

STABLE ISOTOPIC ANALYSIS REVEALS EVIDENCE FOR GROUNDWATER-SEDIMENT-ANIMAL INTERACTIONS IN A MARGINAL-MARINE SETTING

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ABSTRACT

We use isotopic analyses of authigenic siderite and calcite cements within *Rosselia socialis* burrows from shoreface deposits in the Upper Cretaceous Horseshoe Canyon Formation of Alberta, Canada, to reveal the early cementation history of the burrow and geochemical conditions of the initial sedimentary environment. Within the Horseshoe Canyon Formation, two forms of the *Rosselia* burrows are present: bulbous *in situ* burrows, and transported, spindlelike burrows, which display similar internal shaft diameters but smaller overall size compared to *in situ* forms. Transverse, incremental sampling of calcite and siderite cements in the *Rosselia* burrows reveals symmetrical isotopic deviation in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ around the burrow core, representing accretionary records of evolving pore-water conditions. The number of isotopic deviations recorded in bulbous specimens is equal to those observed in spindle-shaped burrows, suggesting that *in situ* and transported burrows underwent similar periods of cementation. Cementation, however, was limited during each accretionary event in the spindle-shaped burrows, making them more susceptible to transport by storm waves because of their small size. Early cementation of *Rosselia*, thus, took place very close to the sediment-water interface at depths where storm waves could rework sediments (i.e., less than 1 m sediment depth). The enriched $\delta^{13}\text{C}$ values for calcite and siderite (3.06–9.45‰ PDB [Peedee belemnite]) suggest that cement precipitation followed bacterially mediated decomposition of the organic matter concentrated within *Rosselia* in the zone of methanogenesis. Oxygen isotope compositions are enriched also, ranging in siderite from 17.5‰ to 29.4‰ SMOW (standard mean ocean water) and in calcite from 16.8‰ to 23.0‰ SMOW, and are more akin to the composition of subsurface groundwater than marine waters. Freshwater discharging through shoreface sediments explains the $\delta^{18}\text{O}$ isotopic signature of calcite and accounts for the early diagenetic precipitation of siderite in shallow marine sediments. In addition, the coexistence of authigenic calcite and siderite cements was most likely controlled by variation in the mixing ratio of meteoric and marine fluids related to variable discharge rates for the freshwater aquifer.

INTRODUCTION

This paper focuses on the isotopic ratios determined from cements formed in association with the trace fossil *Rosselia socialis* from Upper Cretaceous marine deposits in Alberta, Canada. From isotopic and sedimentological evidence, we propose a diagenetic model that represents a composite of processes, including burrowing by invertebrates, the presence of microorganisms, and the activity of the local hydrologic system.

The physical manipulation of grains and introduction of organic matter by animals during burrow construction, feeding, irrigation, and excretion

create millimeter-to-centimeter-scale heterogeneities in the physicochemical properties of sediment (Cadée, 1979; Dobbs and Guckert, 1988). Physical changes of sediment properties influence solute diffusion by reducing pore-water spaces (Aller, 1982). In general, different phyla of burrowing invertebrates produce distinct burrows to manage the physicochemical parameters of the environment in which they inhabit: trace fossils are paleoecological tools (Seilacher, 1964; Howard and Frey, 1973, 1975; Ekdale et al., 1984). The question, however, remains unresolved as to how animals affect, in turn, the physical and chemical properties of sediment. This is because few studies address bioturbation from a geochemical point of view (i.e., Aller, 1982, 1994; Rice, 1986; Bird et al., 2000).

As with ichnofossils, the stable isotopic composition of early diagenetic carbonates has been used as a paleoecologic indicator (e.g., Mozley and Wersin, 1992; Mozley and Burns, 1993). For instance, isotopic fractionations of oxygen (O) and carbon (C) provide a record of physical, chemical, or biological processes, and those fractionations observed in O have been related to such water source properties as salinity and temperature (Mozley and Wersin, 1992). On the other hand, C isotopic ratios in modern and ancient carbonates have been linked to biological fractionation, in association commonly with microbial degradation of organic matter (Curtis et al., 1986; Fisher et al., 1998).

BACKGROUND

Rosselia socialis is a conical to bulbous structure composed of a central, vertical shaft surrounded by convex-downward, cone-in-cone laminae (Dahmer, 1937; see Figs. 1A–B). The laminae represent successive burrow linings added to the inner wall of the central tube by the *Rosselia* tracemaker from the central shaft (Nara, 1995). Within the proximal marine deposits at the Boot Coulee study area, siderite and calcite cements accumulated preferentially within the sediments of the central shaft and surrounding laminae, forming a concretion that encompasses the burrow. These burrow concretions display two forms, bulb shaped and spindle shaped (Fig. 1C), which reflect the incidence of burrow transportation following cementation and exhumation.

Modern analogues of *Rosselia* are produced by a group of annelid worms referred to as terebellid polychaetes (Nara, 1995). One genus of terebellid polychaete, *Cirriformia* (Fig. 1D)—found on the west coast of North America—produces a structure similar to *Rosselia* (Fig. 1E), consisting of a central shaft and mucus-lined concentric laminae, located on each arm of a broad U-shaped burrow (Gingras et al., 1999, fig. 3, p. 355). Although the trace fossil is most common in proximal marine environments (Metz 1998), modern analogues of *Rosselia* are known only from marginal-marine habitats.

GEOLOGICAL SETTING

Specimens analyzed during this study were collected from Boot Coulee near Drumheller, Alberta, Canada (Fig. 2A). In the Late Cretaceous, this area was situated at the head of an embayment located on the western

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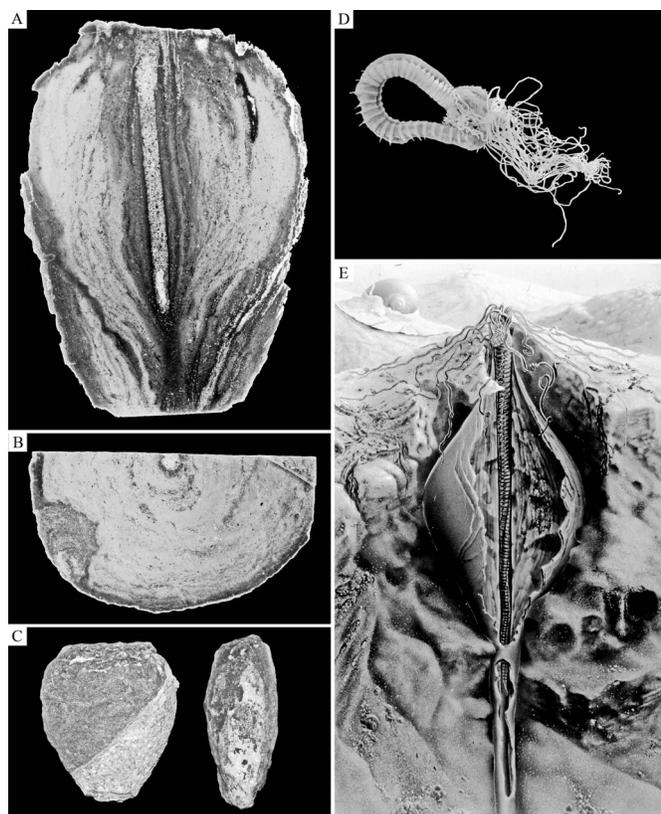


FIGURE 1—*Rosselia socialis* trace fossil and its modern analogue. A) Longitudinal section of *Rosselia socialis* showing concentric laminations tapering to central shaft. B) Cross section of *R. socialis* showing concentric laminations around burrow core. C) Example of *in situ* (left) and transported (right) *Rosselia socialis* burrows from Horseshoe Canyon Formation, Alberta, Canada. D) *Cirriformia luxuriosa*, a modern terebellid polychaete that produces a *Rosselia*-like burrow. E) Reconstruction of *Rosselia* tracemaker in burrow (from Pemberton et al., 2001).

margin of the Western Interior Seaway (Rahmani, 1981, 1983, 1988; see Fig. 2B). Because of the progradational nature of this embayment, deposits from the Drumheller Valley are considered to be transitional between the marine shales of the Bearpaw Formation and the marginal-marine to continental shales and sandstones of the Horseshoe Canyon Formation (Shepherd and Hills, 1970; see Fig. 2C). The Bearpaw-Horseshoe Canyon transition has been interpreted as a progradational deltaic sequence (Shepherd and Hills, 1970; Saunders, 1989; Lavigne, 1999) and as an incised valley (Rahmani, 1981, 1983, 1988; Eberth, 1996).

Within the transition zone, *Rosselia* are located in a sandstone package informally referred to as the Appaloosa zone, which is interpreted as a sequence of lower shoreface through backshore deposits reflecting the regression of a wave-dominated delta (Saunders, 1989). The lower part of the Appaloosa zone at Boot Coulee is composed of laminated-to-burrowed, fine-grained sandstone, with storm-generated hummocky and swaley cross-stratification and a trace-fossil assemblage of *Macaronichnus*, *Rhizocorallium*, *Ophiomorpha*, *Rosselia*, and *Teichichnus*, characteristic of a moderate-to-high-energy depositional environment.

Rosselia burrows at Boot Coulee are found in life position (Fig. 3A) and concentrated along depositional horizons within clean, fine-grained, 1–10 cm thick, well-sorted sandstone beds interpreted as storm sands. These horizons are characterized by small-scale, low-angle, cross-stratification and display preferential carbonate cementation (Figs. 3B–C). Bulbous, *in situ* specimens are up to 20 cm in diameter, and burrows extend to depths of as much as 25 cm below depositional contacts.

Several kilometers away from Boot Coulee, spindlelike *Rosselia* burrows with diameters less than 10 cm are well represented in storm-lag

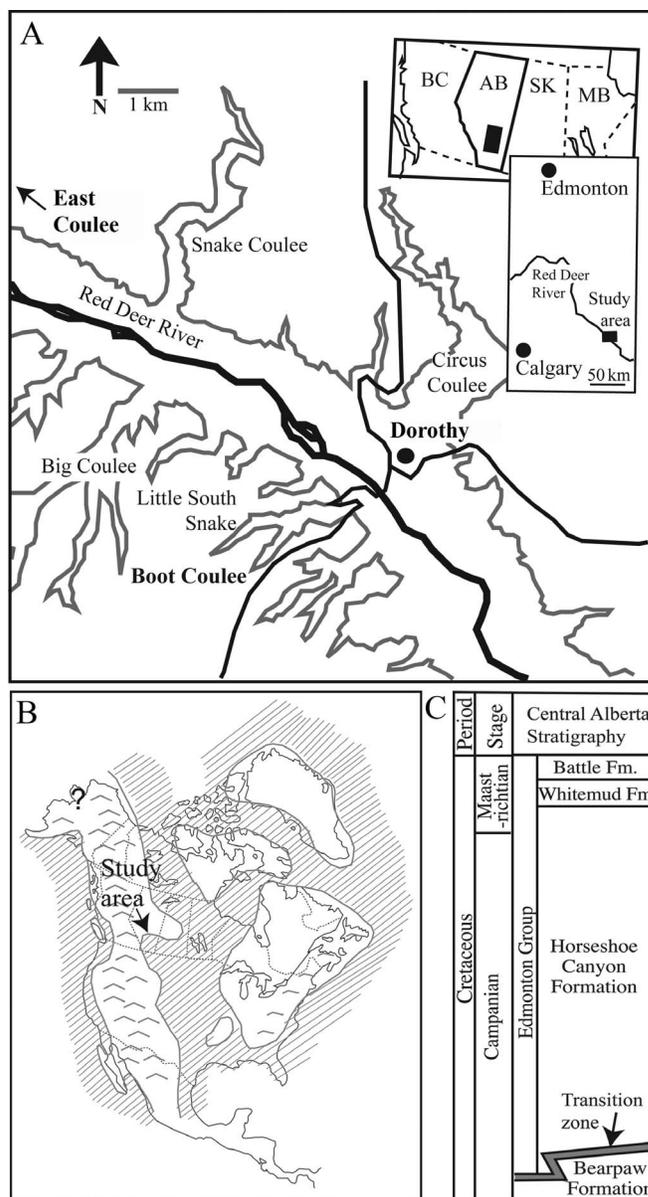


FIGURE 2—Location and stratigraphic relationships of study area. A) Locality map for Boot Coulee, Drumheller area, Alberta, Canada (modified from Saunders, 1989). B) Paleogeographic reconstruction of North America during deposition of Horseshoe Canyon Formation in Early Maestrichtian (modified from Rahmani, 1988). C) Summary of stratigraphic relationships associated with the Bearpaw-Horseshoe Canyon Formation transition zone in central Alberta.

deposits (Fig. 3D)—a residual accumulation of sediments deposited in the waning flow of a storm—within the lower Appaloosa unit (Saunders, 1989; Lavigne, 1999). These lie parallel to bedding and are found at the base of low-angle, cross-laminated beds. The presence of *Rosselia* in storm-lag deposits indicates that the burrows were cemented early, prior to being exhumed, and redeposited before lithification of the surrounding matrix.

METHODS

Lithological Analysis

Specimens of *Rosselia* were examined using standard petrographic thin-section techniques, scanning-electron microscopy (SEM), and electron microprobe analysis. We prepared 23 serial thin sections from three separate burrows to analyze the lithological characteristics of the burrows

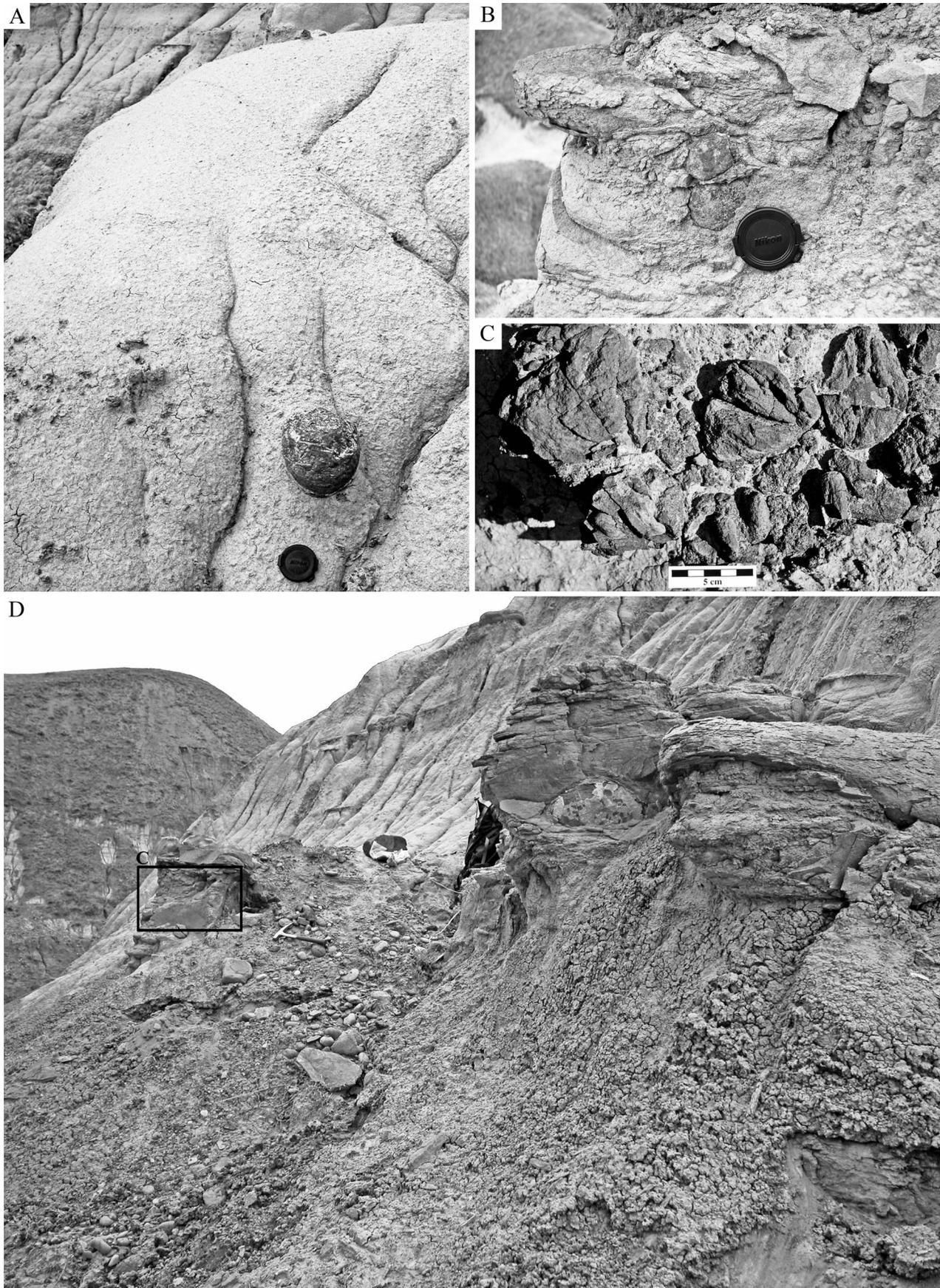


FIGURE 3—*Rosselia* within the Bearpaw-Horseshoe Canyon Formation transition zone. A) *R. socialis* in life position in Boot Coulee. B) *R. socialis* (to left of lens cap) in cemented horizon. C) *R. socialis* as clasts in lag deposits near East Coulee, Alberta. D) Cemented horizon with *R. socialis*.

and matrix. One of these sections was prepared and coated with carbon prior to analysis on the JEOL 8900 electron microprobe, from which a qualitative analysis of the abundance of Ca, Mg, Fe, and Mn in the carbonate cements was completed. We chose 57 sampling positions. Positions 1–51 are spaced 0.5 mm apart, and positions 52–57 are randomly spaced, to ensure analysis of the disseminated calcite cements along a straight transverse from the central shaft to the outermost lamination of the bulb.

The central shaft and laminae from the top and base of a small and large bulb were examined also with a JEOL 6301F Field Emission SEM. Specimens were mounted to a base with silver glue and subsequently coated with gold prior to SEM analysis.

Isotopic Analysis

The calcite and siderite cements from 38 samples—including 30 samples from three *Rosselia socialis* trace fossils, 6 samples from matrix neighboring the burrows, and 2 samples from siderite beds northwest of Boot Coulee—were analyzed for their C and O isotopic compositions. Sediments associated with the burrow concretions and nearby siderite beds, within the Drumheller area containing no burrows, were analyzed to determine the local or regional extent of diagenetic cementation.

The conical burrow concretions were cut longitudinally through the central-burrow core, and a second cut was made parallel to the first at an offset distance of 1 cm, creating a vertical cross section, or slab (Fig. 4A). Three transverse slices, each 2–3 mm thick, were taken from the top, middle, and bottom of the resultant longitudinal slab. The top, middle, and bottom slices were broken subsequently into 10 equal segments measured across the length of the burrow for analysis (Figs. 4A–C).

Each segment was crushed manually, and a portion of the powdered sample, weighing between 0.10 g and 0.51 g, was reacted with 100% phosphoric acid. To analyze the isotopic composition of the calcite cement, samples were reacted overnight at 25°C using the technique of Degens and Epstein (1964). Evolved CO₂ was extracted and analyzed using a Finnigan-MAT 252 mass spectrometer. Following calcite extraction, samples were returned to a 50°C water bath for 1 week to allow for analysis of the siderite cement. Evolved gas associated with the siderite cement was extracted and analyzed in the same manner as the calcite.

RESULTS

Lithological and Ichnological Description

The burrow infill comprises very-fine-to-fine sand (0.0625–0.25 mm). Laminae surrounding the central tube are dominantly finer grained, and they are composed of clay-to-silt-sized particles (>0.0039–0.0625 mm). The outer margin of each concentric lamination, however, is demarcated by a silt to very-fine-grained sand layer (0.0039–0.125 mm). The framework grains are composed primarily of quartz (50%), feldspar (15%), and chert (35%) with rare accessory minerals, including muscovite and magnetite; sediment in *Rosselia* is classified as a feldspathic arenite. No pyrite grains were observed.

Scanning-electron microscopy analysis of the burrow shaft and laminae show that small amounts of smectite are present in curvilinear clay seams and as rare clay coatings on otherwise unaltered feldspar grains. The extent of diagenetic overprinting of Fe oxides on the mineral surfaces prevented determination of the type and amount of the detrital clay fraction. Thin coatings of Fe oxide are observed also on feldspar and quartz grains. Rare feldspar overgrowths are present.

Siderite and Fe oxides predominantly cement the burrows, but the burrows also contain minor amounts of calcite and dolomite. Siderite cement is disseminated as crystals throughout the burrow, whereas calcite primarily is in the outer margins of each concentric lamination. Electron microprobe analysis shows that siderite cements are Ca-poor, while calcite cements are commonly Fe-poor (Table 1). Both calcite and siderite contain minor concentrations of Mg and Mn.

Within the fine-grained burrow fill, we observed fibrous plant fragments

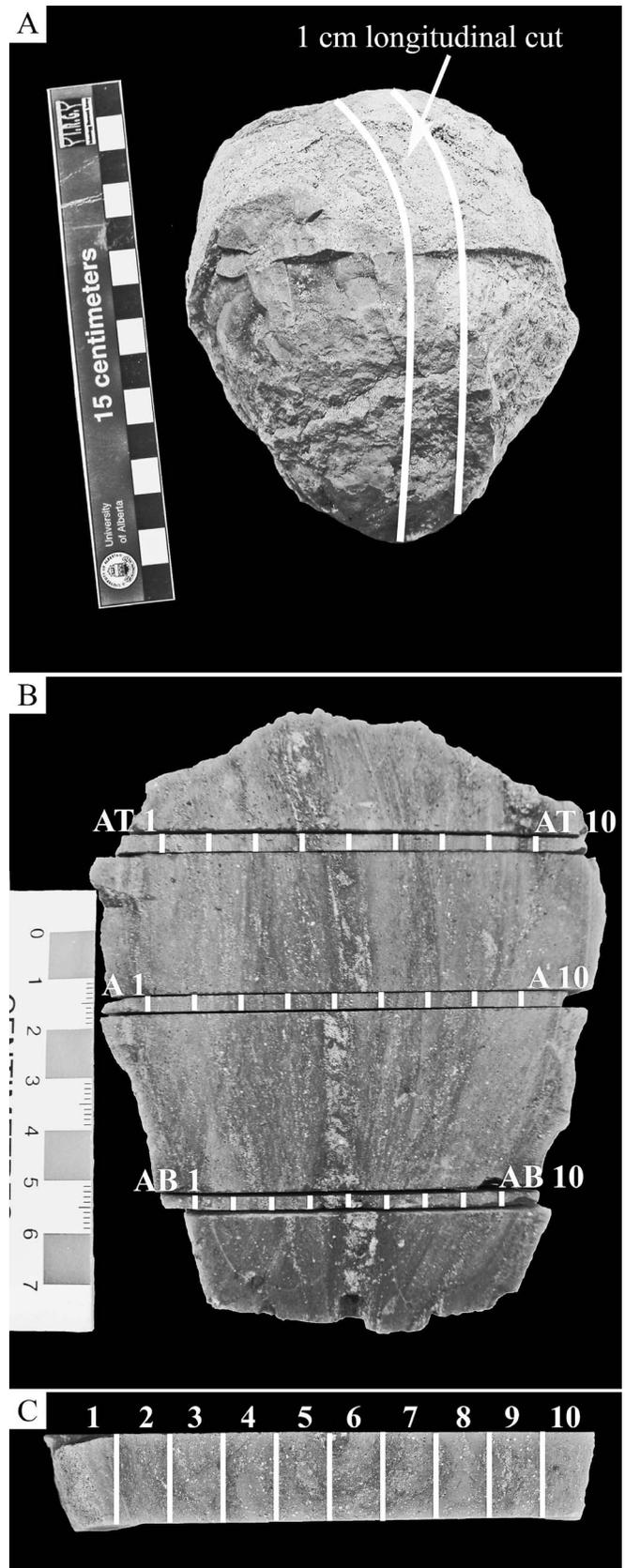


FIGURE 4—Sampling method for isotopic analysis of burrows. A) Placement of longitudinal cuts through *R. socialis*. B) Placement of transverse cuts at top, middle, and bottom of burrow, as well as 10 equal segments. C) Location of segments across burrow.

TABLE 1—Qualitative composition of *Rosselia* burrow from central shaft to outer laminae.

No.	CaO	MgO	FeO	MnO	Total (%wt)
1	0.702	2.063	56.234	1.119	60.118
2	1.104	1.374	56.367	1.164	60.009
3	1.588	2.206	47.158	0.710	51.662
4	1.551	1.081	53.177	0.956	56.765
5	1.506	0.647	52.549	0.938	55.640
6	1.399	0.481	53.809	0.856	56.545
7	1.018	0.416	54.332	0.537	56.303
8	0.640	0.028	55.469	1.076	57.213
9	1.060	0.871	52.950	1.011	55.892
10	1.153	0.584	54.222	0.714	56.673
11	0.985	0.385	54.012	0.780	56.162
12	1.469	1.012	51.164	0.986	54.631
13	1.183	0.612	53.635	0.824	56.254
14	0.955	0.418	53.901	0.781	56.055
15	1.474	0.777	52.317	0.931	55.499
16	0.620	0.265	54.856	0.725	56.466
17	0.834	0.276	54.248	0.884	56.242
18	1.093	0.412	53.965	0.895	56.365
19	1.238	0.551	53.785	0.873	56.447
20	1.397	0.845	53.386	0.737	56.365
21	0.625	0.253	55.047	0.630	56.555
22	1.021	0.510	52.218	0.718	54.467
23	1.257	0.562	53.347	0.910	56.076
24	1.047	0.524	54.454	0.481	56.506
25	1.237	0.525	53.558	0.838	56.158
26	1.570	0.597	53.419	0.652	56.238
27	0.979	0.455	54.248	0.862	56.544
28	1.178	0.391	53.591	0.840	56.000
29	1.351	0.413	53.886	0.902	56.552
30	1.874	0.460	51.665	0.948	54.947
31	0.617	0.260	55.168	0.941	56.986
32	0.995	0.754	53.150	1.032	55.931
33	1.370	0.464	53.417	0.927	56.178
34	1.121	0.516	52.894	0.812	55.343
35	1.095	0.851	51.528	0.837	54.311
36	0.941	0.490	54.226	0.788	56.445
37	1.256	0.773	52.846	1.090	55.965
38	0.811	0.307	54.933	0.846	56.897
39	1.335	0.605	54.033	0.618	56.591
40	1.420	0.538	52.977	0.863	55.798
41	1.424	0.886	53.058	0.861	56.229
42	1.566	0.893	53.091	0.659	56.209
43	0.577	0.318	54.576	1.017	56.488
44	1.507	0.897	52.667	0.853	55.924
45	0.988	0.360	53.827	0.943	56.118
46	1.268	0.514	53.114	0.978	55.874
47	1.582	0.437	52.504	0.937	55.460
48	1.265	0.473	52.639	0.926	55.303
49	0.964	0.400	54.164	0.779	56.307
50	1.080	0.445	53.485	0.968	55.978
51	0.838	0.389	52.329	0.885	54.441
52	50.731	0.330	2.543	0.191	53.795
53	52.547	0.355	2.781	0.217	55.900
54	51.868	0.374	2.562	0.180	54.984
55	51.682	0.661	2.566	0.451	55.360
56	49.904	0.625	2.807	0.936	54.272
57	49.047	0.756	2.844	0.706	53.353

and thin mucuslike strands (Fig. 5A–B). The degraded mucoic threads, produced by the tracemaker or by decomposition of associated organic fragments, indicate the presence of a microbial community, likely chemoheterotrophs, which use the organic substrate as a carbon source. The tests of foraminifera were observed also with the burrow. As this research is not biostratigraphic in nature, the forams were not identified.

Isotopic Data

In general, there is a strong positive correlation between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ from the 38 samples from burrows and surrounding matrix (Fig. 6A). The

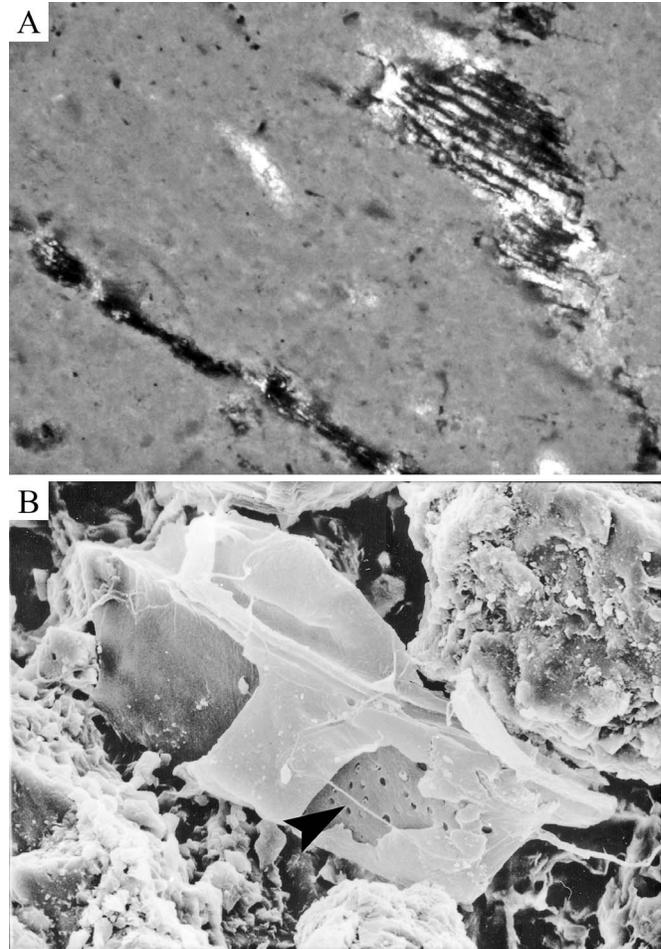


FIGURE 5—Organic matter composing burrow fill. A) Fibrous plant fragments. B) Mucuslike strands on organic fragments. Arrow = mucoic thread.

C-isotopic compositions of siderite are 5.79‰–9.45‰ PDB (Peedee belemnite), whereas that of calcite are 3.06‰–15.85‰ PDB, both of which are enriched (–4.35‰–1.47‰ PDB) compared to the siderite beds outside Boot Coulee (Table 2). O-isotopic compositions are enriched also, ranging in siderite from 17.5‰ to 29.4‰ SMOW (standard mean ocean water) and in calcite from 16.8‰ to 23.0‰ SMOW (Table 2).

Correlation of the transverse samples across the burrows reveals symmetrical deviations in the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values around the central shaft (Fig. 6B). For *in situ* burrows, the least enriched $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopic values are at or near the central tube, whereas the most enriched values are recorded toward the burrow margins. This trend is more apparent in the isotopic compositions of the calcite cement as compared to the siderite. Though samples from the top, middle, and bottom of the *Rosselia* show a similar pattern of isotopic deviations around the core, there is no apparent pattern of enrichment across vertical sections of the burrow. Within these burrows, the only pattern in isotopic variability is associated with the lateral distance of the samples from the core of the burrow.

INTERPRETATION AND DISCUSSION

Symmetrical isotopic deviations in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ observed in the *Rosselia* burrows are explained best through a series of cementation events, by which cements were produced in a crudely spherical pattern laterally around the central, vertical shaft like the layers of an onion, and represent accretionary records of changing pore-water compositions. Although burrow concretion diameter expanded with each cementation event, there does not appear to be a simple size relationship between

during initial construction and that cement thickness is unrelated to the prelithified burrow diameter. More likely, cement thickness during an accretionary event was controlled by variations in the geochemical conditions of the burrow microenvironment. Variability in the concentrations of reactants or their precursors could have created local deficits in cement production volume during a cementation event as compared to other *Rosselia* bulbs.

Cement starved, spindle-like bulbs were more susceptible to transport during storm surges than their larger, robust counterparts. Transportation of the spindle-like bulbs, without disaggregation of the burrow, indicates that these burrows were cemented prior to entrainment but before lithification of the surrounding sediments. The depth at which burrow cementation took place can be inferred from typical erosional amalgamation during storms. In the Western Canadian Sedimentary Basin, ichnological evidence suggests that storm amalgamation is generally less than 1 m (MacEachern et al., 1991; Pemberton and MacEachern, 1997). Transported burrows, thus, were cemented at sediment depths potentially shallower than 1 m. It is likely that the *in situ* burrows were cemented in a similarly short period of time and sediment depth before the trace fossil passed into the historical deposits of the sedimentary record, as the bulbous *in situ* burrows share the same number of isotopic deviations as the transported *Rosselia*.

Formation of $\delta^{13}\text{C}$ -enriched calcite and siderite is hypothesized to have resulted as a by-product of bacterial decomposition of burrow organic matter. Concentrated organic detritus incorporated by the *Rosselia* tracemaker into successive burrow linings acted as a C source for a diverse community of anaerobic microbes following rapid, storm-induced sedimentation and burial of the *Rosselia* burrow. Under these anaerobic conditions, it is plausible that the bicarbonate for the calcite and siderite cements was produced by fractionation of dissolved inorganic carbon during microbially mediated (1) Fe(III) reduction or (2) methanogenesis—consumption of CO_2 to produce methane (Hesse, 1990). Although Fe(III) reduction creates conditions conducive to carbonate precipitation, Fe reduction cannot account for the highly enriched ^{13}C values observed within the burrows (Coleman, 1993). In addition, the absence of pyrite within these samples indicates that cement precipitation occurred in the zone of methanogenesis, below the zones of Fe(III) and sulfate reduction, where concentrations of hydrogen sulfide ions (HS^-) and Fe(II) are low. Within this zone, bacterially mediated CO_2 reduction consumed CO_2 to produce $\delta^{13}\text{C}$ -depleted methane. Removal of methane from the burrow through diffusion, fluid advection, or ebullition produced a residual pool of $\delta^{13}\text{C}$ -enriched CO_2 that then dissociated into bicarbonate and subsequently combined to form $\delta^{13}\text{C}$ -enriched calcite and siderite cements.

As with the formation of isotopically heavy carbon cements, the conditions for siderite precipitation—that is, (1) a low p_{O_2} of $\leq 10^{-60}$ atm, (2) a high p_{CO_2} of $> 10^{-1.4 \pm 0.2}$ atm, (3) slightly acidic to slightly basic pH (~ 5.5 to ~ 7.5), (4) a low Eh of $< -0.1\text{V}$, and (5) a high Fe(II) pore-water concentration—are achieved rarely in strictly marine conditions (Langmuir, 1997). This is because the condition of a high-soluble Fe concentration ($\text{Fe(II)} \geq 5\% \text{ Ca(II)}$; see Berner, 1971) is difficult to achieve in modern environments because the high concentration of HS^- from reduction of sulfate induces FeS formation in preference to FeCO_3 . Siderite precipitation within *Rosselia*, however, would be more probable in the zone of methanogenesis if soluble Fe(II) was introduced to the pore waters through an external freshwater source. This hypothesis is supported by the O isotope compositions, many of which fall into the freshwater range of 18‰–25‰ SMOW (Taylor, 1967), and may help to explain the lack of sulfate reduction within marine sediments.

The most likely explanation for siderite precipitation is that *Rosselia* were situated along the discharge margin of a freshwater aquifer, inferred from the sedimentologic and ichnologic characteristics of the lower part of the Appaloosa zone (Fig. 7). A freshwater aquifer that transported Fe-rich groundwater into the lower shoreface could raise the ratio of Fe(II) to Ca(II) above the threshold necessary to favor siderite precipitation over calcite. Thus, the mixing ratio of marine to meteoric waters, and ultimately

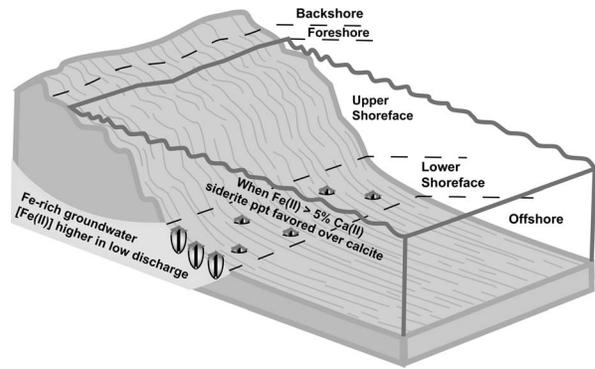


FIGURE 7—Reconstruction for formation of stable isotopic signatures for calcite and siderite cements. Regional view of lower shoreface environment showing aquifer discharge route (modified from Clifton, 2003).

mately the aquifer discharge rates (volumetric flow), governed the balance between siderite and calcite precipitation within *Rosselia*. During periods of high-groundwater discharge, the concentration of soluble Fe(II) was low owing to dilution by the large freshwater volume. This decreased the concentration of soluble Fe brought into the lower shoreface and promoted calcite precipitation over siderite. In contrast, throughout intervals of low-groundwater discharge, soluble Fe(II) became concentrated within the reduced freshwater volume, and concentrations rose above 5% Ca(II), resulting in precipitation of siderite.

The $\delta^{18}\text{O}$ values recorded for the siderite and calcite cements supports the idea of a fluctuating marine to meteoric water ratio. Siderite cements are more enriched in $\delta^{18}\text{O}$, compared to calcite, indicating that siderite precipitated when the ratio of marine to meteoric waters was higher than when calcite was precipitated. Moreover, the predominance of siderite cements within the burrows approximately 10-fold over calcite indicates that the geochemical conditions of soluble Fe(II) concentrated in low-groundwater flow occurring during siderite precipitation represent the norm over the duration of burrow cementation.

SUMMARY

The cementation history of *Rosselia socialis* burrows, based on sedimentologic and isotopic analyses, from lower shoreface deposits in the Horseshoe Canyon Formation of Drumheller, Alberta, Canada, can be summarized by the following steps:

1. The *Rosselia* tracemaker incorporates mucus, plant detritus, and fecal matter into successive burrow linings.
2. Rapid, storm-induced sedimentation buries the burrow and traps the tracemaker in the zone of methanogenesis.
3. A diverse suite of anaerobic microbes mediated the decomposition of organic matter stored in the burrow (i.e., mucus, plant detritus, and fecal matter).
4. Within the burrow, $\delta^{13}\text{C}$ -enriched CO_2 —produced as a byproduct of methanogenesis—dissolved in the pore waters and was later incorporated within the calcite and siderite cements.
5. Burrow cementation took place very close to the sediment-water interface (i.e., less than 1 m sediment depth), and the balance between precipitation of the calcite and siderite cements was determined by the concentration of soluble Fe(II) brought in to lower shoreface from regional freshwater aquifer.
6. Calcite precipitation took place during periods of high-groundwater flow when the concentration of soluble Fe was below 5% Ca(II).
7. Siderite precipitation dominated the cementation process and occurred during intervals of low-groundwater flow when the concentration of soluble Fe rose above 5% Ca(II), forming siderite cements with more enriched $\delta^{18}\text{O}$ compositions than calcite cements.
8. Following cementation, storm waves entrained smaller spindle-

shaped *Rosselia* and transported these burrows several kilometers from the location of burrow construction.

This study is one of the first to illustrate a clear relationship between biogeochemical processes within a burrow microenvironment shortly after burial and the cementation history of a trace fossil. Our results show that macroscopic animal behaviors, when used in conjunction with stable isotopes, can provide effective interpretations of depositional environments even in such complex depositional systems as those found in the transitional zone between continental and marine environments.

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