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 thin dark and thick dark grey laminas, sub-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-ray diffraction data permitted rapid stratigraphic analysis of millimetre-scale lithologic variation in the 5.0-m thick formation. Spectral analysis of grey-scale density time series revealed strong power concentrations at intervals of 23 ± 2 and 79 ± 3 couplets. These results are interpreted to represent secular and cyclical fluctuations in the Sunbury Shale. 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), presenting difficulties in resolving annual layers (e.g., Cusack 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 Keg-1 core from Lewis County, Kentucky, over its entire 5.0 m thickness (except for a 0.6 m gap due to prior sampling). We determined cycle frequencies using time-series analysis of grey-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 laminae coupled with the formation’s (averaging 4.5 mm) apatite, a result of high sedimentation rates in the central Appalachian basin during Sunbury time.

INTRODUCTION

Variations in solar insolation as a result of orbital cycles have been shown to affect Earth’s climate at time scales of 10^3-10^4 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 10^2-10^3 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; Wigglesworth, 1986; 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 occur in varved black shales (e.g., Anderson and Dean, 1988; Peterson et al., 1991; Rippey et al., 1991), but sedimentation rates are typically rather low (<1 mm/yr). Present address: Department of Geological Sciences, University of Southern California, Los Angeles, California 90089-0749

Figure 1. X-raylograph Image of Sunbury Shale and corresponding grey-scale density (GSD) values from Keg-1 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 grey laminae in image.

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 illite-smectite, kaolinite, mixed-layer 2:1, 5%–20% organic matter, 5%–10% pyrite, and 15%–25% bituminous minerals). The formation exhibits cyclicity at two scales: (1) millimetre-thick laminae couplets, and (2) decimetre-scale banding (Figs. 1, 2). Laminae are found in pairs that are alternately thin (~0.1–0.5 mm) and thick (~3–6 mm) and dark grey to black for breccy, termed "black" and "gray" laminae, respectively. Decimetre-scale banding is visible in X-radiographs as color variations and in outcrop as irregular pattern reflecting variable weathering resistance (Fig. 2).

The Sunbury Shale was deposited in the central Appalachian basin, located between lat 35° 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 Cask Ski Delta front to the northeast (Potter.

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METHODS AND RESULTS
Successful outcomes

Figure 3. GSD deviation per 1 m (A) and core intervals [cm] based on a priori geophysical and geological scale values corresponding to rock density and gas hydrate concentration. The TOC ci Kresling graph line is in black.
The most fundamental solar activity cycles are the 11 yr Schwabe, 22 yr Hale, and 70-300 yr Gleissberg cycles. Schwabe cycles are characterized by variation in sunspot number and by latitudinal migration of solar minima (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 droughts in the western United States, solar surface temperatures from North America, England, and the rest of the world, and 30 mbar Arctic air temperatures (Currie, 1978; Schiwinski, 1978; Mitchell et al., 1979; Lubin, 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 14C values, ice-core k18O values, and sea-surface temperatures (Johnsen et al., 1979; Fryman and Fougeré, 1984; Reid and Gage, 1988; Stuiver and Braarud, 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., 1979; Gilliland, 1981; Fryman and Fougeré, 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) could become amplified to 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 deeper lower atmosphere is poorly understood (see Variability, Weather, and Climate, 1982). Direct radiative effects on surface heating may exist (Reid and Gage, 1988), but the relationship is complex because of disquilibria related to thermal inertia of the ocean-atmospheric system and to nonlinear climatic response to solar forcing as a result of internal atmospheric dynamics (Gilliland, 1982; Wigley, 1988). A commonly postulated solar-climate connection involves forcing through slight warming or cooling trends in the lower atmosphere (e.g., Friss-Christensen and Lasen, 1991).

Identification of frequency ratios consistent with solar activity cycles in proxy records is a key finding in this study. Sunspot minima coupled with maxima in insolation—e.g., the Black Sea, Carlsco basin, or Gulf of California—must be interpreted as coincidental accumulation of organic-rich muds, which is illuminated by the long-term climatic response to solar forcing. The new evidence of solar forcing on organic accumulation in these basins supports the hypothesis that organic-rich sediments are deposited during solar minima.

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 164-couple sliding window, shifted 35 coupled points per analysis. Window width was defined as fixed number of coupled points, such as fixed length to permit construction of frequency scale in coupled points per cycle. Interval for light contours is 5 power units; for heavy contours, 15 power units.
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