Eolian-derived siltstone in the Upper Permian Phosphoria Formation: Implications for marine upwelling

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ABSTRACT

Previously described organic-rich shale facies of the Meade Peak Member of the Phosphoria Formation at Soda Springs, Idaho, consist of well-sorted, laminated siltstone containing little or no clay. The planar-parallel fabric preserved in many of the siltstone beds suggests suspension settling onto the outer shelf or upper slope, most likely under low oxygen conditions. Evidence for transport of silt to the depositional site by sediment gravity flows is absent, as are sandstone beds. We propose that Meade Peak siltstone facies record subaqueous deposition of windborne silt that was transported southward from central Montana. As such, they provide the first direct geologic evidence of a wind regime favorable for marine upwelling, the process commonly postulated to have localized the deposition of Permian phosphatic sediments. They may also provide indirect evidence of upwind eolian sand transport at that time.

INTRODUCTION

Sheldon (1964) and numerous other workers postulated that the richly phosphatic Permian deposits in the northern Rocky Mountains record oceanic upwelling adjacent to a marine shelf. Shore-parallel winds related to circulation around an oceanic subtropical high are thought to have induced Permian upwelling, via Ekman transport (Sheldon, 1964; Parrish, 1982). Direct geologic evidence for this wind regime has been elusive, however, owing to the lack of preservation of coeval eolian sandstone facies in onshore environments. Known Permian erg (eolian sand sea) deposits in western North America are almost entirely restricted to older, Leonardian and Wolfcampian strata (Blakey et al., 1988), whereas the Phosphoria Formation is Guadalupian.

Even in the absence of eolianites sensu stricto, eolian-derived siltstone facies deposited in offshore marine environments may provide evidence for wind transport of sediments. For example, Fischer and Sarthein (1988) suggested that laminated, deep-marine siltstone of the Guadalupian Brushy Canyon Formation in west Texas originated as wind-borne dust, on the basis of an analogy to Quaternary eolian-marine deposits off the west coast of Africa. For modern sediments, criteria for eolian transport include a dominance of well-sorted silt with a paucity of clay (e.g., Tiedeman et al., 1989). No previous studies have examined the possibility of eolian contributions to the Phosphoria Formation. The embayed continental shelf onto which the Phosphoria Formation was deposited (Fig. 1) would have been an ideal trap for wind-borne dust blown from surrounding continental environments. Such dust deposits may represent the only preserved record of an eroded eolian system.

The purpose of this study is to evaluate possible eolian silt contribution to the Meade Peak Member of the Phosphoria Formation at Soda Springs, Idaho. Recognition of eolian-derived siltstone facies within the Meade Peak Member would represent the first concrete evidence for the association of a specific wind regime with upwelling in an important phosphorite deposit, and would help confirm surface wind directions predicted by global circulation models for this period (Parrish, 1982; Kutzbach and Ziegler, 1993). More detailed future studies of eolian-derived siltstone facies could eventually yield a highly resolved record of temporal variations in wind intensity and direction, and provide a crucial link with incompletely preserved records of continental eolianites.

STRATIGRAPHIC SETTING OF THE MEADE PEAK MEMBER

The Meade Peak Member at the Monsanto Soda Springs Mine, southeast Idaho, records continuous deep-water deposition. Conodont and brachiopod assemblages place it within the Roadian stage (Wardlaw and Collinson, 1986). A 17 cm interval of amalgamated phosphatic hardgrounds disconformably overlies shallow-marine dolomite of the Grandeur Member (Fig. 2), and grades upward into siltstone. At Soda Springs, the Meade Peak Member consists

Figure 1. Paleogeography of Phosphoria Formation (modified from Maughan, 1984), and surface wind directions derived from GENESIS v. 2.0 global climate model (J. E. Kutzbach and M. Gibbs, 1998, personal commun.). "Winter" wind direction is averaged over December-January-February; "summer" is over June-July-August. MT—Montana, WY—Wyoming, SD—South Dakota, NE—Nebraska, CO—Colorado.
of interbedded peloidal phosphorite, siltstone, and minor carbonate facies, that grade upward into spicular chert of the Rex Chert Member. Regionally, the Meade Peak Member onlaps what is interpreted to be a tectonically enhanced sequence boundary (Hendrix and Byers, 1998). It progressively thins to the east, and grades into dolomite, red mudstone, and evaporite facies on the Wyoming shelf (Maughan, 1984, Fig. 1). The lower part of the Meade Peak Member in Idaho therefore appears to be restricted to more deeply subsided western areas of the basin.

ORGANIC-RICH SILTSTONE FACIES

Our field investigation at the Monsanto mine revealed that organic-rich shale (cf. McKelvey et al., 1959) and other fine-grained nonphosphatic facies consist predominantly of laminated siltstone having very low clay content (Fig. 2). Hiatt (1997) also recognized the silty nature of these beds. In outcrop, the siltstone facies exhibits pervasive planar-parallel lamination and is commonly fissile. Some Meade Peak Member siltstone beds are massive, however, and have rare burrows. Perhaps the most striking feature of the siltstone facies is the nearly total lack of any sedimentary structures indicative of sediment gravity flows. Graded beds, cross-lamination, and Bouma subdivisions are absent, as are sandstone beds. The presence of hardgrounds may indicate that contour or bottom currents periodically winnowed the sediments and concentrated phosphatic minerals, but sedimentary structures indicative of such processes are ambiguous or absent at Soda Springs. The lack of any cross-stratification suggests deposition below storm wavebase, possibly in an outer shelf environment.

Thin-section examination of nine representative samples from a correlative section of the nearby Dravo E-63 core confirms that well-sorted, coarse silt predominates in this facies (Table 1; Fig. 3); estimated modal grain sizes are between 30 and 50 μm. The grains are angular to very angular, consistent with previous experimental data indicating that very little eolian abrasion occurs for fine quartz sand and silt (Kuenen, 1960), and with observed grain textures in loess deposits (Pye, 1987). Silt grains are dominantly quartzose, although there are minor amounts of mica, plagioclase, and potassium feldspar. The planar-parallel fabric seen in outcrop is less apparent at thin-section scale, owing to a lack of contrasting clay-rich laminae in this facies. The same is true for similar siltstone facies of the Brushy Canyon Formation (M. B. Wegner, 1997, personal commun.). In both cases, the planar-parallel fabric results from subtle differences in organic matter distribution and from preferential grain orientation, and is enhanced by outcrop weathering. Semi-quantitative X-ray diffraction analyses of 18 samples indicates a dominantly quartzose composition; no measurable clay peaks were detected. Silt grains are also common within phosphorite facies, both as the nuclei of phosphatic peloids as separate grains (Fig. 4). A full range of gradations exists, between dominantly siltstone and dominantly phosphorite facies.

Meade Peak siltstone facies are very rich in sedimentary organic matter. Total organic carbon content (TOC) of the siltstone samples in this study ranges between 1.15% and 15.63%. Rock Eval temperature (Tmax) measurements from these samples average approximately ~530 °C, supporting previous interpretations of very high thermal maturity of organic matter in southeast Idaho (e.g., Edman and Surdam, 1984). Assuming Type II marine kerogen, it is therefore likely that original (pre-oil generation) TOC values were about twice the present values (cf. Raiswell and Berner, 1987), in good agreement with previous reports of up to 30% TOC in less thermally mature sections (Maughan, 1995). High organic enrichments are consistent with high productivity during Phosphoria deposition, as has been noted previously (e.g., Parrish, 1982). The scarcity of burrows and preservation of finely planar-parallel fabric also support enhanced preservation of organic matter under anoxic conditions (Demaison and Moore, 1980).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Position above Grandeur Member (m)</th>
<th>Maximum grain size (μm)</th>
<th>Modal grain size (μm)</th>
<th>Sorting*</th>
</tr>
</thead>
<tbody>
<tr>
<td>E63-37</td>
<td>36.0</td>
<td>100</td>
<td>40</td>
<td>Well sorted (0.35-0.50 μm)</td>
</tr>
<tr>
<td>E63-35</td>
<td>35.1</td>
<td>130</td>
<td>50</td>
<td>Very well sorted (0.25-0.35 μm)</td>
</tr>
<tr>
<td>E63-31</td>
<td>31.3</td>
<td>100</td>
<td>40</td>
<td>Well sorted (0.35-0.50 μm)</td>
</tr>
<tr>
<td>E63-30</td>
<td>31.1</td>
<td>100</td>
<td>40</td>
<td>Well sorted (0.35-0.50 μm)</td>
</tr>
<tr>
<td>E63-29</td>
<td>29.3</td>
<td>110</td>
<td>50</td>
<td>Well sorted (0.35-0.50 μm)</td>
</tr>
<tr>
<td>E63-27</td>
<td>26.8</td>
<td>70</td>
<td>30</td>
<td>Well sorted (0.35-0.50 μm)</td>
</tr>
<tr>
<td>E63-25</td>
<td>22.6</td>
<td>110</td>
<td>50</td>
<td>Very well sorted (0.25-0.35 μm)</td>
</tr>
<tr>
<td>E63-18</td>
<td>12.5</td>
<td>80</td>
<td>40</td>
<td>Well sorted (0.35-0.50 μm)</td>
</tr>
<tr>
<td>E63-5</td>
<td>1.2</td>
<td>120</td>
<td>50</td>
<td>Well sorted (0.35-0.50 μm)</td>
</tr>
</tbody>
</table>

*Sorting based on comparison with reference photographs of Beard and Weyl (1973) for very fine sand, lower division (estimated standard deviation in parentheses).
CASE FOR EOLIAN TRANSPORT

In addition to the association of the siltstones with phosphatic sedimentary rocks, three principal lines of evidence point toward eolian input of silt into a marine setting at Soda Springs. First, the grain size distribution of the organic-rich siltstone facies is remarkably similar to known modern eolian-derived sediments found in nearshore environments. For example, Sarnthein and Koopman noted that modal grain sizes of 30–40 μm characterized Pleistocene eolian-derived silt deposited within ~200 km offshore of northwest Africa, downwind of the Sahara Desert. Similarly, Tiedeman et al. (1989) reported of northwest Africa, downwind of the Sahara derived silt deposited within ~200 km offshore and Koopman noted that modal grain sizes of modern eolian-derived sediments found in siltstone facies is remarkably similar to known silt into a marine setting at Soda Springs. First, with phosphatic sedimentary rocks, three principal

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For example, Harms (1974) estimated median diameters of 10–50 μm for the Brushy Canyon Formation, and Soreghan (1992) estimated 20–40 μm grain sizes for eolian-derived Lower Permian silt in the Pedregosa basin in Arizona. Maximum grain size was not reported in any of these studies, but grain sizes to fine sand are known to be carried in suspension in modern dust storms (Pye, 1987). For example, Nickling (1983) indicated a maximum suspended grain size of ~2.5 μm for dust storms in Yukon Territory; this is equivalent to 177 μm (fine sand), and is slightly coarser than the maximum grain size in the Meade Peak siltstone facies (Table 1). Tiedemann et al. (1989) distinguished eolian dust from fluvial-derived sediments offshore northwest Africa on the basis of modal grain size versus percentage of siliciclastic silt. They found that eolian transport results in well-sorted silt with relatively little clay. Meade Peak Member siltstone facies are well-sorted to very well-sorted (Table 1), and contain very little clay, consistent with eolian derivation.

Second, ample evidence exists for markedly arid climatic conditions during deposition of the Meade Peak Member. Paleogeographic reconstructions of the Phosphoria shelf correlate phosphorite formation with large areas of evaporite deposition farther east (Fig. 1; Maughan, 1984). Aridity is conducive to eolian transport, although other factors such as basin configuration, sediment supply, and sand-flow patterns are also important (Kocurek, 1988).

Third, the lack of evidence for tractive transport of Meade Peak siltstone facies by sediment gravity flows leaves little alternative other than deposition by settling of suspended material through the water column. Suspension of silts derived from major fluvial deltas could also provide suspended silt, but fails to explain the near absence of clay. There is also no geologic evidence for the existence of such fluvial systems. The Phosphoria shelf received predominantly fine-grained siliciclastic and carbonate facies, with only limited areas of sandstone deposition (Fig. 1; Maughan, 1984). The Sherdorn Sandstone, the nearest correlate to Meade Peak siltstone facies to the Meade Peak Member at Soda Springs (Fig. 1), contains exclusively shallow marine, fine-grained facies lacking any features suggestive of fluvial transport (Thornburg, 1990). Possibly coeval siliciclastic facies to the southeast of Soda Springs have been interpreted as semiarid to arid alluvial fan deposits (Mack and Rasmussen, 1984); it is unlikely (although not impossible) that suspended silt from these systems could have been deposited as far away as Soda Springs. The lack of tractive sedimentary structures within the Meade Peak Member also argues against thermohaline density currents, such as proposed by Harms (1974) for the Brushy Canyon Formation.

SOURCE OF MEADE PEAK SILTSTONE

The absence of eolian sandstone units equivalent to the Meade Peak Member does not necessarily indicate the cessation of eolian sand transport in this region. Rather, it may simply reflect the lack of preservation of any coeval cratonic rock units outside the Phosphoria basin. Wardlaw et al. (1994) documented a major unconformity that removed most of the Guadalupian through Lower Triassic strata in the western United States. Within the study area, the only preserved Guadalupian rocks are those of the Phosphoria Formation and time-equivalent strata deposited on anomalously low areas on the Wyoming shelf (Fig. 1). Eolian dust that was deposited within these flooded areas thus provides the only record of what could have been more extensive eolian systems. Additional volumetric data on Phosphoria Formation siltstone facies are needed to fully assess the potential significance of such systems. Another Late Permian marine embayment existed to the south, where the Brushy Canyon Formation was deposited in the Delaware basin. Fischer and Sarnthein (1988) argued that Brushy Canyon Formation siltstone facies also correlate to an updip hiatus; however, Kocurek and Kirk-land (1998) have argued for derivation of silt from a specific area of eolianite deposition in the Anadarko basin.

Although the lack of preserved Guadalupian eolianites precludes their direct correlation with Meade Peak siltstone, global circulation models for Early Permian and Triassic time frames have consistently deduced northern or northeasterly surface winds in northwestern Pangea (present-day coordinates), due to circulation around a subtropical high located to the west. The model predictions agree closely with paleowind indicator measurements from Permian eolian sandstones older than the Meade Peak Formation, preserved on the Colorado Plateau and in eastern Colorado (Parrish and Peterson, 1988). Similar wind directions were modeled by Kutzbach and Ziegler (1993) for the Late Permian (Kazanian stage), suggesting the persistence of a relatively stable circulation pattern. More recent modeling for the Wordian stage, conducted at a higher spatial resolution (3° × 3° cells), confirms this pattern for several carbon dioxide partial pressures (GENESIS v. 2.0 global climate model; J. E. Kutzbach and M. Gibbs, 1998, personal commun.). Surface winds derived from this model vary from northwesterly in the summer (June-July-August), to northeasterly in the winter (December-January-February).

Tsoar and Pye (1987) concluded that silt particles >20 μm are transported mainly near the ground, on the basis of modern observations and calculated settling velocities in turbulent flows. On the basis of a hypothetical severe windstorm (u, drag velocity, = 70 cm/s), they predicted that the concentration of particles >20 μm at 100 m above the surface will be only 26% of the concentration at 0.5 m. It is therefore appropriate to assume that surface wind patterns exert the dominant control on the dispersal of silt grains equivalent to those contained in the Meade Peak Member. On the basis of model-derived surface winds and reconstructed paleogeography, the likely source area for Meade Peak Formation siltstone facies is to the north and northeast in the Milk River uplift of central Montana (Fig. 1). No Upper Permian strata are preserved there, but the shallow-marine Sherdorn Sandstone of southwest Montana and northwest Wyoming could conceivably contain sands derived from reworking of eolianites. Thornburg (1990) correlated the Meade Peak Formation to the Lower Sherdorn Sandstone, which was deposited on a shallow-marine shelf. Compositionally mature grain compositions and very fine to medium grain sizes for the Sherdorn Sandstone (Thornburg, 1990), together with interpreted paleogeographic relationships, are consistent with a low relief, central Montana provenance.

Owing to trapping of saltating grains by contact with the ocean surface, it is unlikely that low-level transport could carry silt grains great distances offshore. For example, Sarnthein and

Figure 3. Photomicrograph of typical Meade Peak Member siltstone facies, Soda Springs, Idaho (sample E63-27 from Dravo E63 core).


Manuscript received April 17, 1998
Revised manuscript received August 6, 1998
Manuscript accepted August 17, 1998.