10 k.y. depositional cyclicity in the early Eocene: Stratigraphic and ^{40}Ar/^{39}Ar evidence from the lacustrine Green River Formation

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ABSTRACT

^{40}Ar/^{39}Ar dating of sanidine from two interbedded tuffs reveals that the maximum average duration of depositional cycles in the Wilkins Peak Member, Green River Formation, was $\sim$10 k.y., marking the first time that subprecessional cycles have been recognized in lacustrine strata. The origin of these cycles is uncertain, but may relate to a nonlinear climatic response to orbital forcing of insolation. Alternatively, regional tectonic and geomorphic controls on drainage stability may have promoted autocyclic delivery of sediment to the lake. Owing to an interaction between basin-floor relief and varying amplitudes of lake expansion, only one-third of the cycles identified near the basin center are present near the basin margin. This spatial variability in the temporal completeness of the stratigraphic record is not apparent from examination of individual localities, indicating that studies based on time-series analysis from other lacustrine systems may need reevaluation.

Keywords: lacustrine, cyclicity, Eocene, Green River Formation.

INTRODUCTION

The early Eocene was globally the warmest period of the Cenozoic (Zachos et al., 2001). Faunal and floral remains from western North America are consistent with this greenhouse climate (Wilf, 2000; Wing et al., 2000). The Green River Formation spans this interval and contains depositional cycles of lake expansion and contraction (Fig. 1) that may reflect periodic oscillations in precipitation and evaporation. We use the term cycle to describe repetitive sedimentary successions interpreted to represent lacustrine expansion and contraction. These cycles have been interpreted to record precession of the equinoxes and orbital obliquity (Bradley, 1929; Fisher and Roberts, 1991; Cole, 1998). Global circulation modeling suggests that during the Eocene, precession may have periodically forced ± 5 °C temperature shifts at high northern latitudes, a twofold variation of upwelling in extratropical regions of the Pacific, Atlantic, and Tethys Oceans (Sloan and Morrill, 1998), and, in western North America, oscillations in shortwave radiation large enough to affect evaporation (Morrill et al., 2001). To address these issues, we reexamined the cycles of the middle Wilkins Peak Member of the Green River Formation in Wyoming by using a combination of basin-scale stratigraphic correlations and ^{40}Ar/^{39}Ar dating of interbedded tuffs to determine permissible cycle durations.

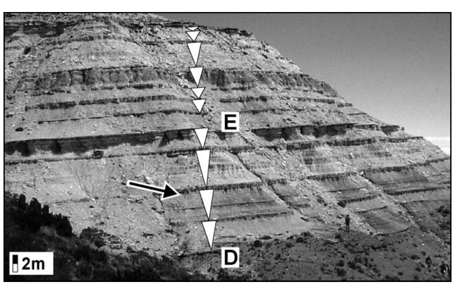

Figure 1. Lacustrine cycles at Apache Lane section (for location, see Fig. 2). Triangles mark cycles, and arrow points to position of Grey tuff. Arkosic marker beds D and E are labeled.

GEOLOGIC SETTING

The Wilkins Peak Member represents an underfilled, evaporative phase of Lake Gosiute when lake level remained below that of the outflow sill and was sensitive to subtle changes in basin hydrology (Carroll and Bohacs, 1999). An exposed transect from near the basin center to its margin along the western flank of the Rock Springs uplift enables individual beds to be traced continuously for $>$50 km; correlations were verified by several distinctive tuffs and sandstone marker beds (Fig. 2). Outcrop and core examination permitted the identification of cycles down to the decimeter scale, in contrast to previous studies that relied on lower-resolution indirect techniques such as Fischer assay (Roehler, 1993). Furthermore, our use of several laterally correlative sections reduces the misidentification or omission of cycles that may occur when relying on single or composite sections (e.g., Olsen, 1986; Steenbrink et al., 1999).

CYCLES

Cycles in the Wilkins Peak Member are asymmetrical (Fig. 3), with thin transgressive lithofacies at the base overlain by thicker regressive successions (Eugster and Hardie, 1975; Smoot, 1983). Typically 0.1–2.0 m thick, cycles are bounded by flooding surfaces and defined by six lithofacies related to specific stages of flooding or desiccation (Fig. 4). Lithofacies 1 comprises very fine grained to fine-grained calcareous sandstone with platy mudstone intraclasts. Beds typically contain wavy lamination that is inferred to reflect wave action. We interpret this lithofacies to record initial flooding and shoreline transgression, during which underlying mudstone facies were reworked. Lithofacies 2 and 3 are laminated organic-rich calcimicrites and massive calcimicrites, respectively, that were deposited during maximum lake expansion. Lithofacies 4 comprises interbedded dolomicrite, calcareous siltstone, and thin, very fine grained calcareous sandstone beds that were deposited as the lake shrank to form shallow, partly subaerial mudflats. Mudcracks abound in the micrite and siltstone beds, whereas nonparallel and wavy lamination and wave ripple marks are common in sandstone beds (Fig. 4). Lithofacies 5 is defined by authigenic minerals (e.g., shortite) formed within micrite and siltstone during evaporative concentration of overlying lake water (Bradley and Eugster, 1969). Lithofacies 6 is composed of bedded evaporite minerals, mostly trona and halite, that represent the terminal stages of lake desiccation.

STRATIGRAPHIC VARIABILITY

Figure 2 documents a general thickening of basin fill southward, corresponding to an increase of profundal lithofacies (2–3) and basin-center evaporites (5–6). In detail, numerous lake cycles that are apparent in the southern part of the section terminate to the north (Fig. 2). In the White Mountain #1 core we identified 42 cycles that occur between two regionally correlated time markers, the Grey and Main tuffs (Fig. 2). The number of cycles systematically decreases northward to 13 at Boar's Tusk. Below the H marker bed, many cycles terminate northward by lateral gradation into lake-margin facies (Fig. 4), rather than by onlap of a pre–Wilkins Peak Member surface as previously proposed (Roehler, 1993). In contrast, most cycles above this marker can be traced continuously for 50 km (Fig. 2). This upward change coincides with an abrupt increase of organic richness and more consistent cycle thicknesses, implying slower sedimentation and more uniform subsidence (Carroll et al., 2002). Several previous studies also concluded that maximum basin subsidence occurred early in the deposition of the Wilkins Peak Member (Steidtmann et al., 1983; Roehler, 1993; DeCelles, 1994).

Below the H marker bed, lower-amplitude lake-level rises were progressively filtered out of the stratigraphic record going northward. This implies either that accumulation rates decreased or that hiatuses increased northward, in response to the interaction of varying lake level with a south-dipping depositional gradient. Studies of Quaternary deposits have shown that playa lithofacies (4–6) can accumulate to three times more quickly than profundal lithofacies (2–3), suggesting that slow sedimentation rates are unlikely to have occurred in the northern Green River basin (e.g., Bobst et al., 2001). Furthermore, long-term accumulation rates for evaporative facies of the Wilkins Peak Member were higher than for fluctuating profundal facies of the Tipton and Laney Members (Carroll et al., 2002; Smith et al., 2003). Thus, we favor a northward increase in length and number of hiatuses within the upper parts of cycles and between cycles. Although the southernmost locations preserve a more complete temporal record, abundant lacunae are evident even there. Desiccation cracks below and mudstone intraclasts above cycle boundaries attest to periodic exposure of the entire basin floor for unknown periods. Moreover, vertisols that developed prior to deposition of several sandstone beds indicate relatively long periods of subaerial surface stability. A truly complete geochronologic record may not be available anywhere within the basin.

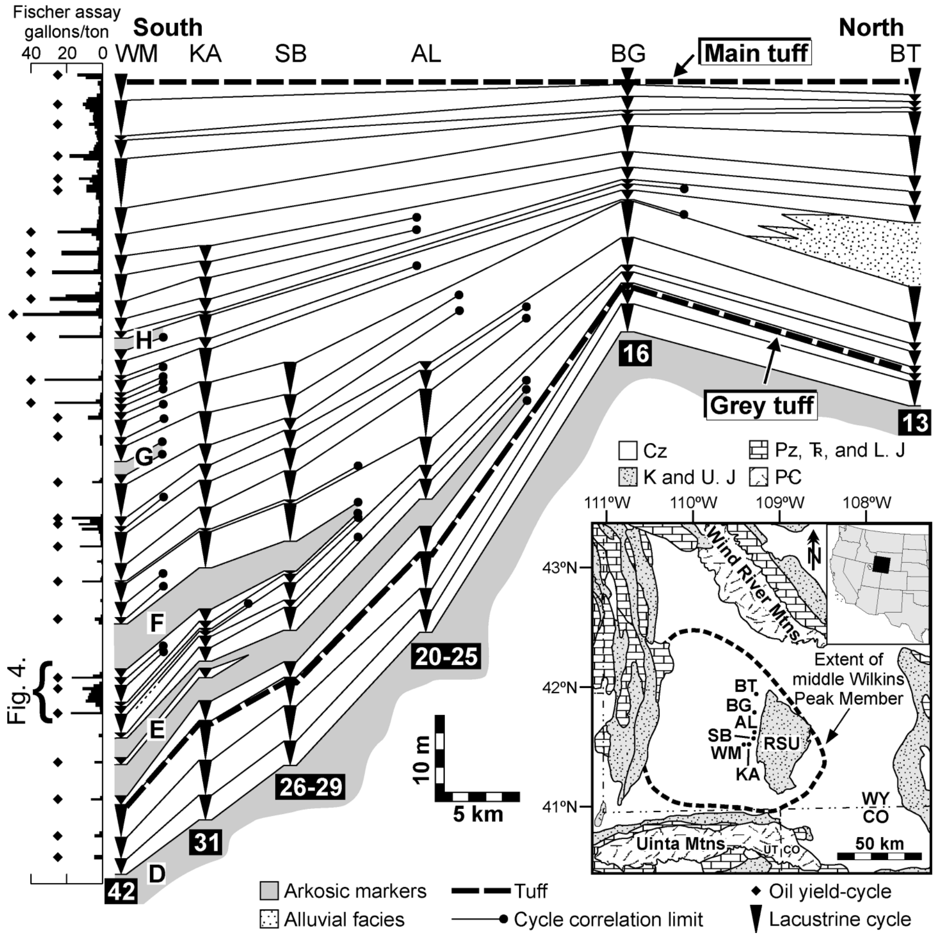

Figure 2. Correlation of cycles within middle Wilkins Peak Member of Green River Formation. See inset map (Witkind and Grose, 1972; Roehler, 1993) for locations. WM—White Mountain #1 core, KA—Kanda, SB—Stagecoach Boulevard, AL—Apache Lane, BG—Breathing Gulch, BT—Boar's Tusk. Values below each section refer to number of cycles recorded between Grey and Main tuffs. Fisher assay data are expressed as gallons of oil per ton of rock. D–H are marker beds. Cz—Cenozoic; K—Cretaceous; U. J—Upper Jurassic; PЄ—Precambrian; Pz—Paleozoic; Ꝭ—Triassic; L. J—Lower Jurassic.

ARGON GEOCHRONOLOGY

Tuff Description

To measure average cycle durations, $^{40}Ar/^{39}Ar$ ages for the Grey and Main tuffs were determined by laser fusion of sanidine phenocrysts (Smith et al., 2003). The Grey tuff, at the base of the section, is a 5-cm-thick ash located 5–10 m above the D arkosic sandstone marker bed and contains 10%–15% phenocrysts (Figs. 1, 2, and 3). The Main, or Third, tuff (Culbertson, 1961) is a 25-cm-thick bed containing 5%–10% phenocrysts. Both are composed of volcanic sanidine, biotite, plagioclase, and quartz with minor amphibole, pyroxene, and zircon in a matrix of altered glass. Neither tuff shows evidence of fluvial reworking; thus they are interpreted as primary air-fall deposits.

Analytical Techniques

Sanidine phenocrysts 75–150 μm in diameter were separated by crushing, heavy liquids, handpicking under refractive-index oil, air abrasion, and ultrasonic cleaning in 10% HF. Crystals were irradiated at Oregon State University where they received a fast neutron dose of $\sim 5–7.5 \times 10^{18}$ neutrons/cm^2. Fusion of crystals with a CO_2 laser, mass spectrometry, mass discrimination corrections, nucleogenic reactor corrections, and error propagation methods followed Smith et al. (2003). Mean ages were weighted by the inverse variance of each measurement and reported at the 2σ level. Uncertainty in the neutron fluence parameter J was 0.12%–0.24% on the basis of measurements of 28.34 Ma Taylor Creek Rhyolite sanidine standard crystals (Renne et al., 1998); this uncertainty was propagated into the final age for each sample. The Grey and Main tuffs yielded isochrons of 50.55 $\pm$ 0.21 Ma and 49.98 $\pm$ 0.09 Ma with $^{40}Ar/^{36}Ar$ intercepts of 285.7 $\pm$ 11.3 and 293.4 $\pm$ 6.4, respectively. No evidence of excess argon was present at detectable levels; thus we take the weighted mean apparent ages as the best estimate of time elapsed since eruption and deposition of the tuffs.

Results

Eighteen multigrain sanidine aliquots from the Grey tuff yielded a well-defined Gaussian distribution with a weighted mean age of 50.39 $\pm$ 0.13 Ma (2σ) and mean square of weighted deviates (MSWD) of 0.67 (Fig. 5). Similarly, 30 multigrain fusions of sanidine from the Main tuff yielded a weighted mean age of 49.96 $\pm$ 0.08 Ma (2σ) with an MSWD of 0.78 (Fig. 5). At the 95% confidence level, the time interval represented by strata between these two tuffs is 430 $\pm$ 150 k.y.

CYCLE DURATION

The apparent average cycle duration for the middle Wilkins Peak Member ranges from 33.1 $\pm$ 11.5 k.y. in the north to 10.2 $\pm$ 3.6

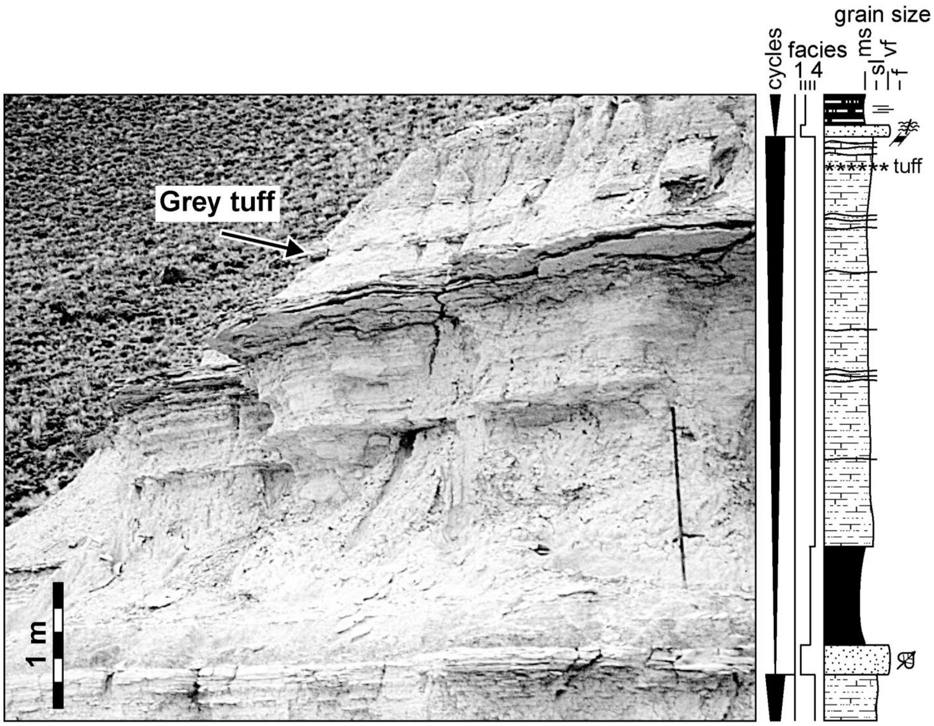

Figure 3. Asymmetric cycles in Wilkins Peak Member at Apache Lane section. See Figure 4 for explanation of symbols; ms—mudstone; sl—siltstone; f—fine grained; vf—very fine grained sandstone.

k.y. in the south. However, this estimate does not take into account the time required for deposition of sandstone marker beds, paleosol formation, hiatuses, or erosional surfaces. Therefore, 10.2 ± 3.6 k.y. represents a maximum average duration for discrete episodes of lake expansion as recorded in the southern part of the transect; the true duration is likely shorter.

These cycles cannot be directly correlated to the 19–23 k.y. precessional periodicity, although our finding does not exclude the possibility that precession or other longer-term orbital signals might be expressed in the overall vertical succession of beds. For example, spectral analysis of bed-thickness patterns may reveal the presence of longer-term, higher-amplitude cycles (e.g., Olsen, 1986; Olsen and Kent, 1999). Further, because the ~10 k.y. cycles are progressively filtered out toward the north, the dominant preserved mode at some locations may be precessional or longer. Another unresolved problem is the duration of cycles below the H marker bed versus those above. Because the durations of cycles above the H marker bed are approximately the same at all localities, there must exist at some localities a sharp discontinuity in cycle duration. This fact is not apparent from observation of any one section, implying that accurate interpretation of lacustrine cyclicity requires detailed knowledge of lateral stratigraphic variability.

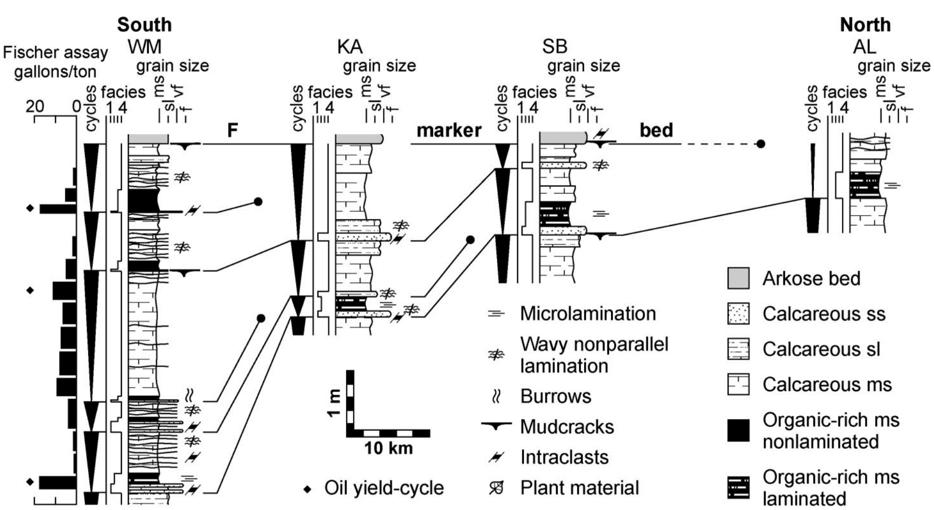

Figure 4. Correlation of measured sections highlighting termination of cycle boundaries into lake-margin facies. See Figure 2 for location and further explanation of symbols; ms—mudstone; sl—siltstone; f—fine grained; vf—very fine grained sandstone; ss—sandstone.

DISCUSSION

Climatic cycles of ~10 k.y. duration have not been previously identified in any Eocene strata and could indicate an unrecognized feedback among orbital forcing, climate, and configuration of the continents. In the Upper Cretaceous of the South Atlantic Ocean, a signal of approximately this frequency is thought to imply a nonlinear response to opposite extremes of the precessional insolation cycle (Park et al., 1993). Together with modeling, these observations suggest that a half-precession response occurs on or near continents that straddle the equator owing to parts of the continent receiving maximum sunlight during each solstice (Short et al., 1991). However, this mechanism is unlikely to apply to Eocene North America because of its northern position. The absence of glacial ice during the Eocene also precludes an explanation involving higher-frequency phenomena such as the ice-rafting episodes that occurred in the late Quaternary (Heinrich, 1988).

Several factors other than climate are known to cause rapid changes in lake level, including tectonic modification of drainage patterns (Sáez et al., 1999; Pietras et al., 2003), diversion of rivers by volcanic flows (Bouchard et al., 1998), and catastrophic failure of basin outlets (Malde, 1960). The first two tend to occur relatively infrequently and so probably cannot account for a regular repetition of facies. Periodic failure of a basin outlet might potentially recur with sufficient frequency if associated with breaching of a rising tectonic drainage divide, but the resultant lake-level drop would tend to expose basin-floor muds almost instantaneously (Malde, 1960), contradicting our observation of gradual desiccation (Fig. 4).

Another mechanism that has not been fully explored is drainage-network instability upstream of the lake. This geomorphic process, unrelated to a specific climatic signal, may promote autocyclicity of lacustrine facies by periodically altering runoff. Because Lake Gosiute was one of several large lakes that existed in western North America, the runoff it received was determined in part by the position of drainage divides between it and surrounding lakes. Physical modeling by Hasbargen and Paola (2000) suggests that natural

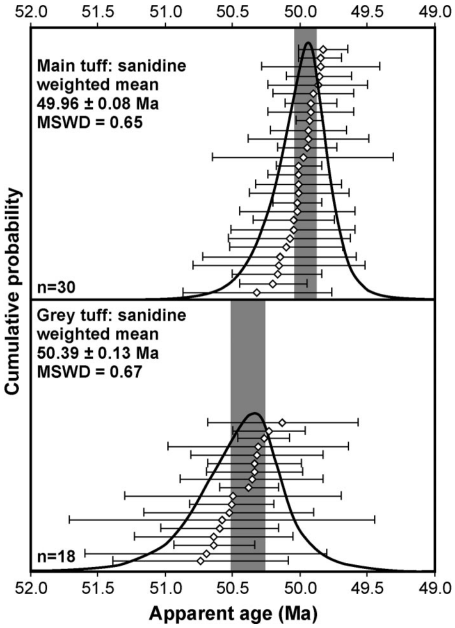

Figure 5. Cumulative-probability diagrams of $^{40}Ar/^{39}Ar$ ages for Grey and Main tuffs. Each diamond represents one multigrain age determination. MSWD—mean square of weighted deviates.

streams draining poorly lithified substrates may be characterized by continuous migration of ridges and valleys and autocyclic propagation of stream terraces. Moreover, this model produced significant variations in sediment discharge through time, which might result in depositional cyclicity at the fluvial terminus. An implication of this model is that the drainage divide between two adjacent closed basins might also experience considerable instability, which could result in a drastically altered hydrologic balance. This hypothesis could be tested by a careful comparison of the absolute timing of cycles in two adjacent lake basins to determine their relative phase.

CONCLUSION

Our approach demonstrates that $^{40}Ar/^{39}Ar$ dating in combination with high-resolution stratigraphy can directly test whether observed cyclicity occurs at a specific orbital frequency. Counter to both previous interpretations of the Green River Formation and predictions borne from global circulation modeling of Eocene climate, we find that the fundamental depositional units of the Wilkins Peak Member do not record precession-induced changes in climate. Detailed basin-wide correlation of several widely spaced outcrop sections further implies that relying exclusively upon one-dimensional records from individual drill cores or a composite section (e.g., Olsen, 1986; Fisher and Roberts, 1991; Roehler, 1993; Olsen and Kent, 1999; Steenbrink et al., 1999) may seriously misrepresent the amount of time recorded by lacustrine strata. Further work is needed to assess alternative, autocyclic mechanisms that may be regionally superimposed upon, or even overwhelm, relatively weak global climatic influences on sedimentation in large long-lived lakes.

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