Stratigraphic hierarchy of organic carbon–rich siltstones in deep-water facies, Brushy Canyon Formation (Guadalupian), Delaware Basin, West Texas

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ABSTRACT
The first systematic test for a predictive relationship between organic carbon content and stratigraphic hierarchy in a deep-water slope to basin-floor deposit was performed. The studied section includes the Pipeline Shale, the Brushy Canyon Formation, and the lower part of the Cherry Canyon Formation of the Delaware Mountain Group, West Texas. This interval represents one large-scale, 3rd-order genetic sequence within which 4th- and 5th-order stratigraphic cycles are recognized. Samples of fine-grained facies throughout the section were collected from outcrop and analyzed for organic carbon content and hydrogen index. Degree of pyritization was also determined for a subset of the samples. The results indicate that organic enrichment is closely correlated to the stratigraphic hierarchy at the 3rd-, 4th-, and 5th-order levels. The data suggest that quantity and quality of preserved organic matter are controlled by changes in bulk sedimentation rate (dilution vs. condensation), which affect organic matter inputs to the sediment, as well as the balance between (1) burial and preservation of organic matter and (2) its degradation on the sea floor during times of sediment starvation.

INTRODUCTION
The Upper Permian (Guadalupian) Brushy Canyon Formation of West Texas represents a major 3rd-order lowstand wedge deposited in slope to basin environments of the Delaware basin seaward of the San Andres carbonate platform (Kerans et al., 1993; Gardner and Sonnenfeld, 1996). It mainly consists of gravity-flow deposits that are stacked in a hierarchical set of depositional sequences (Gardner, 1992). Throughout its thickness, however, the Brushy Canyon Formation contains organic carbon–rich siltstone beds. These widely traceable units form important marker beds in the outcrop belt and are proven source rocks for oils being produced from reservoirs in the Brushy Canyon Formation to the east of the outcrop (Hays and Tieh, 1992). The purposes of this study are to (1) test whether trends in organic carbon ($C_{org}$) content and the quality of preserved organic matter within the siltstone beds are correlated to the overall stratigraphic hierarchy that characterizes the slope and basin depositional system and (2) assess the controls on organic matter burial in this environment. The results have significant implications for interpreting the evolution of Delaware basin paleoenvironments and for understanding the controls on accumulation of organic matter in deep-water facies.

GEOLOGIC BACKGROUND
The Delaware basin is the western subbasin of the Permian basin (Fig. 1), which developed as a cratonic depression in response to Early Pennsylvanian crustal shortening in the Marathon fold- and-thrust belt (Hills, 1984). During Leonardian-Guadalupian time, a broad carbonate platform rimmed the basin to the north (Meissner, 1972). At times of sea-level fall and platform emergence, siliciclastic sediments bypassed the shelf and were deposited as major submarine fan complexes in the basin (Fig. 1) to form the Delaware Mountain Group (King, 1948; Kerans et al., 1992, 1993; Gardner and Sonnenfeld, 1996). Water depths have been estimated at 300–600 m in the Delaware basin (King, 1948; Newell, 1957; Meissner, 1972).

The deep-water depositional system of the Brushy Canyon Formation includes three major facies: (1) submarine-canyon fills confined within bedrock canyons incised into underlying carbonates of the Victorio Peak Formation, (2) slope deposits consisting of isolated, kilometer-scale, slump-scar-confined sandstone bodies encased in thick successions of interbedded sandstone and siltstone, and (3) basin-floor deposits of laterally continuous, nonamalgamated sandstone sheets cut by erosive-based multistory channel complexes (Gardner and Sonnenfeld, 1996). Although gravity-flow deposits form the dominant facies type, dark, organic carbon–rich
siltstones (ORS) occur commonly as beds from <0.1 to >2 m in thickness throughout the Brushy Canyon Formation and are interpreted as sediment-starved suspension deposits (condensed sections) marking the basinward equivalent of marine flooding surfaces (Gardner and Sonnenfeld, 1996).

Cycle Hierarchy

The Brushy Canyon Formation is interpreted as a prograding basin-floor fan to retrograding slope-fan complex (Kerans et al., 1992, 1993; Gardner and Sonnenfeld, 1996). This complex is bracketed below by ORS of the Pipeline Shale and Cutoff Formation, and above by a regionally correlative package of ORS within the lower Cherry Canyon Formation (Fig. 2), termed the genetic top of the Brushy Canyon Formation (Gardner and Sonnenfeld, 1996). Between these 3rd-order condensed intervals deposited at maximum highstands, 4th-order relative accommodation cycles constitute informal members of the formation (Gardner and Sonnenfeld, 1996). These include two basinward-stepping cycles of successive coarsening-upward (CU) to fining-upward (FU) packages designated as the lower and middle members, and a shelfward stepping cycle of successive CU-FU packages that constitute the upper member (Fig. 2). The 4th-order packages are themselves defined by smaller, higher-frequency CU-FU stratigraphic cycles whose stacking patterns delineate the larger cycles (Figs. 2, 3). It is the geometry and position of channel complexes within slope facies, as well as the thickness and frequency of ORS units, that make possible the recognition of a stratigraphic hierarchy (Gardner and Sonnenfeld, 1996). Although the ORS units play an important role in defining this stratigraphic hierarchy, there has been no systematic effort to quantify trends in C$_{org}$ content within these facies.

METHODS

Bulk samples were collected from fresh outcrop exposures of a section (Rest Area Gully) measured in the western escarpment of the Guadalupe-Delaware Mountains (Figs. 1, 2). The samples included the upper part of the Bone Springs Limestone, the Pipeline Shale, the Brushy Canyon Formation, and the lower part of the Cherry Canyon Formation (i.e., through the "genetic top"; Fig. 2). Within the Brushy Canyon Formation, samples of the finest-grained facies were collected wherever they occurred in the measured section. These included dark ORS beds as well as lighter-colored siltstones. A total of 210 samples was prepared for analysis (crushed to <2 µm) and analyzed for C$_{org}$ (wt%) by coulometry (Engelman et al., 1985). Hydrogen index data (HI) were generated by RockEval pyrolysis (Espitalie et al., 1977). Finally, degree of pyritization (DOP) was analyzed for a set of representative samples from the study interval. DOP is defined as [sulfide Fe]/[(sulfide Fe + reactive Fe)] (Raiswell et al., 1988). The methods of Canfield et al. (1986) and Raiswell et al. (1988) were used to determine DOP values.

OBSERVATIONS

The Rest Area Gully section (Figs. 2, 3) begins with 8 m of the uppermost Bone Springs Limestone, which consists of thin-bedded, dark limestones. The overlying 4-m-thick Pipeline Shale is composed of dark, organic carbon–rich, finely laminated siltstone with thin volcanic ash beds and spheroidal phosphatic concretions. The basal contact of the Brushy Canyon Formation with the Pipeline Shale is marked by a shift to lighter-colored, fine-grained sandstone and siltstone facies. The entire 3rd-order genetic sequence at the Rest Area Gully section is about 450 m thick (Figs. 2, 3). It is characterized by silty to sandy slope facies containing slump-scar-confined channel complexes and occasional debris flow deposits dominated by carbonate allochems. Although grain size trends through the Rest Area Gully section broadly reflect the 4th-order sequences (Fig. 3), these cycles are demonstrated most clearly in the regional cross section (Fig. 2). Throughout the study interval, individual thin laminae to compact 20–50-cm-thick beds of organic carbon–rich, finely laminated siltstone compose the ORS facies. Trends in the organic richness of these facies plotted in Figure 3 are correlated to the stratigraphic hierarchy in Figure 2 by arrows representing prominent cycle-bounding ORS units.

Organic Carbon Content

The Pipeline Shale, like the genetic top of the Brushy Canyon Formation, contains some of the highest C$_{org}$ levels (>4%) measured in this study (Fig. 3). Upward through the remainder of the Brushy Canyon Formation, C$_{org}$ levels vary from ~0.5% to ~3%, and these variations broadly parallel changes in grain size that are due to progradation and retrogradation of the depositional system (Figs. 2, 3). Basinward shifts are characterized by decreasing C$_{org}$ levels, whereas landward or backstepping shifts show increasing C$_{org}$ values. The frequency of black ORS beds is higher, and the correlation of changes in C$_{org}$ to stratigraphy is more strongly developed during the back-stepping or transgressive phases (Fig. 3). Note especially the three progressively C$_{org}$-enriched ORS units correlating to three back-stepping sequences in the transition from the middle to upper member, and within the upper member itself (units UB4–UB6; Figs. 2, 3).

In an effort to test whether these enrichment trends are consistent laterally, two additional short sections were sampled within a few hundred meters of the Rest Area Gully site (Fig. 2). Despite changes in section thickness, the three major 5th-order flooding surfaces of the middle to upper transition, as well as those of the upper member were identified by discrete C$_{org}$ peaks in the MT and Unocal Canyon sections (Fig. 3).

Figure 2. Schematic cross section of depositional stratigraphy of Brushy Canyon Formation (modified from Gardner and Sonnenfeld, 1996). Note location of Rest Area Gully (RAG), Unocal Canyon, and MT sections. Major shelfward-stepping condensed sections correlated to geochemical data in Figure 3 with arrows. Labels UB1 to UB6 mark 5th-order sequences in the upper member bounded by channel complexes (stippled). King (1948) defined lithostratigraphic top of Brushy Canyon Formation at top of cycle UB3. Gardner and Sonnenfeld (1996) define genetic top of Brushy Canyon 3rd-order lowstand wedge at top of cycle UB6.
Hydrogen Index and Degree of Pyritization

Hydrogen index provides information about the sources and preservational history of sedimentary organic matter. High HI values suggest a dominance of aquatically sourced (algal and/or bacterial) organic matter that is relatively well preserved. Decrease in HI may reflect either contributions from higher plants or oxidation of marine organic matter (e.g., Pratt, 1984). Our HI data vary from 5 to 375 through the section (Fig. 3) with a mean value of 200. In general, HI values are highest in association with retrogradation of the slope depositional system (Fig. 3). The lowest values occur in organic carbon-poor facies of maximum lowstands, but also in some organic carbon-rich units of maximum highstands. As a result, although trends in HI appear to broadly parallel trends in C\textsubscript{org} during 4th-order cycles (Fig. 3), the two parameters are rather poorly correlated (Fig. 4).

Degree of pyritization records the extent to which iron available for early diagenetic sulfide mineral formation has, in fact, formed pyrite. It is regarded as one of the best geochemical indicators for redox conditions in ancient depositional environments (Jones and Manning, 1994). We analyzed 12 samples from the Pipeline Shale and Brushy Canyon Formation (square symbols in C\textsubscript{org} plot, Fig. 3) to investigate depositional and early burial redox conditions. The results vary from 0.04 to 0.57 with an average DOP value of 0.4. This is within the range typically attributed to deposition under normal, oxygenated marine waters (Raiswell et al., 1988).

DISCUSSION

The major processes responsible for enrichment of C\textsubscript{org} in fine-grained siliciclastic strata are enhanced preservation (i.e., anoxic bottom waters, commonly caused by density stratification of the water column), excess production (i.e., phytoplankton blooms, commonly associated with nutrient upwelling), and sediment starvation or condensation (i.e., decreased dilution by terrigenous siliciclastic sediment, characteristic of marine transgression) (Arthur and Sageman, 1994). For over two decades, preservation has been the mechanism most commonly favored for petroleum source rock formation (e.g., Demaison and Moore, 1980). In recent years, however, the role of excess primary production has received increasing attention (e.g., Pedersen and Calvert, 1990). Although the effect of stratigraphic condensation on C\textsubscript{org} accumulation has been investigated for a variety of facies (e.g., Johnson-Ibach, 1982), its role in sequence stratigraphic studies is usually focused on the correlation potential of C\textsubscript{org}-rich condensed sections or downlap surfaces (e.g., Loutit et al., 1988).

Two recent studies have examined trends in the quantity and quality of preserved organic matter as a function of position within stratigraphic hierarchies. Based on analysis of a wide range of marine and lacustrine source rocks, Creaney and Passey (1993) concluded that observed trends in C\textsubscript{org} richness reflect changes in sedimentation rate combined with anoxic depositional conditions. The thickness of source rocks and quality of organic matter were greatest in the extreme distal parts of systems tracts, and maximum C\textsubscript{org} values were strongly correlated with times of maximum flooding (Creaney and Passey, 1993). Pasley et al. (1993) found the same general relationships in shelf deposits of the Cretaceous Western Interior basin. However, these authors illustrated that (1) changes in organic matter sources (terrestrial vs. marine) and (2) degradation processes occurring during deposition of 3rd-order sequences result in restriction of optimum source potential to the transgressive systems tract rather than the interval of maximum starvation (where bacterial processes may degrade organic matter quality over time). The Brushy Canyon Formation offers an ideal opportunity to test these hypotheses in a deep-water slope and basin-floor setting.

The Delaware basin was interpreted by King (1948) to be density stratified and anoxic. His interpretation was based on depauperate faunal content and the C\textsubscript{org}-richness of many units, and there has been no significant change in this view by subsequent studies (e.g., Newell, 1957; Harms, 1974; Meissner, 1972; Harris, 1988). Although the stratified water column model implies relatively stable, anoxic conditions at depth, conventional interpretation of our DOP results (i.e., Raiswell et al., 1988) would suggest that only mild dysoxia characterized deposition of the ORS units, even at maximum 4th-order deepening events. Given the potential for complications in the interpretation of DOP (e.g., Canfield et al., 1996), a conservative interpretation of the data would suggest only that sulfate reduction, or the exposure of reactive Fe to sulfide, was not extensive in the benthic zone (possibly because of episodic and rapid sedimentation). But the HI data from our study are also not consistent with stable anoxia.

Although little is known about levels of primary productivity in the Delaware basin, organic matter in slope and basin-floor facies of the Delaware Mountain Group has been reported to include a mixture of Type II and Type III kerogen (Hays and Tih, 1992), suggesting both algal inputs and terrestrial contributions associated with downslope transport of siliciclastic material. Our samples had HI characteristics consistent with a mixture of Type II and Type III organic matter. Decreases in HI associated with progradational cycles of the Brushy Canyon Formation offers a unique opportunity to test these hypotheses in a deep-water slope and basin-floor setting.

The level of correlation between trends in C\textsubscript{org} and the established stratigraphic hierarchy (Figs. 2, 3) is a significant observation: It indi-
icates a potentially predictive relationship between such trends. Although the data we have presented are preliminary, they indicate to us that changes in sedimentation rate related to relative sea-level cycles act as the master variable for $C_{org}$ accumulation in the Brushy Canyon Formation. These changes controlled the composition and concentration of deposited organic matter and influenced the decomposition of this material at the sediment-water interface by controlling burial rate. It appears that a balance between source and burial rate determined the character of preserved organic matter and its ultimate hydrocarbon potential in the high sedimentation regime of the Delaware basin slope setting.

CONCLUSIONS

This study presents the first systematic analysis of trends in $C_{org}$-rich source rocks and their relationship to stratigraphic hierarchy in a deep-water lowstand depositional system. The results yield the following conclusions: (1) Variation in the $C_{org}$ content of ORS beds within the lower Guadalupian Brushy Canyon Formation is strongly correlated to the stratigraphic hierarchy of the depositional system. This hierarchy includes 3rd-, 4th-, and 5th-order cycles independently identified from detailed measured sections and process sedimentology. (2) Most ORS units occur within shelfward-stepping phases of each cycle resulting in maximum concentration of organic matter within the transgressive systems tracts. (3) Preliminary sampling indicates that this relationship is maintained laterally to a distance of at least several hundred meters. (4) The quantity and quality of the preserved organic matter appear to be influenced by variations in organic matter inputs and the balance between burial and preservation of organic matter vs. its degradation on the sea floor during condensation intervals. (5) Both of these factors are controlled by bulk sedimentation rate (dilution vs. condensation), which is rapid but highly episodic and which changes depending on basinward or shelfward stepping of the depositional system. (6) Vertical trends in $C_{org}$ content may be useful in helping to predict stratigraphic hierarchies in other deep-water depositional systems.

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