Seasonal Resolution of Laminated Sediments in Santa Barbara Basin: Its Significance in Paleoclimatic Studies

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Sediments in Santa Barbara Basin contain microfossil and sedimentological information that allows reconstruction of major features of the California Current such as water temperature, strength of upwelling, and productivity. Changes in the California Current are correlated with the climatic pattern in the North Pacific, and with rainfall in Southern California (Namias 1975). The Santa Barbara Basin underlies a very productive coastal ocean and is characterized by high sedimentation rates (>2 mm per year). Oxygen depletion in the near-bottom waters inhibits bioturbation by macrobenthos and allows for preservation of discrete laminae. The varves (light/dark lamina pairs) originate from seasonal variations in the composition of particles supplied to the basin floor and from change in bottom water conditions associated with seasonal flow in the California Current (Soutar and Crill 1977; Reimers *et al* 1990). Episodic events within seasons (*eg*, diatom spring blooms) are preserved as distinctive microlaminations within seasonal laminae. Several microfossil paleoclimatic indicators (diatoms, forams, radiolarians) have been used by our group at the Scripps Institution of Oceanography and by colleagues at other institutions to reconstruct decadal variability in the California Current system (see review in Fisher 1990, and Lange *et al* in press).

Until now, investigations of Santa Barbara Basin sediments have utilized analytical techniques that could not resolve seasonal laminae, permitting annual resolution of variations in sediment composition and structure only. With the exception of a study in 1988, no seasonal resolution of the sedimentary record has been attempted. The 1988 data on biogenic and detrital components indicate that seasonality is strong in the Santa Barbara Basin, with episodic events of the order of days to weeks (Reimers *et al* 1990).

Based on a successful technique for preparation of epoxy-embedded and highly polished thin-sections (Spurr 1969; Kemp 1990; Grimm 1992a) that permit economical optical and electron microscope evaluation of laminated sequences, it is our long-term goal to reconstruct, with unprecedented detail, the history of sedimentation processes in the Santa Barbara Basin by developing ultra-high-resolution time series of biotic and detrital proxies.

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Material and Methods

This pilot study focuses on a sediment interval from about 1825 to 1849, including the *Macoma* shell layer, for which we have detailed information from an earlier study (Schimmelmann *et al* 1992). Subsequent to X-radiography of the original sediment slab to be studied (Figure 1), sectioning of it into rectangular "blocks" of about 4x3x1 centimeters was necessary for sizing of thin sections. Saline pore water was removed in a sequence of baths, first with 50:50 acetone/water, then acetone, and finally with a 4-component epoxy-resin (Spurr low-viscosity embedding media, Polysciences, Inc.; Spurr 1969). The resulting epoxy-embedded "blocks" were cured for 2 weeks at 50° to 70°C. Finally, thin sections were made at the Scripps Analytical Facility, including polishing the epoxy block with 1 μm diamond grit and then mounting it onto a 7x5-cm glass slide. The block is cut (perpendicular to bedding) to about 200-μm thickness, then ground to 45-μm thickness in a lapping and optical polishing machine (Logi-Tech LP 30), using a 600-μm silicon carbide grit and water slurry, and followed by polishing steps with 6-μm and 3-μm diamond, and 0.05-μm alumina in ethylene glycol to 35 μm final thickness.

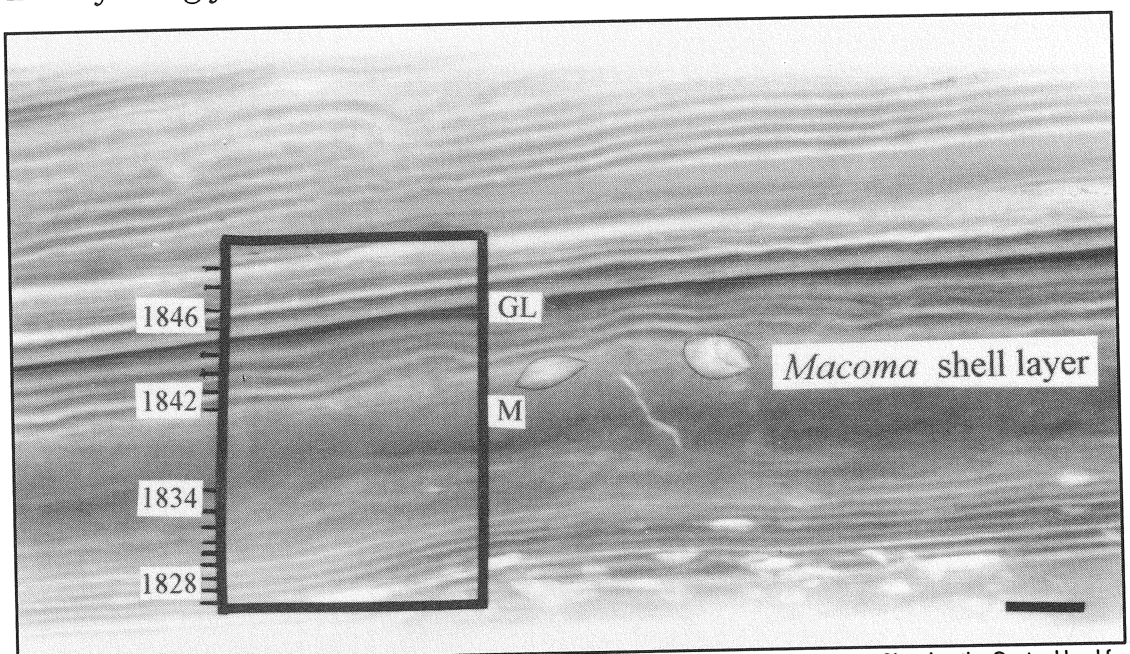

Figure 1. Contact Print of X-Radiograph of the Area Across the *Macoma* Shell Layer, AD 1825-1849, Showing the Sector Used for Preparation of Thin Sections.
A few dates are added as guidelines.
M = Macoma shell layer; GL = gray layer of 1845. Scale at bottom right is 1 cm.

Thin sections were first examined with light microscopy with bright field illumination. For electron microscopy analysis, they were mounted on conductive stubs and carbon coated in vacuum. We used a Cambridge 360 electron microscope equipped with an X-ray detector and associated energy-dispersive analytical system (EDS) for chemical analysis of the composition of selected samples.

Each thin section encompasses about 20 to 25 years of record (Figure 2). The thin sections are easily and unambiguously correlated stratigraphically with our existing sediment X-radiography varve record (continuous from about AD 900 to 1988).

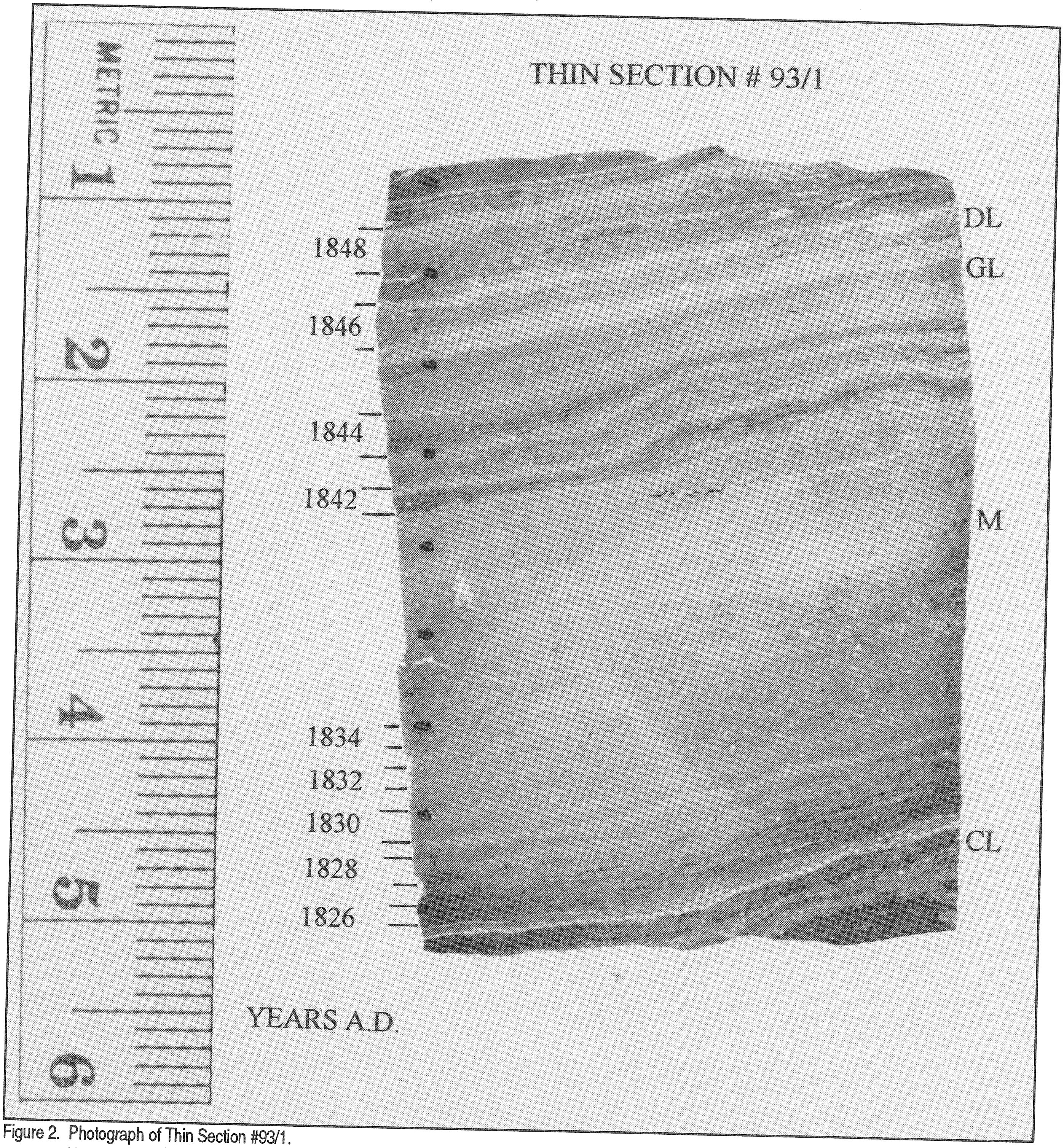

Figure 2. Photograph of Thin Section #93/1.
Varve chronology is marked on left, AD 1825-1849.
Layers: CL = *Chaetoceros*, DL = diatom-rich (abundant *Coscinodiscus*), GL = gray, M = *Macoma*; details of CL and GL are shown in Figures 4 and 5.
Scale in centimeters.

Results and Discussion

Observation of thin sections with light microscopy provided for sample reconnaissance (like an ordinary petrographic thin section). Photomicrographs were taken as a first overview of laminated *vs.* non-laminated sectors within the selected interval to study (Figure 3).

High-resolution analysis of laminae was achieved with an electron microscope in the back-scattered electron mode (Kemp 1990; Grimm 1992a). Grain types in this mode can be differentiated by their morphology and brightness characteristics (Pye and Krinsley 1984; Krinsley and Manley 1989).

The images permit detailed compositional assessment of discrete laminae. Intra-annual/intra-seasonal events can be evaluated, and the nature and origins of the laminae can be determined. For example, laminations rich in diatom spores of the genus *Chaetoceros* are produced by spring blooms. Fine-grained laminae (clay-rich) that contain sparse biogenic grains alternate with biosiliceous-rich ones. The former emerge from winter, low-biomass conditions (Reimers *et al* 1990) and could be attributed to seasonal pulses of enhanced riverine input.

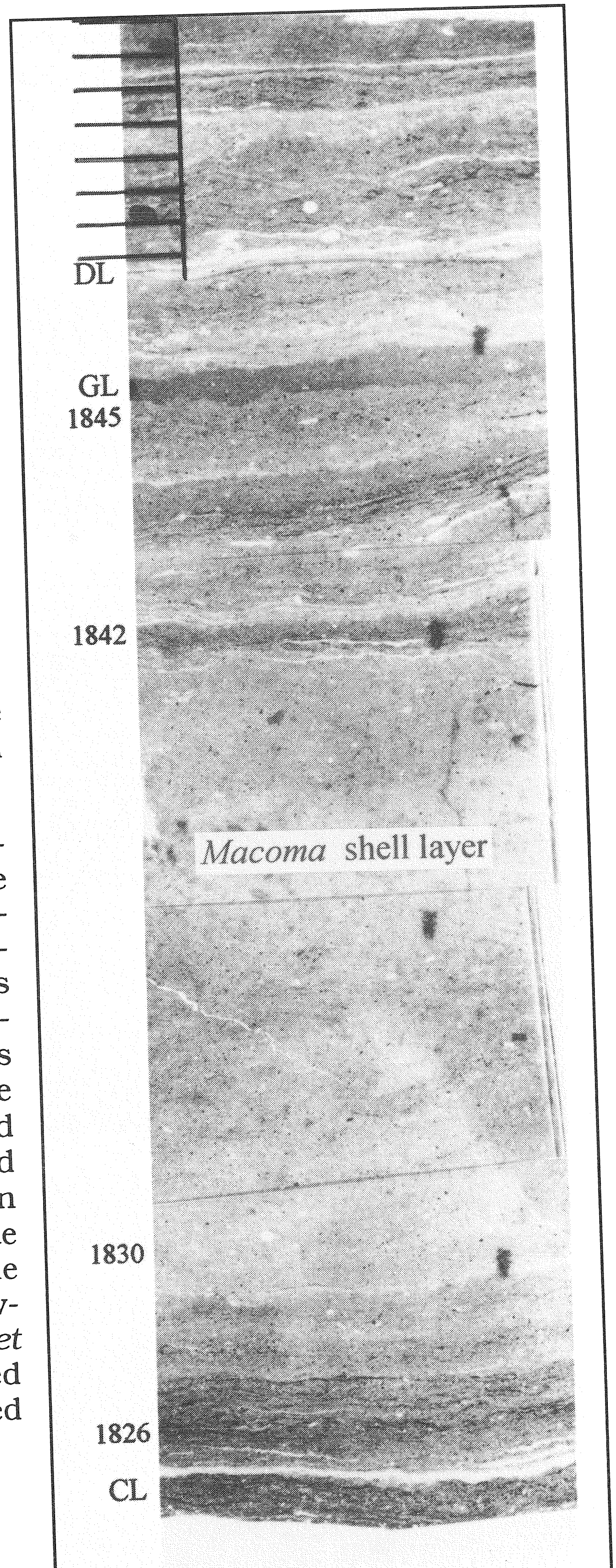

Figure 3. Photomicrograph Composite of the Left Half of Thin Section Shown in Figure 2 Viewed with Bright Field Illumination.
A few dates are added as guidelines.
Abbreviations as in Figure 2.
Scale in upper left corner: the space between tickmarks is 1 mm.

Figure 4 shows a sub-millimeter (typically 100 to 200 micrometers thick) lamination composed of *Chaetoceros* resting spores, mainly *C. debilis*. *Chaetoceros* resting spore laminae are a distinctive lamination type. We interpret them as a single episode of mass flux at the termination of a local phytoplankton bloom. Diatom resting spore flux events are common at the end of an upwelling pulse, when standing stocks are high and availability of dissolved limiting nutrients is low (Smetacek 1985). Spore formation and consequent mass sinking is regarded as an optimal reproductive strategy favoring survival of phytoplankton populations (Smetacek 1985; Garrison 1981; Pitcher 1990).

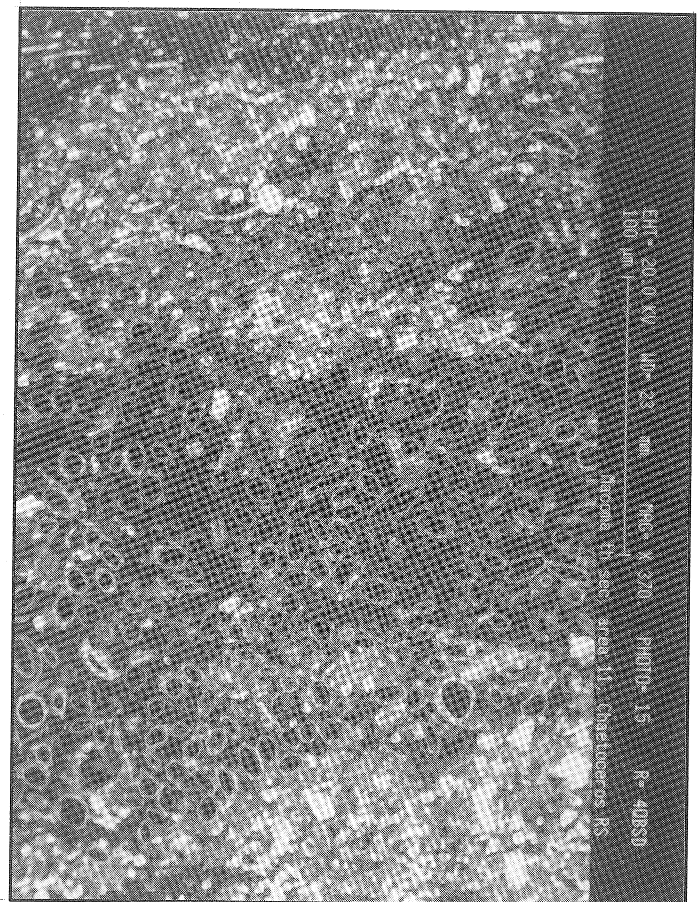

Figure 4. Back-Scattered Electron Image of a Polished Section of Epoxy-Embedded Sediment Showing a Distinct Microlamina Composed of *Chaetoceros* Resting Spores.
The individual spores are between 8 and 25 μm in diameter.
Scale is 100 μm (vertical bar on right side of picture).

In addition to the rythmic alternations of clay-rich and microfossil-rich laminae, discrete laminations of gray silty clay to clayey silt named "gray layers" because of their color (Munsell chart 5Y 5/1), are scattered throughout the laminated sections in the Santa Barbara Basin. They range from millimeters to decimeters in thickness, typically between 1 millimeter and 5 centimeters. Gray layers may result from rapid redeposition of sediment from the upper slope triggered by factors internal to the fan system or to its riverine sources (Thornton 1986). They can be considered instantaneous depositional events whose frequency and local thickness are chiefly controlled by internal mechanisms, with climate playing only a minimal role. Identification of thin, "varve-like" gray layers is necessary to avoid erroneous varve-counts. A 1-mm-thick gray layer was recognized within the 1845 varve; BSEM photo- micrographs are shown in Figures 5 and 6. X-ray microanalysis showed richness in aluminum (Figure 7) in addition to the very strong peak in Si, which is a common feature of every lamina (Figure 8).

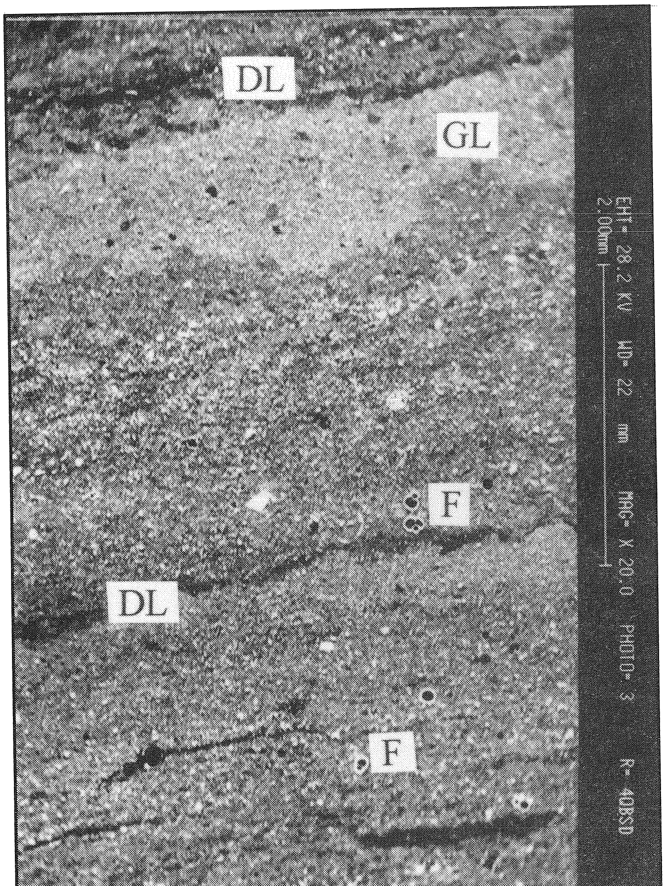

Figure 5. Back-Scattered Electron Image of a Polished Section of Epoxy-Embedded Sediment Showing Fine Detail of Laminations Defined by Differences in Composition.
The impregnating resin shows up black. The pale layer at top is a gray layer (GL) about 1 mm thick. The darkest laminations over the gray layer and at about 2 mm below it are diatom-rich, with *Chaetoceros* and *Coscinodiscus* representatives (DL). The medium dark laminations beneath the gray layer include a mixture of diatoms, coccoliths, silicoflagellates, radiolaria and foraminifers. The small black objects with a white outline are planktonic and benthic foraminifers (F).
Scale is 2 mm (vertical bar on right side of picture).

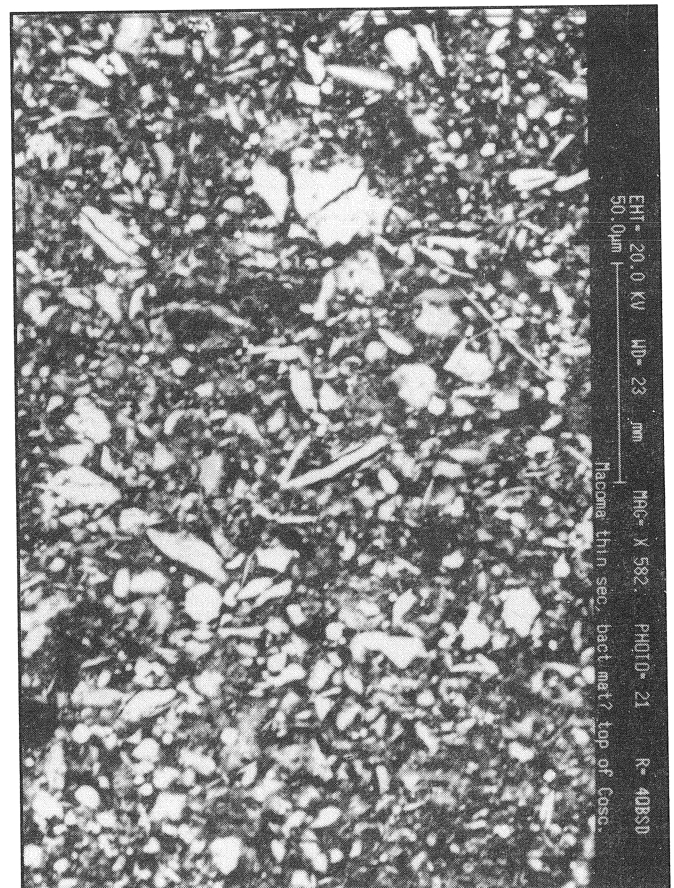

Figure 6. Detail of Gray Layer Showing the Fine-Grained Mineral Composition.
Note the absence of microorganisms.
Scale is 50 µm (vertical bar on right side of picture).

Conclusion

Visual analysis of epoxy-impregnated and highly-polished samples is a fairly new methodological approach for hemipelagic sediments (Kemp 1990; Grimm 1992a, b; Kemp and Baldauf 1993). Applying this methodology to 19th century Santa Barbara Basin laminated sediments permitted detailed compositional assessment of individual lamina to deduce the mechanisms of its formation. It also permitted greatly improved accuracy of dating of 19th century varves, to within 0.5 year. This approach is significantly faster and offers higher resolution than techniques involving wet chemistry and handling of manually-sectioned sediment intervals that have provided us with our 600-year "background record" of previous investigations. Both approaches, used together, will permit attainment of seasonal resolution time series on a level of detail never attempted before and will provide crucial evidence of intra-annual and inter-annual sedimentation fluctuations in the Santa Barbara Basin.

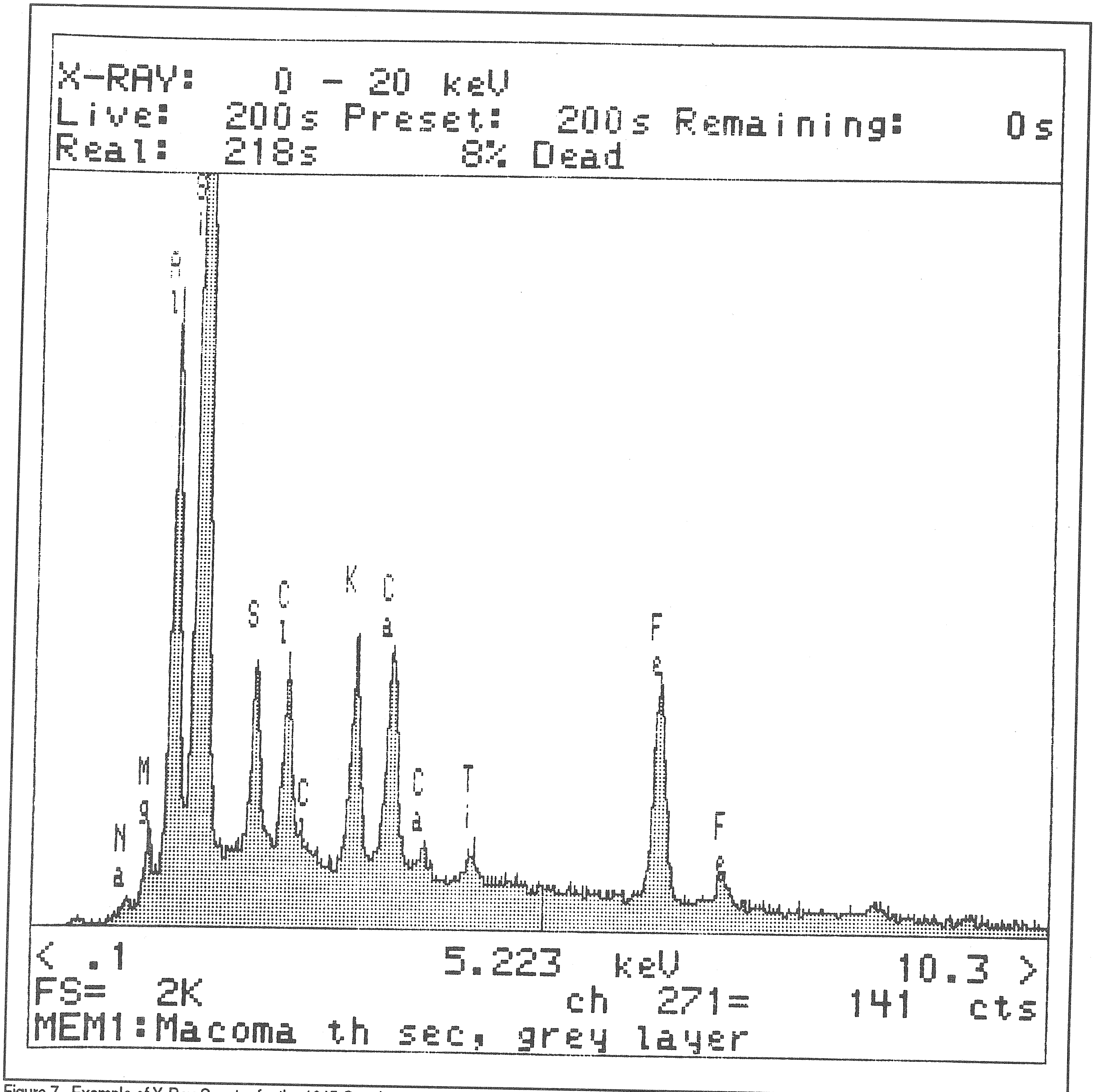

Figure 7. Example of X-Ray Spectra for the 1845 Gray Layer.

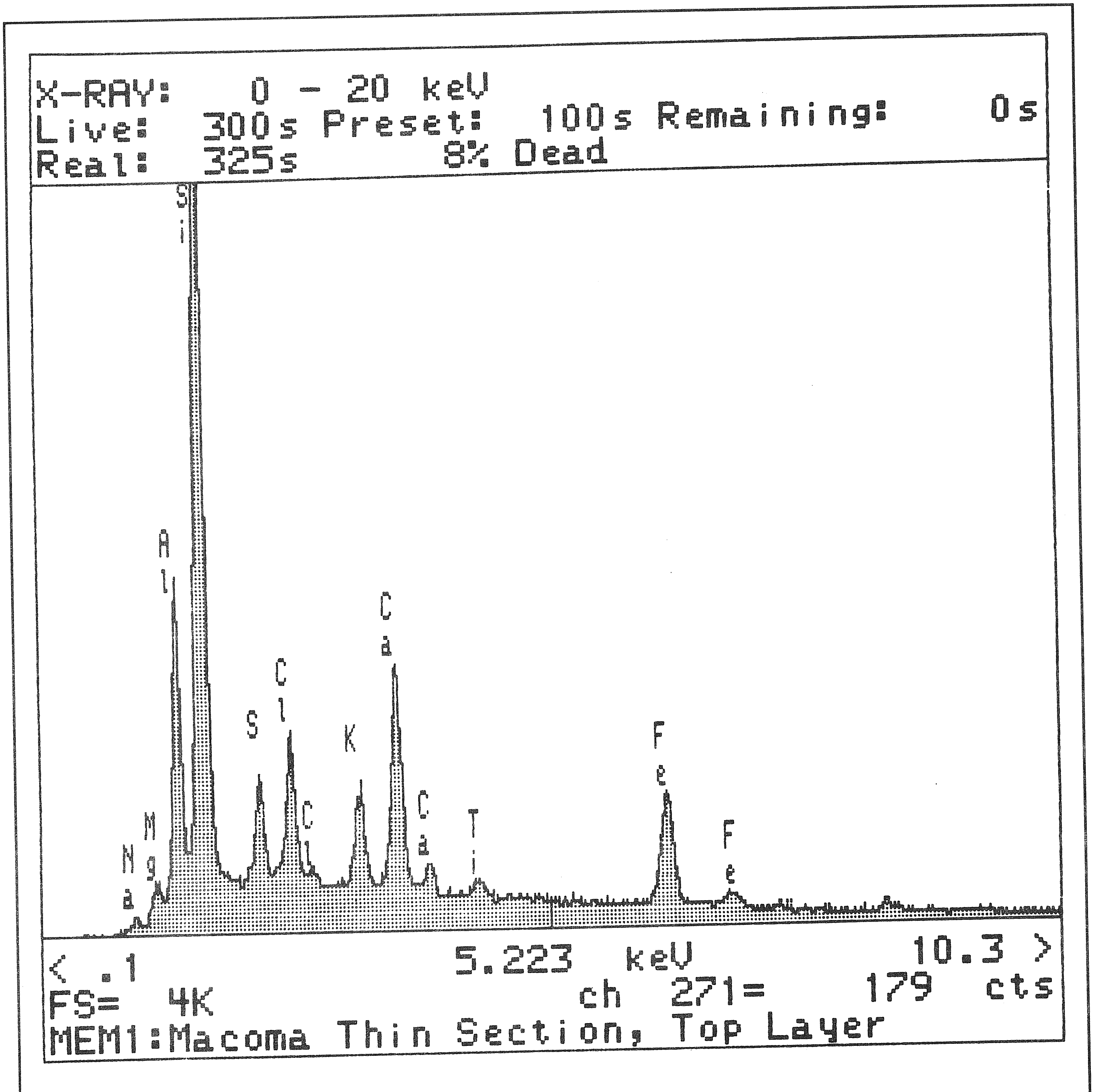

Figure 8. Example of X-Ray Spectra for the Light Lamina of the Year 1848.

Acknowledgments

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