates that the major source of carbon was skeletal carbonate debris (Gross, 1964), with a minor contribution of \(^{13}C\)-depleted carbon derived from oxidation or decarboxylation of organic matter (Curtis, 1978). The location of the skeletal debris that sourced the cement, however, whether inside or outside the sandstone, is unclear. The Ramsey sandstones currently contain only small volumes of detrital calcium carbonate as both calcite fossil fragments (mainly echinoid fragments, fusulinid tests, and mollusk fragments) and carbonate rock fragments (coarsely crystalline limestone and micrite). The average volume of carbonate rock fragments currently in the sandstones is 1%, and the average volume of fossil fragments is less than 0.1%. Sandstones also contain an average of 2% secondary pores.

Thin sections taken at 1-ft (0.3-m) intervals from the Ramsey sandstone in the 41R EFU core contain an average volume of 7% authigenic calcite, consisting of 6% primary-pore-filling cement and 1% grain replacement. Even if all the secondary pores were originally calcium carbonate that dissolved and reprecipitated as calcite cement, the total internal source material does not appear to be sufficient to account for the volume of authigenic calcite in the sandstones. Furthermore, partly dissolved feldspars indicate that much of the secondary porosity was probably derived from feldspar dissolution and not dissolution of skeletal debris.

It is unknown, however, how much calcium carbonate may have been present in the sandstones at the time of deposition but was subsequently completely dissolved, leaving only calcite cement to indicate its former presence. If dissolution happened relatively early in the burial history, grain rearrangement and sediment compaction could have destroyed any secondary pores that developed. No aragonitic fossil debris is present in the sandstones now, although fragments of sponges, scleractinian corals, and phylloid algae could have been derived from the carbonate shelf. These basin-floor turbidites were deposited in water depths of 300 to 600 m (Kerans et al., 1992), so it is unlikely that the Ramsey sandstones were exposed to meteoric water after deposition, even during periods of sea-level lowstand. As a result, any aragonite grains that were deposited probably avoided early dissolution and were carried into the subsurface as the Ramsey sandstones were buried by younger deposits. Aragonite grains may have been unstable in the subsurface Bell Canyon pore fluids, which have high Ca/Mg ratios (McNeal and Mooney, 1968; Williamson, 1978). Therefore, if aragonite grains were originally present in the Ramsey sandstones, their dissolution could have been a source of calcite cement.

Although the former presence of sufficient aragonite skeletal debris to account for the volume of calcite cement in these sandstones cannot be ruled out, there is no evidence to support this interpretation. Williamson (1978) noted that carbonate rock fragments and fossils are more abundant in outcropping Ramsey sandstones, which are close to the shelf margin, than in subsurface reservoir sandstones farther out in the basin. In the basin-floor position of the East Ford and Geraldine Ford fields, it is unlikely that carbonate debris from the
surrounding shelves would have been significantly more abundant than currently observed. Furthermore, the small volume of calcite fossils in the sandstones suggests that aragonitic skeletal debris was probably not abundant either. Even if there had originally been an equal volume of aragonite fossil fragments like the calcite fossils that are still present, it would account for less than 1% of additional internal volume of calcium carbonate. Hendry et al. (1996) interpreted aragonitic fossil debris to be the source of calcite cement in Cretaceous turbidites in the North Sea, but those sandstones still contain evidence of abundant bioclasts, including remaining calcite bioclasts and micritized outlines of former aragonitic skeletal fragments.

The most likely interpretation, therefore, is that the source of calcium carbonate for calcite cement in the Ramsey sandstones was external, coming from organic-rich siltstones or limestones in the Bell Canyon Formation or other carbonate units in the Delaware Basin.

**Depth and Timing of Calcite Cementation**

Isotopic data and textural observations from thin sections were used to interpret conditions of calcite cementation. Textural data indicate that the calcite precipitated at or near maximum burial depth. The average intergranular volume (IGV) of calcite-cemented sandstones is 26% (range of 23 to 29%), essentially the same as the 27% IGV of poorly cemented sandstones (range of 22 to 33%). The fact that the Ramsey sandstones have been compacted to an IGV of 26% suggests that they reached maximum burial of approximately 4800 ft (1.5 km) prior to calcite cementation (Paxton et al., 2002). Precipitation of minor quartz cement prior to calcite also indicates that calcite cementation did not occur shortly after deposition.

The $\delta^{18}O$ of the calcite cement ranges from $-4.55$ to $-6.28\%$ (PDB) (Table 1; Figure 14). The isotopic data do not provide a unique solution with which to interpret conditions at the time of cementation; at least two different scenarios of temperature and water composition are consistent with the isotopic data.

The calcite cement is in equilibrium with the present water composition of $-2\%$ (SMOW) and temperature of $82^\circ F$ ($28^\circ C$) in the Ramsey sandstone at Sullivan field (Williamson, 1978) (Figure 14). Williamson (1978) interpreted calcite cement in the Ramsey sandstone as having precipitated from water similar in isotopic composition and temperature to that of the sodium chloride formation brines present in the Bell Canyon Formation today. This interpretation implies that the calcite precipitated after the late Tertiary tilting of the Delaware Basin and the development of the current hydrodynamic setting at 5 to 10 Ma (McNeal, 1965; Bein and Dutton, 1993).

Alternatively, the calcite could have precipitated from Permian seawater at a temperature of $104^\circ F$ ($40^\circ C$), assuming that the seawater composition was approximately $0\%$ (SMOW) (Land and Lynch, 1996). In this scenario, precipitation may have occurred from formation waters during the Late Permian and Mesozoic burial of the sediments. If the composition of Permian seawater in the Delaware Basin was isotopically depleted compared with that
of today's oceans and had δ¹⁸O of −1.4 to −3.0‰ (SMOW) (Given and Lohmann, 1985; Korte et al., 2005), the calcite could have precipitated at lower temperatures of 77 to 95°F (25 to 35°C).

The second scenario is more likely because of the timing of oil maturation and migration into the fields. Tightly calcite-cemented intervals in the 41R EF2 sandstone (Figure 5) show no hydrocarbon fluorescence, suggesting that the calcite cement precipitated before oil migrated into the reservoirs. Hays and Tieh (1992) calculated that the upper Delaware Mountain Group began generating oil in the middle Eocene (~50 Ma). Organic maturation and generation of organic acids would have occurred well before the late Tertiary uplift and tilting of the Delaware Basin, so it is unlikely that the calcite precipitated in the current hydrodynamic setting. Calcite precipitation is interpreted as occurring near maximum burial depth during the Mesozoic, prior to oil generation and migration in the middle Eocene (~50 Ma).

Precipitation of Calcite Cement
Calcite cement is located preferentially near the margins of the sandstone bodies in both the East Ford and Geraldine Ford fields. Because internal sources of calcite were apparently insufficient to account for the volume of cement in the sandstones, necessary components for the cement are interpreted as having been transported in from the outside. Field-scale maps of cement distribution (Figures 9, 12, 13) suggest that considerable calcite precipitated near the point of entry into the sandstone bodies.

Skeletal carbonate debris and carbonate rock fragments in organic-rich basinal siltstones and limestones are the most likely external sources of necessary components for the cement. Organic acids generated during thermal maturation of organic matter probably provided a source of acid for carbonate dissolution and export into the sandstones. Organic-rich siltstones in the Delaware Mountain Group contain an average of 3% TOC, ranging up to 12% TOC (Hays and Tieh, 1992). Hays and Tieh (1992) determined that the organic matter was oxygen-rich type II and III kerogen that could have generated a significant volume of organic acid. In many formations, the volume of organic acids that can be generated cannot account for the observed volume of secondary pores (Lundegard et al., 1984; Lundegard and Land, 1986), but in the Delaware Basin, the organic-rich siltstones and limestones may have generated organic acid sufficient to keep the dissolved carbonate in solution and transport it out of the siltstones and limestones and into sandstones. When calcium carbonate was transported into the sandstones, abundant reactive feldspar buffered the acid, allowing calcite to precipitate (Milliken and Land, 1991, 1993).

Relatively ¹³C-enriched carbon in the Ramsey sandstone calcite cement (~1.82 to −2.95‰ [PDB]) may result from derivation of carbon primarily from CO₃²⁻ from dissolved inorganic carbonate rock fragments and skeletal debris and not from organic matter (K. L. Milliken, 2006, personal communication). If protons released by dissociation of organic acids dissolve detrital carbonates, the carbon isotopic composition of the resulting inorganic carbon pool will be determined by dissolving carbonate minerals, so long as the acetate ion is not destroyed (Lundegard et al., 1984, p. 402).

Controls on Calcite Distribution
The greater volume of calcite cement near the margins of the Ramsey sandstone bodies may reflect the abundance of feldspars in these sandstones. The feldspars effectively buffered much of the acidic formation waters near where they entered the sandstone, resulting in calcite precipitation near the sandstone-siltstone margins. Zones of high permeability at the top of the Ramsey sandstone may result from extensive feldspar dissolution where acidic formation waters went into the sandstone. Occurrence of calcite cement layers near the top and base of the Ramsey sandstone in the East Ford field (labeled 1 and 7 in Figure 11) fits this model. Furthermore, layers at the top and base of the sandstone body have higher volumes of calcite cement than do cemented zones that are farther from the sandstone-siltstone contact (Figure 15). Turbidite sandstones of the Penêndia Formation, Brazil, also show peripheral calcite cementation at the contact.
with interbedded shales that were the major source of dissolved carbonate (Anjos et al., 2000).

Other laterally extensive calcite cement layers in the lower part of the Ramsey 1 sandstone in the East Ford field (labeled 4, 5, and 6 in Figure 11) are harder to explain by this mechanism. These layers do not occur at the margin of the sandstone body but are located about 0.3 mi (0.5 km) from the southern pinch-out of the Ramsey 1 sandstone (Figure 12). They are in the lower part of the Ramsey 1 sandstone (Figures 10, 11) but not at the base. Each layer is spaced about 3 ft (1 m) apart from the other vertically, similar to the 3-ft (1-m) vertical spacing of calcite-cemented zones in turbidites of the Namorado Sandstone in Brazil (Sombra et al., 1998). The lateral extent and continuity of these calcite-cemented zones suggest that they are localized by a stratigraphic control that is also laterally extensive, such as coarser-than-average sediment layers or within certain zones of the Bouma sequence. One hypothesis to explain the location of these laterally extensive calcite layers is that they are located at the base of turbidite pulses, in the coarsest grained sandstones. Another possibility is that the shape and hydrodynamics of aragonite skeletal grains may have concentrated them in overbank and splay facies. Recognizing sedimentary structures in the Ramsey sandstones is difficult because they are very well sorted and contain no detrital clay (Figure 5), but a plot of grain size versus depth in the 41R EFU core defines the coarsest grained sandstones and upward-fining packages (Figure 15). The calcite layers tend to be located at, or somewhat above, coarser grained layers, near the base of upward-fining packages. These zones may have had slightly higher initial porosity and permeability and, thus, transmitted larger volumes of formation water.

However, no statistically significant correlation between calcite cement and grain size is seen. The interpretation that calcite-cemented layers coincide with the base of turbidite deposits is thus uncertain. Unlike the channel lags in the Brushy Canyon sandstone (Beaubouef et al., 1999), these cemented layers in the Ramsey sandstone do not contain increased volumes of bioclastic debris. No evidence is proven that these layers originally contained abundant aragonitic material that was the source of the calcite, but neither can it be disproved. Coarser grained intervals of the Pendência Formation, Brazil, are also preferentially cemented by calcite (Anjos et al., 2000). The coarser and finer grained Pendência sandstones have equivalent detrital compositions, suggesting that selective advection in the coarser laminae carried dissolved carbonate into zones of originally higher permeability (Anjos et al., 2000).

The prediction of calcite cement distribution in sandstone reservoirs remains an elusive goal. In sandstones where the source of calcite cement is interpreted to have been from the outside, cement may preferentially precipitate near sandstone margins, as it did in the Ramsey sandstone. However, precipitation near the immediate point of entry into the sandstone bodies may occur only where feldspar is sufficiently abundant to buffer most of the acidic formation waters near where they entered the sandstone, allowing calcite to precipitate there (Milliken and Land, 1991, 1993). Distribution of other calcite-cemented zones that are not at the margins of the sandstone bodies may relate to grain-size variations that exert a control on fluid flow (Sullivan and McBride, 1991; McBride et al., 1995; Dutton et al., 2000; McBride and Milliken, 2006).
In sandstones where the source of calcite cement was the dissolution of internal aragonite skeletal grains, the prediction of cement distribution is transferred to the prediction of distribution and concentration of bioclasts.

CONCLUSIONS

Reservoir quality of deep-water turbidite deposits in the Upper Permian (Guadalupian) Bell Canyon Formation, Delaware Basin, is strongly controlled by distribution of calcite cement. In these sandstones that have little variation in grain size and contain no detrital clay, volume of calcite cement is the most important control on porosity and permeability. The presence of thin layers of tightly calcite-cemented sandstone results in highly variable, streaky permeability distribution throughout the Ramsey sandstone. Most areas that have a high percentage (>15%) of calcite-cemented sandstone occur along the margins of sandstone bodies, where the sandstone pinches out into siltstone. Production data from a well at the south end of the East Ford field indicate that at least some calcite in this field occurs in laterally continuous layers and not as isolated concretions. Four calcite layers are interpreted as having a continuous lateral extent of at least 1000 ft (300 m) because injected CO₂ was trapped below the layers. One or more of the thin calcite layers formed a permeability barrier within the reservoir, and perforations both above and below the cemented layer were required to contact the entire reservoir volume.

Because internal sources of calcite were apparently insufficient to account for the volume of cement in the sandstones, necessary components for the cement are interpreted as having been transported into the sandstone from outside. Skeletal carbonate debris and carbonate rock fragments in organic-rich basinal siltstones and limestones are the most likely external sources of necessary components for the cement. Organic acids generated during thermal maturation of organic matter probably provided a source of acid for carbonate dissolution and export into the sandstones. Feldspars in the sandstones effectively buffered much of the acidic formation waters near where they entered the sandstone, resulting in calcite precipitation near the sandstone-siltstone margins. Other calcite-cemented layers may coincide with the base of turbidite deposits.

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