Microstratigraphy of the Lower Mississippian Sunbury Shale: A record of solar-modulated climatic cyclicity

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ABSTRACT

Microstratigraphic analysis of the Sunbury Shale has yielded a high-resolution record of probable short-term climatic changes in the Early Mississippian central Appalachian basin. The formation is a laminated black shale that contains pervasive millimetre-thick couplets composed of alternating thin black and thick dark gray laminae, and decimetre-thick bands that are alternately dark and light. Total organic carbon content varies at length scales corresponding to both orders of cyclicity, and correlation of total organic carbon values to X-radiograph gray-scale densities permitted rapid stratigraphic analysis of millimetre-scale lithologic variation in the 5.0-m-thick formation. Spectral analysis of gray-scale density time series revealed strong power concentrations at intervals of 23 ± 2 and 70 ± 5 couplets. These results are interpreted to represent varved deposition of the Sunbury Shale modulated by the ~22 yr Hale and ~70–90 yr Gleissberg solar activity cycles. These cycles were probably recorded because of deposition in a stratified anoxic environment that was sensitive to short-term climatic fluctuations and subject to high sedimentation rates (4.5 mm/yr).

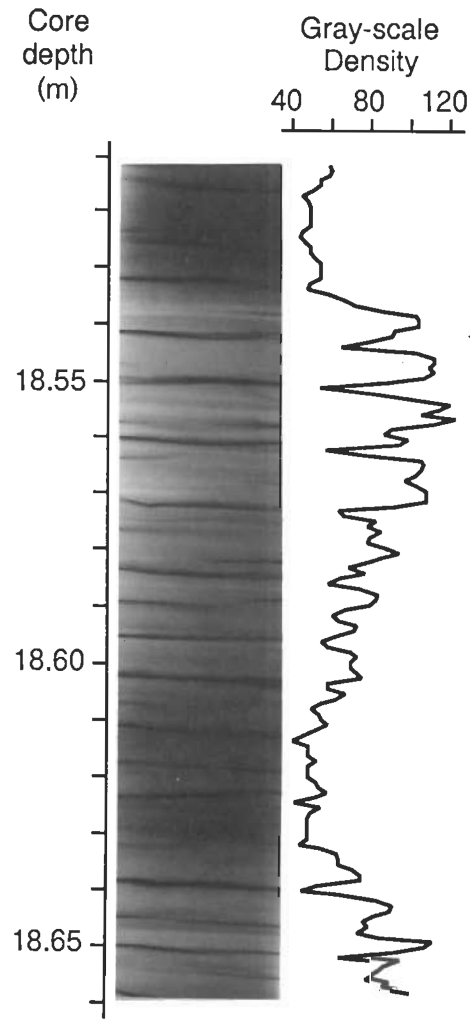

Figure 1. X-radiograph image of Sunbury Shale and corresponding gray-scale density (GSD) values from Kep-3 core. Paired gray and black laminae form couplets that are present throughout core and average 4.5 mm in thickness. Note decimetre-scale variation in GSD values, readily apparent as color variations of gray laminae in image.

INTRODUCTION

Variations in solar insolation as a result of orbital cycles have been shown to affect Earth's climate at time scales of 10^4–10^6 yr during the Pleistocene and older epochs (e.g., Imbrie et al., 1992). In contrast, the effect on climate of variations in insolation as a result of solar activity cycles at time scales of 10^0–10^3 yr remains a matter of considerable debate. The main issues are (1) the degree of coupling of solar activity cycles and terrestrial climate (Pecker and Runcorn, 1990, and articles therein; UNESCO, 1992), (2) mechanisms by which relatively small variations in solar radiative flux (~0.2%–0.4%) may be amplified in Earth's atmosphere (Panel on Solar Variability, Weather, and Climate, 1982; Reid and Gage, 1988; Wigley, 1988; Fröhlich, 1993), and (3) the existence of long-period (>100 yr) solar activity cycles commonly cited as a potential cause of major climatic fluctuations such as the Little Ice Age (e.g., Foukal, 1990). Because of the short length and variable reliability of modern climate records, paleoclimatic proxy records are potentially of considerable importance in understanding solar-climatic links.

To date, the stratigraphic record has contributed relatively little to these debates because of a paucity of well-documented examples of solar-modulated sedimentary cyclicity. Modern and ancient anoxic basins commonly accumulate varved black shales (e.g., Anderson and Dean, 1988; Peterson et al., 1991; Ripepe et al., 1991), but sedimentation rates are typically rather low (<1 mm/yr), presenting difficulties in resolving annual layers (e.g., Crusius and Anderson, 1992). In this paper, we document a high-resolution record of probable short-term climatic variation in the Lower Mississippian Sunbury Shale of the central Appalachian basin. We studied this laminated black shale formation in the Kep-3 core from Lewis County, Kentucky, over its entire 5.0 m thickness (except for a medial 0.6 m gap due to prior sampling). We determined cycle frequencies using time-series analysis of gray-scale densities (GSD) of core X-radiographs (Fig. 1). Our ability to resolve high-frequency events in this ~360 Ma unit is due to the unusual thickness of lamina couplets within the formation (averaging 4.5 mm), apparently a result of high sedimentation rates in the central Appalachian basin during Sunbury time.

STRATIGRAPHY AND PALEOGEOGRAPHY

The Sunbury Shale is a black, finely laminated, carbonaceous shale of Early Mississippian (Kinderhookian) age that contains 25%–30% quartz silt, 40%–50% clay (illite, mixed-layer I/S, chlorite, mixed-layer S/C), 5%–20% organic matter, 5%–10% pyrite, and 1%–3% authigenic minerals. The formation exhibits cyclicity at two scales: (1) millimetre-thick lamina couplets, and (2) decimetre-scale banding (Figs. 1, 2). Laminae are found in pairs that are alternately thin (~0.1–0.5 mm) and black, and thick (~3–6 mm) and dark gray to black (for brevity, termed "black" and "gray" laminae, respectively). Decimetre-scale banding is visible in X-radiographs as color variations and in outcrop as a ribbed pattern reflecting variable weathering resistance (Fig. 2).

The Sunbury Shale was deposited in the central Appalachian basin, located between lat 15° and 30°S during the Early Mississippian (Witzke and Heckel, 1988). At this time, the Appalachian basin had a Mediterranean-type tropical dry climate, and the Acadian Mountains to the east and northeast may have exerted a rain-shadow effect that contributed to seasonal precipitation (Woodrow, 1985). Clastic material originated mainly in turbidites emanating from the Catskill Delta front to the northeast (Potter

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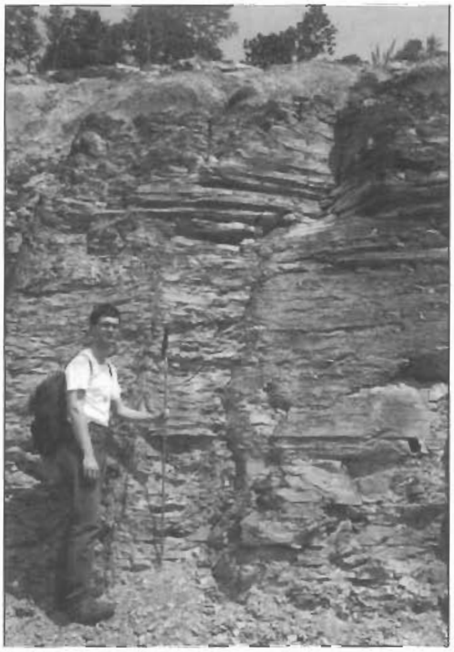

Figure 2. Decimetre-scale
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METHODS AND RE

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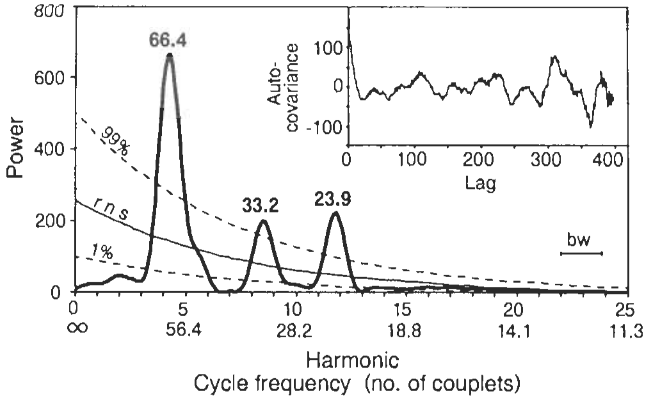

Figure 4. Smoothed power spectrum of auto-covariance function (inset) of GSD series of lower core interval (Fig. 3B). Rns is model red-noise spectrum; 1% and 99% are significance levels; bw is bandwidth of filter used in smoothing raw power spectrum. Frequencies of major peaks (as number of couplets) indicated in bold type.

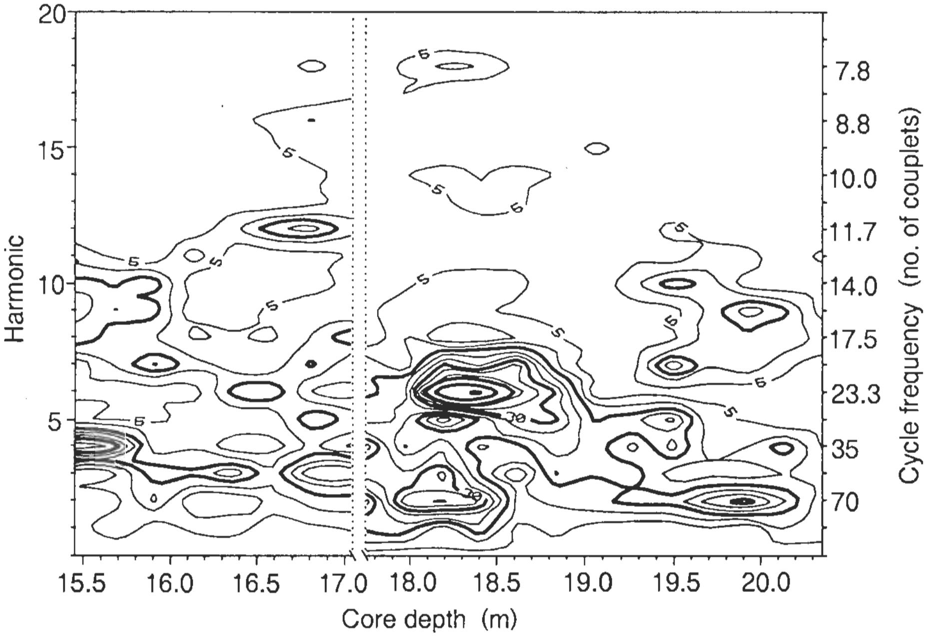

Figure 5. Power spectral contour map, constructed from 8 and 13 equally spaced power spectra for upper and lower core intervals, respectively; calculated by using 140-couplet sliding window, shifted 35 couplets per analysis. Window width was defined as fixed number of couplets rather than as fixed length to permit construction of frequency scale in couplets per cycle. Interval for light contours is 5 power units; for heavy contours, 15 power units.

an origin. With regard to potential allocyclic controls on Sunbury Shale deposition, the frequency ratios between decimetre- and millimetre-scale cycles (i.e., 1:23 ± 2 and 1:70 ± 5) are incompatible with Milankovitch-band processes (e.g., Imbrie et al., 1992) but consistent with climatic forcing at decadal time scales by known solar activity cycles (e.g., Foukal, 1990).

The most fundamental solar activity cycles are the 11 yr Schwabe, 22 yr Hale, and ~70–90 yr Gleissberg cycles. Schwabe cycles are characterized by variation in sunspot number and by latitudinal migration of solar eminences (e.g., flares and faculae). During successive 11 yr Schwabe cycles, the solar magnetic field is alternately of normal and reversed polarity, producing 22 yr Hale cycles. These cycles have been identified in records of drought in the western United States, surface air temperatures from North America, England, and the rest of the world, and 30 mbar Arctic air temperatures (Currie, 1974; Schönwiese, 1978; Mitchell et al., 1979; Labitzke, 1987). Gleissberg cycles reflect quasi-periodic expansion and contraction of the solar diameter (Gilliland, 1981) and have been identified in records of sunspot cycle amplitudes, auroral sightings, tree-ring ^{14}C values, ice-core $\delta^{18}O$ values, and sea-surface temperatures (Johnsen et al., 1970; Feynman and Fougere, 1984; Reid and Gage, 1988; Stuiver and Brazunias, 1988; Foukal, 1990). The period of the Gleissberg cycle is not well known; it has been estimated at 76 ± 8, 78, and 88 ± 1 yr (Johnsen et al., 1970; Gilliland, 1981; Feynman and Fougere, 1984).

Although solar activity, climate, and sedimentary records are known to exhibit variation at similar time scales, causal connections remain speculative. One enigma is the mechanism by which relatively small changes in solar irradiance (~0.2%–0.4% over a 22 yr Hale cycle; Fröhlich, 1993) become amplified into much larger climatic changes. Response of the upper atmosphere to variations in incoming solar radiation is rapid and of large magnitude, but coupling to the denser lower atmosphere is poorly understood (Panel on Solar Variability, Weather, and Climate, 1982). Direct radiative effects on surface heating may exist (Reid and Gage, 1988), but the relation is complex because of disequilibria related to thermal inertia of the oceanic-atmospheric system and to nonlinear climatic response to solar forcing as a result of internal atmospheric dynamics (Gilman, 1982; Wigley, 1988). A commonly postulated solar-climate connection invokes forcing through slight warming or cooling trends in the lower atmosphere (e.g., Friis-Christensen and Lassen, 1991).

Identification of frequency ratios consistent with solar activity cycles is prima facie evidence that Sunbury lamina couplets may be varves (Fig. 1). Annual depositional rhythms would imply similarity of the Sunbury depositional environment to that of many modern anoxic basins in which laminated organic-rich muds are accumulating—e.g., the Black Sea, Cariaco basin, or Gulf of California. In these basins, thick organic-poor laminae are commonly deposited during spring runoffs and thin organic-rich laminae during summer phytoplankton blooms (e.g., Hay et al., 1990; Cooper and Brush, 1991). Decade-scale correlations between climate and sedimentation have also been reported from modern anoxic basins (e.g., Soutar and Crill, 1977; Peterson et al., 1991). In the Sunbury Shale, such correlations are evidenced by decimetre-scale covariance between TOC values, sedimentation rates, and organic carbon accumulation rates (Table 1). Although negative covariance of TOC and sedimentation rates might imply dilution of organic carbon by clastic influx, negative covariance of sedimentation and organic carbon accumulation rates requires that clastic influx (or some covarying factor) actively depressed the production or preservation of organic carbon in the Sunbury depositional environment. Likely covarying factors are increased dissolved-oxygen levels with increased freshwater runoff, resulting in an increase in oxidation of organic matter in the water column, or decreased water temperature or salinity with increased runoff, resulting in a decline in primary productivity. Although mechanisms for solar forcing remain speculative, one possible scenario is that solar activity cycles inter-

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