Importance of high-frequency tectonic sequences during greenhouse times of Earth history

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ABSTRACT

The relative importance of tectonism in the stratigraphic record should be more clearly expressed during greenhouse times of Earth history due to the lack of overmasking effects of high-frequency and high-amplitude sea-level changes typical for icehouse periods. Establishment of the importance of tectonism, especially at temporal scales comparable to durations of typical transgressive-regressive cycles, has been plagued by poor temporal resolution. Our outcrop and subsurface-based study of a Cenomanian shallow-marine siliciclastic interval, constrained by bentonite-based geochronology and detailed biostratigraphy, examines this problem. In a 2.2 m.y. interval, we identified four tectonically driven erosional surfaces that dominate preserved stratigraphy. Biostratigraphic correlation to a sea-level curve for the Cenomanian—where coeval high-frequency low-amplitude eustatic cyclicity has been demonstrated—allows the first direct comparison of the effects of eustasy and tectonics at temporal scales of hundreds of thousands of years during a global greenhouse time. We suggest that minor tectonic pulses locally overshadow the effects of eustasy and exert the dominant control over preserved stratigraphy. While subtle tectonic control on sedimentation has been documented throughout the Cretaceous Western Interior, the results of this study suggest that much of that deformation occurred at sub-million-year frequencies and at time scales comparable to eustatic transgressive-regressive cycles.

Keywords: tectonic controls, Milankovitch theory, sequence stratigraphy, biostratigraphy, erosion surfaces, foreland basins.

INTRODUCTION

There remains a significant debate as to whether sequence-bounding unconformities are dominated by tectonic, eustatic, or other controlling mechanisms, such as climatic variation (e.g., Van Wagoner, 1995; Yoshida et al., 1996). While Quaternary sediments are better suited for resolving such issues due to typically excellent time control (e.g., Ito et al., 1999), such systems are poorly representative of greenhouse times in Earth history, when amplitudes of sea-level variation were much lower (Gale et al., 2002). Resolving the importance of tectonic and eustatic control directly from ancient data is problematic, since depositional events often occurred at time scales shorter than available temporal resolution (Miall, 1992). The Cretaceous section of the Western Interior of North America was one of the first places where sub-million-year coarsening-up cycles (parasequences) were investigated, resulting in various hypotheses for their generation. Some workers suggested domination of glacio-eustasy (e.g., Plint, 1991; Van Wagoner, 1995), while others preferred tectonic forcing (Yoshida et al., 1996). More recent high-resolution work has suggested that long Milankovitch-frequency eustatic variation (400 k.y.) was a factor during the Cenomanian (Gale et al., 2002). Because both eustasy and tectonics can independently generate high-frequency sequences, external criteria, such as recognition of diagnostic stratigraphic architecture or correlation of coeval base-level changes at far-removed localities, must be used to distinguish tectonic from eustatic stratigraphic cycles. Our study illustrates the first geochronologically and biostratigraphically constrained example, which shows high-frequency tectonic control in a stratigraphic interval during a greenhouse time. We build on a detailed allostratigraphic framework developed by Bhattacharya and Willis (2001), as well as comparisons with late Cenozoic and Quaternary high-frequency tectonic analogs (e.g., Fortuin and DeSmet, 1991; Ito et al., 1999).

STUDY AREA

The study area, located on the western flank of the Powder River Basin (east-central Wyoming) (Fig. 1), was situated in a shallow overfilled distal foreland to cratonic setting during Cenomanian time. The area was subsequently affected by large-scale basement-involved deformation during the Laramide orogeny, which reached eastern Wyoming by the early Tertiary (Crowley et al., 2002). The Frontier Formation has been subdivided into three unconformity-bounded members—Belle Fourche, Emigrant Gap (locally missing), and Wall Creek Member, which span ~8 m.y. (Merewether, 1996). These unconformities, identified by absence of molluscan fossil zones, have been interpreted to be of tectonic origin and recur with frequencies of several million years (Merewether and Cobban, 1986). Regional outcrop and well-log–based mapping within the lower portion of the Belle Fourche Member has defined four distinct

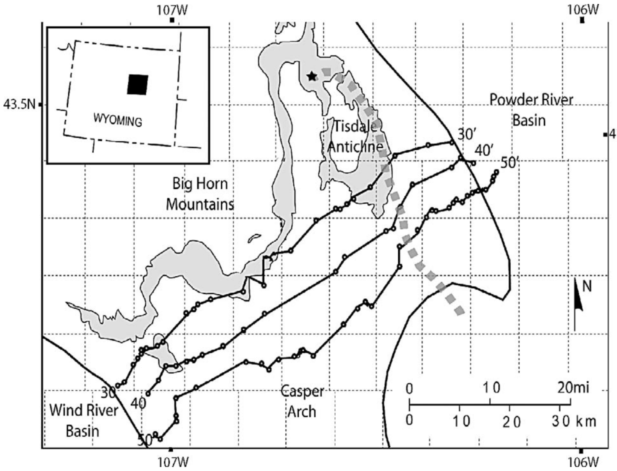

Figure 1. Map showing positions of Frontier Formation outcrop belt (light gray), well-log cross sections (30–30′, 40–40′, 50–50′), location of Second Frontier truncation in outcrop (black star), regional Second Frontier erosional trend identified in subsurface (dashed gray line), and Tisdale Anticline. Triangles, stars, and squares displayed on cross-sections 30–30′ and 40–40′ correspond to well logs shown in Figures 3A, 3B, and 3C.

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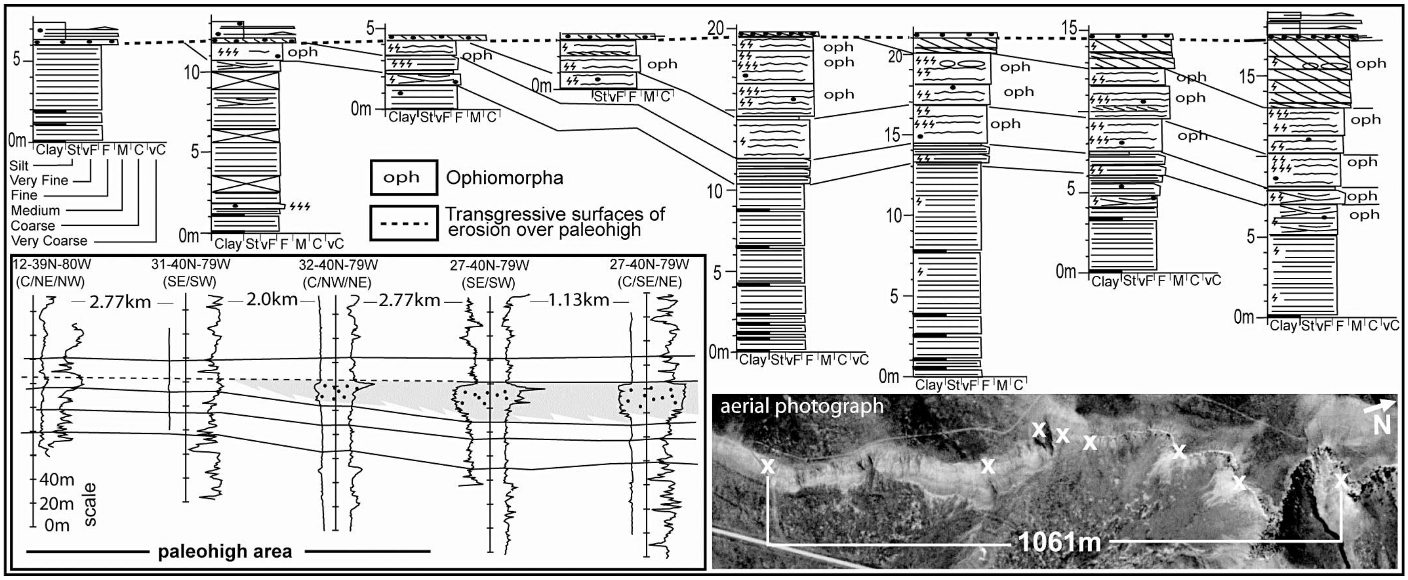

Figure 2. Examples of tectonically driven erosion of Second Frontier Sandstone in outcrop and subsurface. Top: Eight measured sections along continuous outcrop show increased removal of high-energy facies to left. Bottom right: Locations of measured sections on aerial photograph in same order from left to right. Bottom left: Expression of same erosional event in resistivity well logs from portion of cross-section 50–50′.

discontinuity-bounded allomembers: Harlan, Willow, Frewens, and Posey, from lowest to highest (Bhattacharya and Willis, 2001). Each allomember is composed of an upward-coarsening mudstone-to-sandstone lithofacies succession erosionally capped by a chert-pebble lag, which has been interpreted as a detached lowstand deltaic deposit (Bhattacharya and Willis, 2001). These units are overlain by the coarsening-up succession of the Second Frontier Sandstone, which is also capped by a pebble lag.

Seven regionally extensive bentonite beds (three dated) allow placing of mapped erosional surfaces within a high-resolution chronostratigraphic framework. The Harlan allomember overlies the Clay Spur Bentonite dated at 97.17 ± 0.69 Ma (^{40}Ar/^{39}Ar, sanidine; Obradovich, 1993) and underlies Bentonite 5, dated at 95.86 ± 0.45 Ma (^{40}Ar/^{39}Ar, sanidine; Obradovich, 1993). The Willow allomember, the Posey allomember, and the overlying Second Frontier Sandstone are capped by the Soap Creek Bentonite, dated at 94.93 ± 0.53 Ma (^{40}Ar/^{39}Ar, sanidine; Obradovich, 1993). Bentonite ages and biostratigraphic control allow placement of stratigraphic units and erosional surfaces within a high-resolution temporal framework.

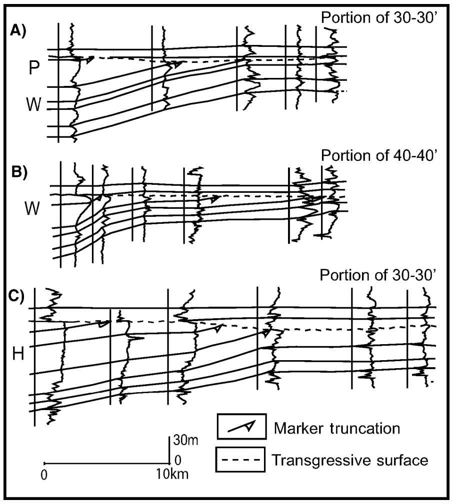

Figure 3. Examples of tectonic truncations in Harlan (C), Willow (B), and Posey (A) allomembers from portions of resistivity well-log cross-sections 30–30′ and 40–40′. Locations of well logs are shown in Figure 1 (see figure caption for details). H—Harlan, W—Willow, P—Posey.

EVIDENCE FOR TECTONIC ORIGIN OF FOUR BELLE FOURCHE UNCONFORMITIES

Several criteria suggest that four of the erosional surfaces mapped in the study are tectonically driven. Rather than representing a marine-to-nonmarine contact, as would be expected if erosion was due to valley incision, these surfaces show characteristics typical of a transgressive surface eroded by waves, such as presence of the *Glossifungites* ichnofacies (firm-ground burrowing organisms commonly associated with transgressive erosion surfaces; MacEachern et al., 1992), shark-teeth–bearing pebble lags, and overlying offshore marine deposits (Cattaneo and Steel, 2003). Such surfaces do not show undulating channelized geometries, are never overlain by nonmarine fluvial channel or floodplain facies, and can overlie upper shoreface, lower shoreface, or offshore facies. The lateral variation of erosion depth results in abrupt truncation of sand-dominated intervals, which are mappable in both outcrop and closely spaced well-log data. The regional trends of these truncations appear linear and parallel to modern structural features, which further supports a tectonic interpretation. Additionally, no significant coarse-clastic accumulations have been mapped ''seaward'' of the trend of these erosional surfaces, which might be expected if these were river-cut valleys.

An outcrop example is shown in the Second Frontier Sandstone (Fig. 2, see star in Fig. 1). Eight measured sections along an ~1.3-km-long exposure show the progressive southward removal of high-energy, coarse-grained shoreface facies. Truncation occurs underneath a flat erosion surface that overlies medium-grained, large-scale cross-bedded shore face sandstones in the north, and finer-grained, planar to hummocky cross-stratified, mud lens–bearing lower shoreface sandstones in the south. The erosional surface is identified by a pebble lag, which is overlain by transgressive marine pebble-bearing muddy deposits. The facies directly underlying the erosional surface in the southern portion of the outcrop appear similar to facies ~10 m below the erosional surface in the north (Fig. 2). We interpret such variation in depth of erosion as related to a higher degree of wave erosion over a paleohigh area to the south. An additional outcrop-based example, displaying a similar style of differential erosion over a paleohigh area, was mapped in the Harlan allomember of the lower Belle Fourche (see Figure 4b in Bhattacharya and Willis, 2001), where up to 25 m of sediments was interpreted to have been removed. In both examples, erosional surfaces appear marine in origin, display flat geometries, and suggest wave reworking as an erosional mechanism.

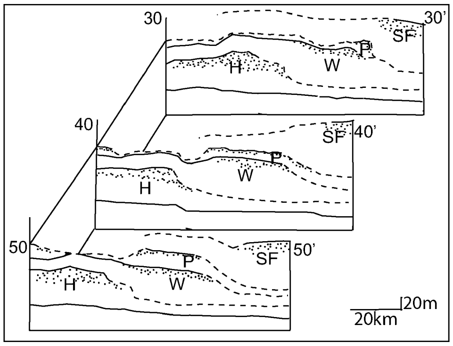

Figure 4. Fence-diagram showing preserved sand-dominated portions of allomembers (dotted pattern) and extent of tectonically driven erosion (dashed lines) in well-log cross-sections 50–50′, 40–40′, and 30–30′. H—Harlan, W—Willow, P—Posey, SF—Second Frontier Sandstone. See Figure 1 for locations.

Closely spaced well logs penetrating the Second Frontier Sandstone (Fig. 2) and the Harlan allomember (Fig. 3C) allow these erosional surfaces to be traced in the subsurface and to be mapped regionally. Differential erosion is indicated by an abrupt lateral decrease in thickness of sand-dominated successions and by truncation of well-log markers, including the bentonites. Erosional trends are linear and subparallel to modern Laramide structures (see Fig. 1), suggesting basement-fault control. We identified and mapped two additional erosion surfaces at the tops of the Willow and Posey allomembers in the subsurface to the east of the outcrop belt (Figs. 3A–3B). All erosional surfaces show abrupt thinning and removal of sand-rich successions, truncation of well-log markers, and a NNW-SSE erosional trend, similar to the Second Frontier and Harlan examples (Fig. 4). The mapped erosion surfaces suggest four individual pulses of tectonic movement over a time span of ~2.2 m.y.

DISCUSSION

The chronometric control from the bentonites (Obradovich, 1993) and the biostratigraphic control allow us to compare the relative importance of tectonics and eustasy at sub-million-year frequencies. Detailed biostratigraphy allows correlation to a high-resolution global sea-level curve for the Cenomanian (Gale et al., 2002) (see Figs. 5 and 6). An exceptionally high level of biostratigraphic correlation was achieved by the use of widely distributed ammonite species belonging to rapidly evolving *Acanthoceratacae* and *Turrilitacea* superfamilies. Relatively complete ammonite-bearing Cenomanian successions of the study area yield 13 ammonite biozones (Merewether and Gautier, 2000), which are plotted against co-occurring ammonite biozones of the Anglo-Paris Basin (Gale et al., 2002). The ranges of all species are not identical in both basins, but their relative orders are the same, and the pattern of occurrence is analogous. Since the lower part of the Belle Fourche Member is missing important biostratigraphic markers, only the interval that spans the middle to upper Cenomanian (corresponding to sequences 6–12 of Anglo-Paris Basin) was used (Fig. 6).

The four tectonically driven erosional surfaces occur in a succession that was previously considered to be conformable and that underlies a prominent regionally mappable 2 m.y. unconformity (see Figure 10 in Merewether and Cobban, 1986) (Fig. 6), which has also been interpreted to be of tectonic origin (Merewether and Cobban, 1986). The first tectonically driven unconformity truncates portions of the Harlan allomember, and occurs in the upper portion of the ammonite-free interval, positioned between the Clay Spur Bentonite and Bentonite 5, a period of 1.31 ± 0.8 m.y. (Figs. 5 and 6). The other three unconformities, topping the Willow, Posey, and Second Frontier units, respectively, occur in the ammonite-bearing Bentonite 5–Soap Creek Bentonite interval over a period of 0.93 ± 0.7 m.y. (Figs. 5 and 6). The number of erosional surfaces per bentonite-bounded interval, taken in conjunction with biostratigraphic events within ammonite fauna (e.g., the first and last occurrence) suggest a sub-million-year rate of recurring of tectonic movements.

Numerical modeling results suggest that intraplate stresses in plate interiors are sufficient to generate significant vertical movements at the scale and frequency observed in this study (Cloetingh, 1988; Peper et al., 1992; Heller et al., 1993). While examples of subtle tectonic control on sedimentation from the Western Interior of the United States are numerous (e.g., Heller et al., 1993; Zaleha et al., 2001), little information is available on recurrence rates. Extracting a tectonic signal from a bentonite-bearing fossiliferous shallow-marine interval

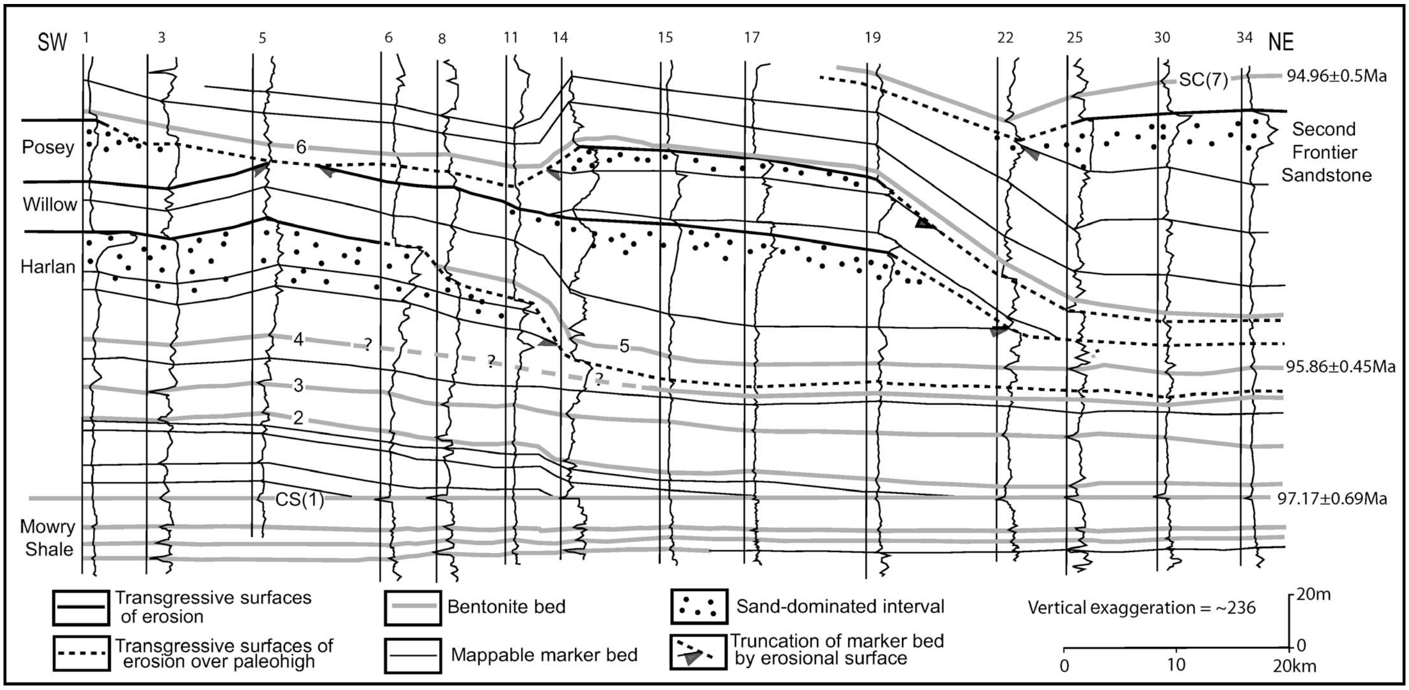

Figure 5. Resistivity well-log cross-section 50–50′ showing distribution of seven regionally recognized bentonites (thick gray lines), sandy portions of allomembers (dotted pattern), and tectonically driven erosional surfaces (dashed lines). Well locations on Figure 1 are determined by using number overlying each well and counting toward NE. Ages for the Clay Spur Bentonite (CS), Bentonite 5, and Soap Creek Bentonite (SC) are from Obradovich (1993).

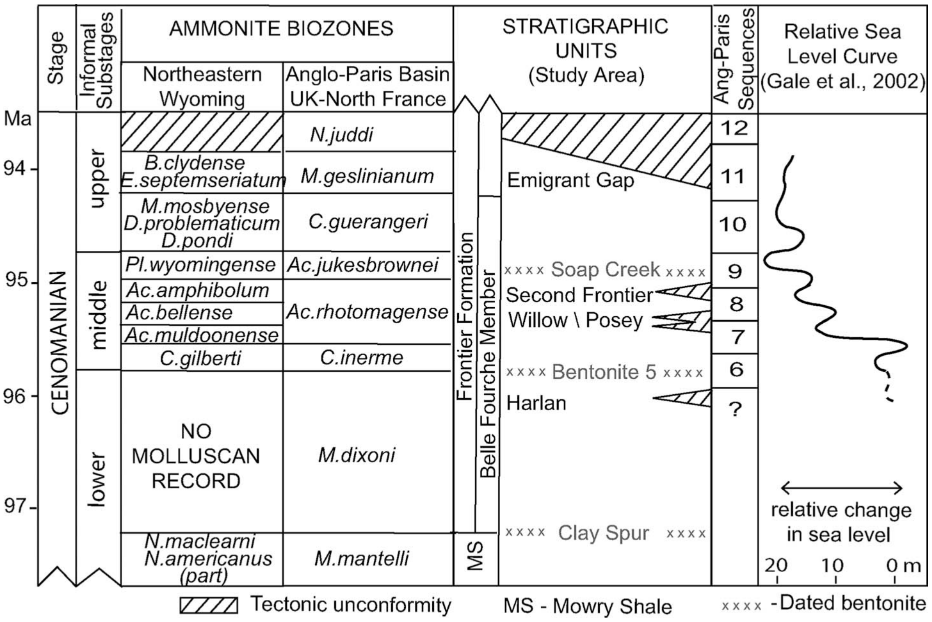

Figure 6. Age and ammonite biozones in study area (Merewether and Gautier, 2000) and Anglo-Paris Basin (Gale et al., 2002), along with major stratigraphic units, temporal position of tectonically driven unconformities, and correlation to relative sea-level curve from Gale et al. (2002). Genus names: *Ac—Acanthoceras*, *B—Burroceras*, *Ca—Calycoceras*, *Co—Conlinoceras*, *Cu—Cunningtoniceras*, *D—Dunveganoceras*, *E—Euomphaloceras*, *Ma—Mantelliceras*, *Me—Metoicoceras*, *Nc—Neocardioceras*, *Ng—Neogastropolites*, *Pl—Plesiacanthoceras*.

demonstrates that fault movement at depth can generate sufficient surface topography with recurrence intervals of several hundreds of thousands of years.

Comparison between mapped Cenomanian movements and modern structural features allows examination of the relative importance of early Laramide thick-skinned basement deformation. While trends of all erosional surfaces are subparallel (Fig. 4), only the Second Frontier tectonic unconformity appears directly related to early activation of a present-day Laramide feature (Tisdale Anticline, Fig. 1). We thus interpret mapped movements as being due to periodic activations of inherited subparallel basement faults driven by intraplate stresses, and major slip along one of these during later Laramide deformation. Evidence for activation of subparallel but adjacent faults and related overlying topographic highs suggests the effects of stress shadowing between these fault systems (Stein, 1999). Our study suggests that during greenhouse times, when rapid, high-amplitude changes in sea level do not occur, subtle tectonically related changes in topography are better expressed and exert a first-order control on preserved stratigraphy. Interpretations of controls on sedimentation ought to be based on independent criteria, such as diagnostic stratigraphic architecture or coeval base-level changes at far-removed localities, rather than through assumption of eustatic control.

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