HIGH-RESOLUTION X-RADIOGRAPHY OF LAMINATED SEDIMENT CORES

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INTRODUCTION

Laminated sediments commonly contain significant information on the depositional history of a rock unit at a millimeter or submillimeter scale (e.g., Anderson 1984; Williams 1989; Peterson et al. 1991; Ripepe et al. 1991). However, analysis of fine-scale lithologic or geochemical variation over thick stratigraphic intervals is labor-intensive (e.g., Bertrand and Lallier-Vergès 1993) unless automated in some way. X-radiography provides a means of rapid characterization of lithologic variation in laminated sediments, but conventional techniques do not offer millimeter-scale resolution without extensive, and commonly destructive, sample preparation. We have developed a method for production of high-resolution X-radiographs of laminated sediment cores that requires no slabbing or other forms of sample preparation and that yields uniform exposure and resolution along the length of a core. The method uses a conventional X-ray oven, or Faxitron, and a custom-built traveling core stage.

X-RADIOGRAPHY

X-radiography has been widely used in studies of sediment fabric and fine-scale stratification (e.g., Nuhfer et al. 1979a; Soutar et al. 1982; Kravitz 1985; McKinsey and Kepferle 1985; Lyons 1991; Schimmelmann et al. 1992; Ingall et al. 1993). In the conventional procedure, film is placed beneath a rock slab or core, and the entire sample is exposed to X-rays from an overhead point source for a fixed period of time. In the resulting X-radiographs, compositional variation and sedimentary structures are manifested as variations in gray-scale density (GSD) caused by differences in density of the rock matrix. Denser (less dense) areas of a sample of uniform thickness appear lighter (darker) owing to reduced (increased) X-ray penetration.

Resolution in X-Radiograph Images

The utility of X-radiography in any geologic study depends on the ability to resolve features of interest. Because absorption of X-rays is integrative, overlap of features of contrasting density within a sample has a deleterious effect on the resolution of X-radiograph images. Although thin-slabbing can enhance small, nonpenetrative features of interest (e.g., ichnofossils), this is unnecessary in laminated sediment cores owing to the generally penetrative character of individual laminae. In such cores, the length scale of resolution r is largely a function of sample thickness t and the angle of incidence of X-rays relative to stratification (α):

$$r = t \cdot \tan(\alpha) \qquad (1)$$

Conventional X-radiography of a sample with vertically oriented laminae (e.g., a slabbed core positioned face down) causes r to vary from zero directly beneath the X-ray source to a maximum value at the ends of the sample, resulting in progressively greater smearing and loss of resolution from the center outward (Fig. 1A). Given a working distance D of 60 cm and $\alpha_{max} \approx 15°$ (as in standard Faxitrons), a sample thickness t of 2.5 cm yields a range of resolutions from 0 to 3.3 mm (Fig. 2A). Thus, laminae thinner than 3–4 mm are not resolved at the
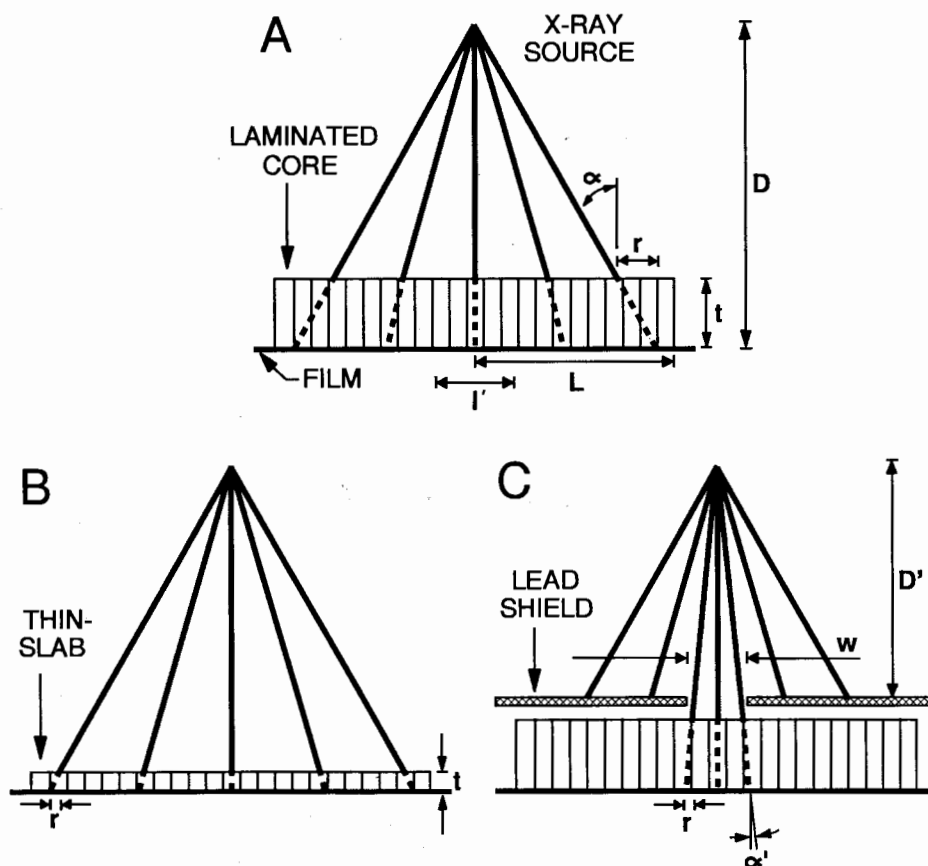

FIG. 1.—Comparison of different methods of X-radiography. In the conventional procedure (A), a rock slab or length of core is X-rayed in its entirety. Resolution r equals $t\tan\alpha$, or tL/D, where t is sample thickness, α is angle of incidence of X-rays relative to stratification, L is the half length of the sample, and D is the working distance. Considerable loss of resolution occurs at the ends of thick samples owing to high values of α. Resolution can be substantially improved by decreasing sample thickness (B) or by constraining the range of incident angles using a windowed lead shield (C). In the latter case, resolution r equals tw/D', or $t\tan\alpha'$, where w is window width, D' is the reduced working distance, and α' is the decreased maximum incident angle of X-rays relative to core stratification.
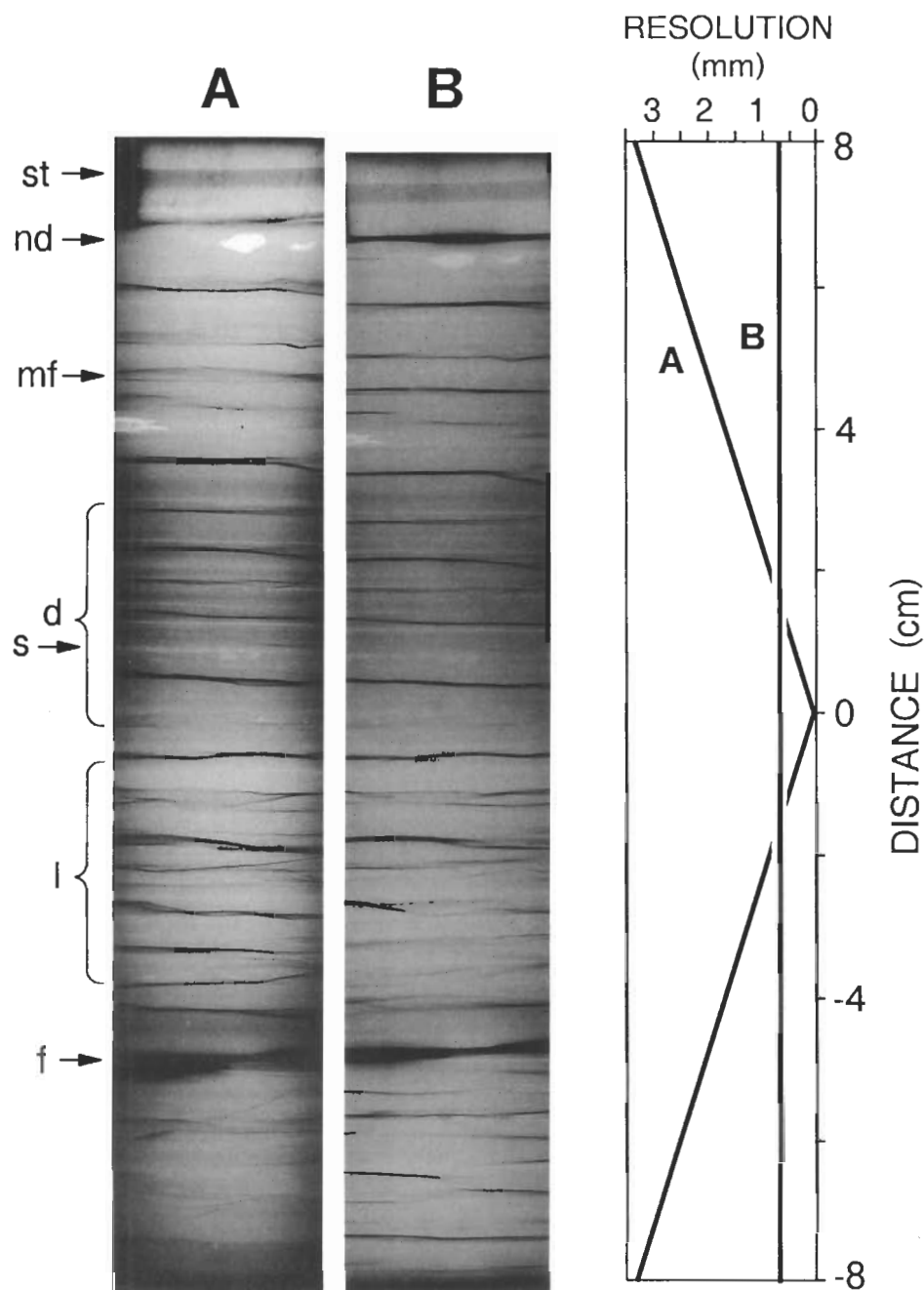
FIG. 2.—X-radiographs of Sunbury Shale taken A) without and B) with traveling core stage. Variations in hue, or gray-scale density (GSD), reflect differences in density of the rock matrix: denser (less dense) areas appear lighter (darker) owing to reduced (increased) X-ray penetration. Decimeter-scale alternation of light (l) and dark (d) core intervals is correlated to variation in TOC content (Algeo and Woods 1993). Other features visible in the core include fractures (f) and microfractures (mf; thin dark lines), sulfide nodules (nd; bright patches), and sulfide-rich laminae (s; bright lines). At the top of each image is a standard (st; a notched rock chip that yielded well-defined density maxima and minima) used to correct for small variations in exposure and development between X-radiograph images. Note that oblique penetration of X-rays resulted in loss of resolution and increased brightness (unrelated to lithologic variation) toward the top and bottom of the conventional X-radiograph image (A).

ends of the sample. In addition to loss of resolution, systematic variation in exposure results from changes in the incident angle of X-rays. This has the undesirable effect of progressively reducing exposure toward the ends of a sample, where oblique penetration of X-rays increases effective thickness to $t/\cos\alpha$.

Improved resolution can be achieved through modification of conventional X-radiograph procedures. The two main methods of enhancing resolution are: (1) reducing sample thickness (t; Fig. 1B), and (2) decreasing the maximum angle of incidence of X-rays relative to core stratification (α_{max}; Fig. 1C). Reduced sample thickness can improve resolution substantially, e.g., for $t = 3.0$ mm, $r = 0.8$ mm. However, this approach requires sample preparation that is laborious and inherently destructive of cores. Samples must be cut and ground to a uniform thickness (thin-slabbing), and, in the case of fissile shales, cementation with epoxy may be necessary to prevent disintegration during preparation (e.g., Nuhfer et al. 1979b). Uniform thickness is critical in thin-slabs, because small irregularities are magnified and result in variable exposure in X-radiographs.

The second method for enhancing resolution is to decrease the maximum angle

of incidence of X-rays relative to core stratification (Fig. 2C).. For example, to achieve a resolution of 2.0 mm, αmax must be no larger than about 5°. Although α_{max} could be reduced by using only the central, high-resolution section of conventional X-radiographs (e.g., l' in Figure 1A), such a method would require splicing together numerous short (centimeter-long) images and, moreover, suffers from the same problems of variable exposure and resolution as conventional techniques. A better method of decreasing α_{max} is to delimit the angle of incidence of X-rays with a physical aperture (Fig. 1C). In this method, X-rays are constrained to a narrow range about the vertical (i.e., nearly parallel to stratification in laminated cores) by positioning a sample beneath a lead shield having a window of specified width. Movement at a constant speed beneath the window results in all parts of the sample experiencing an equal range of incident angles during an equal interval of time, resulting in constant levels of resolution and exposure. The resolution r achievable with this method is a function of sample thickness t, window width w, and working distance D':
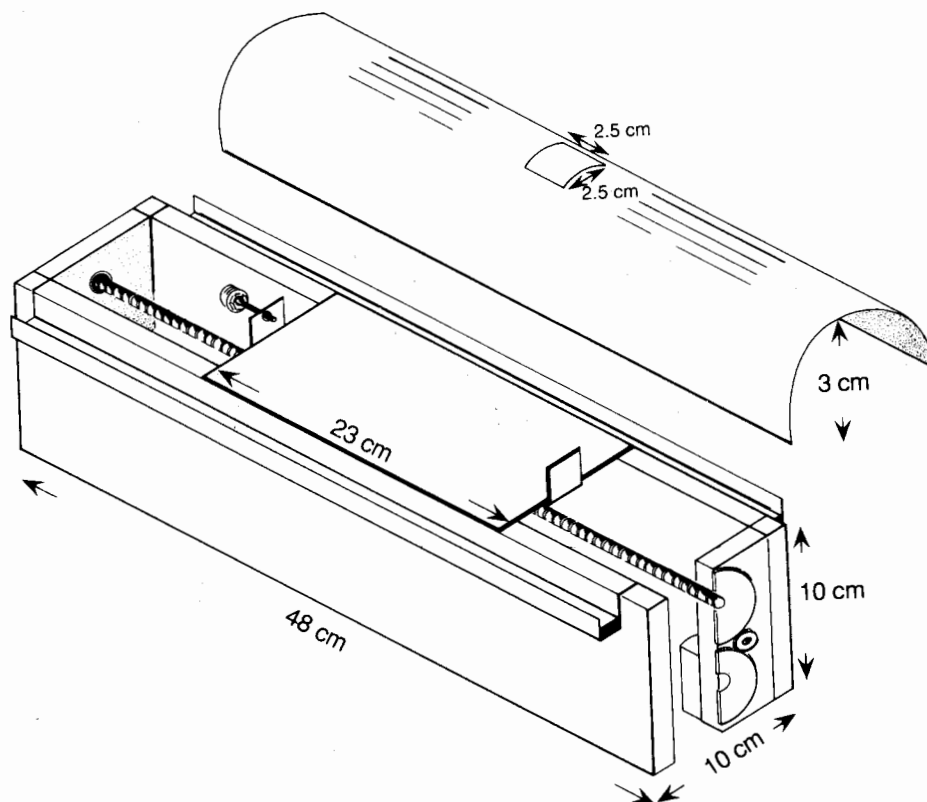
$$r = t \cdot w/D' \qquad (2)$$

Fig. 3.—Traveling core stage used to produce high-resolution X-radiographs. The platform on the stage is advanced by a helical screw connected to a variable-rate stepping motor. A lead shield positioned over the stage protects core and film from exposure to X-rays except through a narrow window (shown here with a 2.5 cm diameter, but later reduced to 1.25 cm to improve resolution). A stage constructed to the dimensions shown in the figure will fit in a standard Faxitron.

For a working distance of 45 cm (reduced owing to the height of the stage) and a core thickness of 2.5 cm, a window width of 1.25 cm yields $r = 0.7$ mm (Fig. 2B). The latter value is equivalent to that obtained for thin-slabs ($t < 3.0$ mm), and further improvements in resolution can be achieved by using narrower window widths.

Traveling Core Stage

We implemented this method of enhancing X-radiograph resolution by constructing a traveling core stage capable of transporting a core segment up to 22 cm long completely beneath an aperture 1.25 cm wide in a stationary lead shield (Fig. 3). The shield was centered beneath the X-ray source, and both core and film were exposed to X-rays only through the window. The stage was advanced at a constant speed using a helical screw driven by a stepping motor, which shifted the stage 0.128 mm per step. Travel rate and corresponding exposure time were directly proportional to the clock frequency of the motor. We used a clock frequency permitting a travel rate of 0.25 cm/min, so that all parts of the core were exposed for about 5 minutes. At this rate, a 20–22 cm segment of core can be exposed in 80–90 minutes, and about 1.2 m of core can be processed per 8-hr day. Although not especially fast, the procedure is not laborious—sample reloading and film development require about 10–15 minutes during each 1.5-hr interval. Details of stage design are available upon request.

UTILITY OF METHOD

The utility of high-resolution X-radiography of laminated sediment cores is in the construction of proxy lithologic records that can be studied using image and time-series analysis to identify patterns of stratigraphic variation. Continuous proxy lithologic records can be constructed much more rapidly by X-radiography than by millimeter-scale lithologic or geochemical analysis, although such records are most useful when the underlying controls on stratigraphic variation in the matrix density of the rock have been identified. High-resolution X-radiographic techniques were tested on the Lower Mississippian Sunbury Shale in a core from northern Kentucky by Algeo and Woods (1993; Fig. 2). In this study, a record of X-radiograph gray-scale densities (GSD) 5.0 m long was constructed and correlated with total organic carbon (TOC) content. Subsequently, the GSD record was used for time-series analysis by (1) scanning individual core X-radiographs into an Optimas image analysis system, (2) taking line transects of optical luminance (i.e.,

gray-scale density) along the center of the long axis of each image, (3) normalizing line luminance transects to the GSD values of a standard, (4) correcting transects for local aberrations in GSD values not related to the lithologic parameter of interest (e.g., sulfide nodules and fractures), and (5) splicing the normalized and corrected GSD values of sequential core segments to produce a continuous time series along the length of the core. Spectral analysis of the resulting GSD time series revealed significant periodic components at several frequencies in the Sunbury Shale (Algeo and Woods 1993).

CONCLUSIONS

Use of a traveling core stage has several distinct advantages over other methods of improving resolution in X-radiographs, including (1) maintenance of uniform levels of exposure and resolution across a sample, (2) rapidity of construction of proxy lithologic records over long stratigraphic intervals, and (3) nondestructiveness of samples, requiring no thin-slabbing or other sample preparation. Length scale of resolution is largely a function of window width: a width of 1.25 cm yields a resolution of 0.7 mm for slabbed 5-cm-thick cores, although finer resolution is attainable with narrower window widths. In principle, the method should be applicable to all types of laminated sediments in which laminae show variations in rock-matrix density.

ACKNOWLEDGMENTS

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