Evidence from the Crow Creek Member (Pierre Shale) for an impact-induced resuspension event in the late Cretaceous Western Interior Seaway

Ryan D. Weber Paleo-Data Inc., 6619 Fleur de Lis Drive, New Orleans, Louisiana 70124, USA
David K. Watkins Department of Geosciences, University of Nebraska, Lincoln, Nebraska 68588, USA

ABSTRACT

The 1–3-m-thick Crow Creek Member is a unique marlstone with rip-up clasts and a basal coarse layer in the Upper Cretaceous Pierre Shale in South Dakota and Nebraska. Although the Member has been thought to represent a marine transgression along the eastern margin of the Western Interior Seaway, the presence of impact ejecta from the Manson Impact Structure suggests an impact-induced genesis.

An upper Campanian in situ nannofossil assemblage with a lower Campanian reworked assemblage (from older Niobrara Chalk) occurs in the Crow Creek at most localities. The reworked assemblage decreases in abundance upward through the marlstone, a pattern consistent with an origin involving gravitational settling rather than marine transgression. Gray marlstone clasts in the basal coarse layer have nannofossils derived from the underlying Gregory Member and Niobrara Chalk. The reworked assemblage decreases in abundance with increased distances from the Manson Impact Structure and the Sioux Ridge (a paleotopographic high). The nonuniform geographic distribution of reworking suggests that Crow Creek deposition was linked to the Manson Impact. These observations, and a fining upward trend, the presence of impact ejecta, and coeval deposition with the Manson Impact Structure, support a resuspension-event origin for the Crow Creek Member.

Keywords: Pierre Shale, Manson impact structure, Nannofossils, Cretaceous, Campanian, Tsunami.

INTRODUCTION

Impact-induced phenomena and their effects offshore are poorly documented in the geological record. Offshore tsunami and sediment gravity-flow deposits may appear lithologically similar to transgressive deposits because both are coarse-grained beds that fine upwards in an otherwise homogeneous mudstone. In fact, offshore impact-induced deposits may have been identified mistakenly as transgressive deposits. For example, deposits around the Gulf of Mexico and western Atlantic containing coarse-grained beds at the Cretaceous-Paleogene boundary were originally attributed to a latest Cretaceous sea-level excursion (Hay, 1960), but subsequently were attributed to an impact-induced phenomenon such as a tsunami or submarine landslide (Bourgeois et al., 1988; Smit et al., 1994; Bralower et al., 1998).

Bretz (1979) hypothesized that the Crow Creek Member of the Pierre Shale in South Dakota and Nebraska was deposited by marine transgression. However, the discovery of shocked quartz prompted reexamination of its origin and deposition (Izett et al., 1993). The likely source of ejecta is the adjacent Manson Impact Structure, a 35-km-diameter buried crater near Manson, Iowa, USA, radiometrically dated as 74.1 ± 0.1 Ma (Izett et al., 1998). Upper Cretaceous marine strata (including Pierre Shale) in cores taken along the Structure suggest that the impact occurred at or near the eastern edge of the Western Interior Seaway. Such an impact may have produced a tsunami and deposited impact ejecta across a broad region (Izett et al., 1993, 1998). Witzke et al. (1993, 1996) have maintained that deposition was controlled by marine transgression during the onset of the Bearpaw Cycle in the Seaway, and recognized impact ejecta as a reworked component.

The Crow Creek, the only unit of similar age and close proximity to the Manson Impact Structure that contains impact ejecta, provides an opportunity to distinguish between an offshore, impact-induced deposit and a marine transgressive deposit. Previous studies of the Crow Creek documented a basal coarse layer composed of reworked sediments from older Cretaceous strata (Crandell, 1952; Bretz, 1979; Hammond et al., 1994). Recent work has suggested additional sediment sources including the Precambrian (Witzke et al., 1996; Katongo et al., 2004). The present study aims to document the nature and distribution of reworked Cretaceous sediment, in the form of calcareous nannofossils, throughout the Crow Creek marlstone to test the two hypotheses of its origin and deposition.

MATERIALS AND METHODS

The Crow Creek was examined at four outcrops in Nebraska and South Dakota (Figs. 1A, 1C, 1D, and 1G), in three South Dakota Geological Survey cores (Figs. 1E, 1F, and 1H), and in one Nebraska Geological Survey core (Fig. 1B). Samples were examined to determine the nannofossil biostratigraphic age and the age and abundance of reworked nannofossils. The latter were recorded by counts of 500 specimens using a light microscope at 1000× power. Slides were also prepared from seven marlstone clasts (described in the next section) isolated from the basal coarse layer. Full taxon names are cited in the GSA Data Repository.[1] This work builds upon a previous pilot study of Hammond et al. (1994) with additional sites over a larger area to define the geographic distribution of the reworked nannofossils as well as using a more precise estimate of reworking.

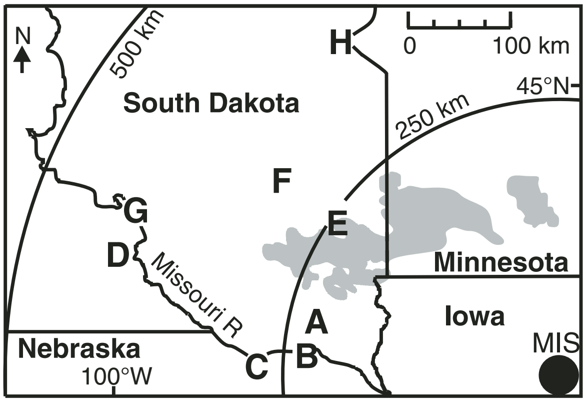

Figure 1. Distribution of outcrop and core sites in relation to the Manson Impact Structure (MIS) and the generalized known distribution of the Sioux Ridge (gray). Arcs denote distances from the Structure. Exact locations are cited in the GSA Data Repository (see footnote 1). Abbreviations: A—Clay Valley outcrop; B—Crofton Core; C—Niobrara State Park outcrop; D—White River outcrop; E—Lake County Core; F—Iroquois County Core; G—Crow Creek outcrop; and H—Sisseton Core.

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[1] GSA Data Repository item 2007277, locations of sites, data, and full taxon names, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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GEOLOGICAL FRAMEWORK

Stratigraphy

The upper Campanian to lower Maastrichtian Pierre Shale lies disconformably above the Niobrara Chalk of the North American Western Interior Seaway. Calcareous shale and marlstone-dominated units in the Pierre Shale are restricted to the eastern margin of the Seaway (Witzke et al., 1993). The lower contact of the Crow Creek is sharp and sits atop the Bearpaw/Claggett erosional disconformity, with the Crow Creek onlapping the underlying Gregory and Sharon Springs Members to the east. Witzke et al. (1996) suggested that this regional disconformity formed during the Judith River progradation on the western margin.

The Cretaceous of eastern South Dakota onlaps Precambrian quartzite. The geometry of the onlapping Cretaceous defines a paleotopographic feature, termed the Sioux Ridge (Fig. 1), near the eastern margin of the Seaway. Witzke et al. (1996) and Katongo et al. (2004) contend that the subsurface extent of the Sioux Ridge is essentially coincident with the known distribution of Crow Creek strata; however, the Member has been observed in localities at least 150 km from the Sioux Ridge (Izett et al., 1998; this work).

Timing of Deposition

Hammond et al. (1994) report the co-occurrence of nannofossil species *Aspidolithus parcus constrictus, Tranolithus phacelosus,* and *Uniplanarius trifidus* within the Crow Creek, indicative of upper Campanian Subzone CC23a of Perch-Nielsen (1985). Izett et al. (1998) radiometrically dated the Manson Impact Structure to 74.1 ± 0.1 Ma (upper Campanian) and Pierre Shale bentonite layers bounding the Crow Creek to 73.8 ± 0.3 Ma and 74.5 ± 0.1 Ma, indicating that the Crow Creek and the Manson Impact Structure were roughly coeval.

Lithology

The Crow Creek consists of two distinct units—a marlstone and a basal coarse layer. The character and composition of the basal coarse layer vary significantly from east to west (Izett et al., 1998). To the east, the layer consists of 3–30 cm of poorly sorted, light-gray, silty, quartz sand with gravel-sized particles of pink and white quartz and detrital carbonate. Detrital carbonate comprises 3%–5% of the layer including semi-angular, gray, calcareous marlstone clasts ranging in size from 0.01 cm to 10 cm (Witzke et al., 1996). Flat, rounded, black, noncalcareous mudstone clasts are also present, and interpreted as rip-up clasts from the Sharon Springs Member (Hammond et al., 1994; Witzke et al., 1996; Izett et al., 1998). To the west, the basal coarse layer appears as 5–30 cm of fragmented inoceramid shells mixed with a significant amount of detrital and skeletal carbonate (~22%) and silt and fine quartz sand (~11%) in a wackestone to packstone fabric (Witzke et al., 1996).

The overlying 100–250 cm is a light-gray marlstone unit composed of nannofossils and clay. Lower portions of the unit contain silt-sized quartz grains (up to ~15%) and carbonate (up to 15%; Witzke et al., 1996). Smectite is the dominant clay mineral with minor kaolinite and illite (Bretz, 1979). Black mudstone rip-up clasts are also present, and vary in size (0.5–5.0 cm).

Sedimentary structures within the Crow Creek marlstone are rare. At locality D, the lower marlstone displays cm-scale laminations with convoluted stratification that is interpreted as soft-sediment deformation. The upper marlstone displays flat, mm-scale laminations. Bretz (1979) reported burrows in the upper 10–40 cm of the marlstone, infilled by the overlying black mudstone. We cannot confirm this observation, but did observe bioturbation in the uppermost 2–5 cm of the Crow Creek marlstone at all localities except H. The Crow Creek at H is ~16 m thick and consists of black mudstone with lamina of light olive-gray calcareous shale and gray marlstone. There are no coarse sediments in the Crow Creek at locality H, nor any evidence of reworking.

Microfossils

Crandell (1952) and Bretz (1979) documented siliceous taxa in the black mudstones above and below the Crow Creek, whereas calcareous taxa are observed within the Member. Radiolaria are present in the upper marlstone, but are absent from the lower marlstone, while foraminifera are abundant in the lower portions of the marlstone and not as abundant in the upper part of the marlstone (Crandell 1952; Bretz 1979; Hammond et al., 1994). Benthic and planktonic taxa within the foraminiferal assemblages are indicative of a shallow paleobathymetry (Bretz, 1979).

Hammond et al. (1994) recognized two distinct nannofossil assemblages within the marlstone unit—an upper Campanian in situ assemblage and a reworked assemblage with species extinct before Crow Creek deposition. It was assumed that this assemblage was reworked from the Niobrara Chalk, based on biostratigraphy and the unique floral elements of the Niobrara.

RESULTS

Nannofossils are abundant and well preserved throughout the Crow Creek marlstone. Nannofossils are present in the basal coarse layer, but in low abundance and with inconsistent preservation. An upper Campanian in situ assemblage was differentiated from a lower Campanian reworked assemblage at all localities except H.

In situ Assemblage

The Crow Creek at locality H is important in determining biostratigraphic age because it contains no reworking. It has *A. parcus constrictus, Biscutum magnum, Reinhardites levis, T. phacelosus,* and *U. trifidus*, an assemblage characteristic of Subzone CC23a. Morphologically late forms of *E. eximius* and *Reinhardities anthophorus* are present in the lower portion of the Crow Creek, but do not occur in the upper portion, recording their last occurrences (LO). We conclude that the nannofossil assemblage at locality H spans the boundary of Subzones CC22b and CC23a. Erba et al. (1995) place this interval between 74.6 and 75.3 Ma, an age roughly compatible with the 74.1 ± 0.1 Ma age of the Manson Impact Structure (Izett et al., 1998).

Reworked Assemblage

Hammond et al. (1994) estimated the amount of reworking based on the abundance of four demonstrably reworked taxa. The estimates in the present work are based on the abundance of ten reworked taxa, yielding a higher estimate of the reworked component. Several taxa in the Crow Creek marlstone are outside of their stratigraphic ranges, including *Bukryaster hayi* (LO Subzone CC19a), *Eprolithus floralis* (LO Zone CC16), *L. grillii* (LO Subzone CC22a), and *M. furcatus* (LO Zone CC18; Watkins et al., 1993). There are also taxa that occur in abundance in the Niobrara Chalk, but are very rare in the Pierre Shale. The ranges for *Boletuvelum candens, Biscutum blackii*, *Biscutum zulloi,* and *S. primitivum* are not well documented, but are considered reworked because they do not appear in the Crow Creek at locality H. The morphologically primitive forms of *A. parcus* (i.e., *expansus*), *E. eximius,* and *Reinhardites anthophorus* do not appear at H, and are interpreted as reworked.

Reworked nannofossils have been found in all Crow Creek localities except H. The major components are *B. blackii* and *B. zulloi* (Fig. 2). The stratigraphic distribution of the reworked assemblage at each location is illustrated in Figure 3.

Sources for Reworked Nannofossils

The reworked taxa within the Crow Creek marlstone are consistent with early Campanian Zones CC17 and CC18. Sediment of this age occurs in the upper Niobrara Chalk in the Western Interior Seaway. Direct evidence of the source for reworked nannofossils comes from six gray marlstone clasts in the basal coarse layer from localities A and E. Four clasts contain *Aspidolitus parcus expansus, B. zulloi, B. blackii*,

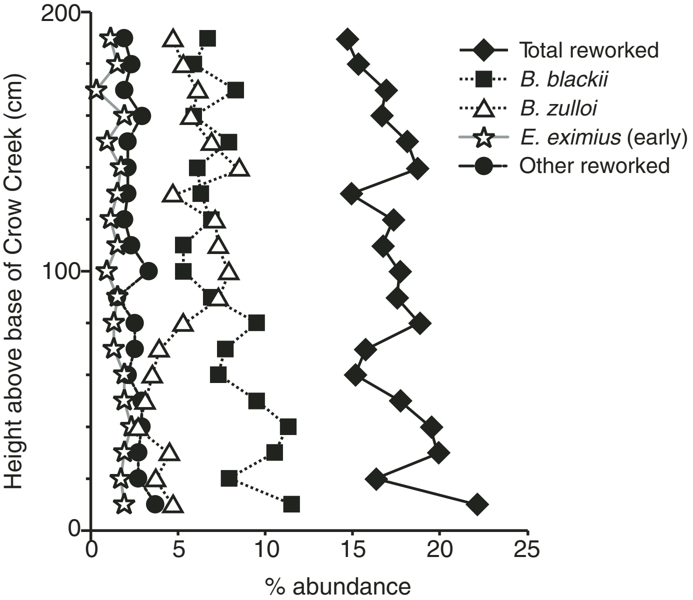

Figure 2. Stratigraphic distribution of taxa interpreted to be reworked at locality C. A decreasing upward trend is apparent in all taxa, except *B. zulloi*.

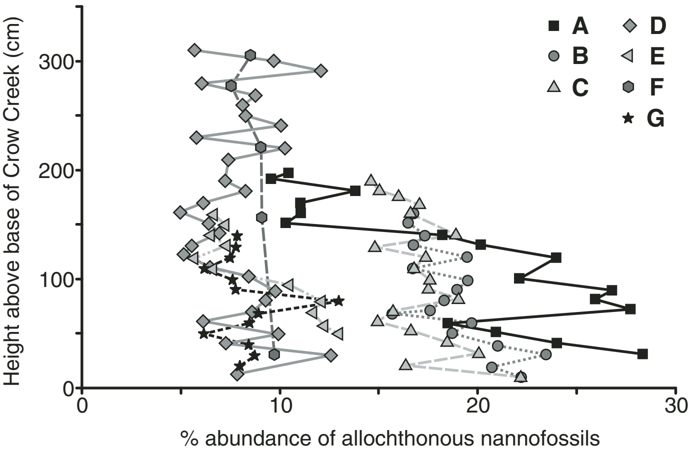

Figure 3. Stratigraphic distribution of reworked nannofossils from seven localities in South Dakota and Nebraska. Abbreviations as in Figure 1.

E. eximius (early-form), *L. grillii, M. furcatus,* and *R. anthophorus* (early-form), indicative of the Niobrara Chalk (Zone CC18). Two clasts (one from each locality) contain *A. parcus constrictus, Ceratolithus aculeus, E. eximius* (late-form), *Prediscosphaera grandis,* and *R. anthophorus*, indicative of the Gregory Member (Zone CC20). These observations indicate that the Niobrara Chalk and lower Pierre Shale are sources for marlstone clasts in the basal coarse layer and the reworked specimens in the marlstone. This suggests that some sites may be missing three to six biozones (CC18–23a) in the sub–Crow Creek disconformity. This time span is represented by ~2–3 m at locality A, ~30 m at locality G, and hundreds of meters in western South Dakota.

IMPLICATIONS FROM REWORKED NANNOFOSSIL DISTRIBUTIONS

Stratigraphic Distribution

The reworked assemblage displays a decreasing upward trend in the Crow Creek marlstone. This trend differs between localities, but never drops below 5% of the total assemblage (Fig. 3). The western localities (D, F, and G) have relatively constant amounts of reworked nannofossils through the marlstone, whereas the eastern localities exhibit a clear upward decrease in reworking (localities A, B, C, and E).

The decreasing trend is best explained by resuspension and gravitational settling. Progressive deposition of Pierre sediments over Niobrara promoted lithification to chalk. Deposition of the Crow Creek ooze above the partially lithified lower Pierre and Niobrara was interrupted by the Manson impact, which is interpreted to have created turbid currents that suspended Crow Creek sediments and eroded underlying, and more indurated, Pierre and Niobrara sediments bearing nannofossils. These components mixed in the water column and then settled as currents subsided. Crow Creek material was redeposited as individual nannofossils, while partially lithified Pierre and Niobrara material descended to the seafloor as larger nannofossil aggregate grains. The larger aggregate grains settled more quickly, in general, resulting in a greater representation of reworked nannofossils in the lower parts of the marlstone. Furthermore, nannofossils are found with larger and denser microfossils, because they were deposited as nannofossil aggregates, which are larger and hydrodynamically denser than isolated microfossils. The presence of Niobrara and Gregory marlstone clasts within the basal Crow Creek at localities A and E supports that gravitational settling occurred in this manner. This model also predicts that larger and denser foraminifera would settle before smaller and lighter radiolarians, so that foraminifera would be concentrated in the lower portions of the Crow Creek marlstone, whereas radiolarians are concentrated in upper portions.

Geographic Distribution

The stratigraphic distributions of the reworked assemblage from each section were compared geographically to determine possible sediment sources, assuming that the amount of reworking was a function of the distance from the sediment source. Comparison of the reworked abundances from localities A, B, C, and D indicates a reduction in the amount of reworked sediment toward the west or distal from the Manson Impact Structure (Fig. 3). A similar reduction is apparent between the localities on the north side of the Sioux Ridge: E, F, and G (Fig. 3). This pattern suggests an eastern source for reworked sediment.

The highest amount of reworking (28%) is at locality A, the most proximal site to the Manson Impact Structure (220 km from the Structure). There is a decrease of ~6% in the maximum percentage of reworking between localities A and B (245 km from the Structure). The same decrease in reworking is not apparent when comparing localities B with C (285 km from the Structure), suggesting that absolute distance from the impact was not the sole factor in determining abundance of reworked sediment. Locality A is the closest of these three localities to the Sioux Ridge and has the highest amount of reworking. Localities B and C, each about twice as far from the Sioux Ridge as A, have similar reworked abundances. This distribution suggests that the Sioux Ridge was one of the sources for reworked sediment (Figs. 1 and 3).

Given the paleotopography of the Sioux Ridge and the basin-wide nature of a sea-level rise, it is reasonable to predict that a transgressive deposit would yield an equal amount of reworked sediment in localities at equal distance away from the Sioux Ridge. However, there is a significant difference between the abundance of reworked material on the north and the south sides of the Ridge, as illustrated well by comparing the reworked component from localities A and E (Fig. 3). The systematic differences between sites on the north and south of the Sioux Ridge are contrary to what is predicted by simple transgression. Reworked nannofossils are concentrated to the east and the south of the Sioux Ridge, toward the impact. This suggests that the Manson impact served as the major source for reworked sediment in the Crow Creek, and that the Sioux Ridge acted as a partial barrier to the transport of reworked material northward.

ANALOGS FOR THE CROW CREEK MEMBER

The stratigraphic and geographic distributions of reworked nannofossils do not support a normal marine transgression hypothesis for the origin and deposition of the Crow Creek. The presence of distal impact ejecta, a chronological link with the Manson impact, fining upward lithologic trends, stratigraphic and geographic distributions of reworked nannofossils, the stratigraphic distribution of foraminiferal and radiolarian faunas, and the lack of bioturbation leads us to interpret both units of the Crow Creek as a resuspension event associated with the Manson impact. Airfall ejecta would also be included, as the settling of resuspended material would have taken a few hours for large grains to a few years for clay-sized grains (Bralower et al., 1998).

Two possible sedimentological analogs for the Crow Creek are pertinent. The first possible analog is cross-bedded sandstone that contains angular chalk and bioclastic limestone clasts that grade up into chalk at the Cretaceous-Paleogene boundary in the basinal Gulf of Mexico at Deep Sea Drilling Program (DSDP) Sites 536 and 540. Bralower et al. (1998) interpreted these and similar K-P boundary deposits at other DSDP and Ocean Drilling Program (ODP) sites in the Gulf of Mexico and Caribbean as turbidites from sediment gravity flows triggered by the collapse of continental margins around the Gulf of Mexico as a result of the Chicxulub impact. Although not at the same scale, the Crow Creek has a diversity of grains similar to the K-P boundary in the Gulf of Mexico. Both contain shock-metamorphosed mineral grains, quartz and feldspar grains, granule-sized fragments of basement rock, granule-sized fragments of shallow-water carbonate from underlying sediments, and reworked microfossils that decrease in abundance upward in a marlstone lithology (Witzke et al., 1996; Bralower et al., 1998; Izett et al., 1998; Katongo et al., 2004; this work). A similar situation may have existed in the Western Interior Seaway during the Manson impact. Sediment gravity flows could have developed along the Sioux Ridge and/or the eastern margin of the Seaway, carried sediment basinward, scoured the sea floor, and redeposited sediment by gravitational settling.

A second possible analogue for the Crow Creek (excluding impact ejecta) is the Holocene megaturbidites from the Mediterranean Sea (Cita and Aloisi, 2000). The collapse of the Santorini caldera created a mega-tsunami that propagated across the Mediterranean Sea and ran ashore on the African coast. As a result, a turbid current generated on the African shelf deposited a thin, basal coarse layer of nearshore reworked sediment on the Ionian and Sirte abyssal plains. This sediment is overlain by a uniform massive marlstone (Cita and Aloisi, 2000). A similar scenario may have existed in the Western Interior Seaway when the Manson impact collided with the eastern margin and created a wave that ran ashore on the Sioux Ridge and/or the eastern margin, causing sediment to be carried basinward and redeposited by gravitational settling.

The presence of eastern-derived sediments in the Crow Creek, such as detrital carbonate, shallow-water foraminiferal assemblages, and kaolinite and illite clay minerals, suggests a nearshore input. This implies that nearshore currents, such as a tsunami, carried sediment offshore. In addition, the presence of black mudstone clasts and gray marlstone clasts suggests that the Manson impact-induced process scoured the offshore sea floor as these clasts represent input from deepwater deposits and older pelagic sources, respectively. We advocate a resuspension of existing, largely unconsolidated sediment by a passing tsunami. Localized gravity flows along the Sioux Ridge could supply part of the reworked sediment, with other contributions from ejecta and nearshore erosion on the eastern margin. Regardless of the sedimentological process, the bulk of the energy from the impact (and thus from the tsunami) would have been directed at the southern flank of the Ridge, with the northern flank being relatively sheltered, because there is a significant decrease in the amount of reworking on the distal (northern) side of the Ridge and no evidence of reworking at locality H (Figs. 1 and 3). These observations suggest that the Crow Creek records an impact-induced resuspension event. This kind of disturbance and rearrangement of the biostratigraphic record might be expected in sites proximal to impacts.

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