Lithofacies and geochemical facies profiles from nuclear wire-line logs: New subsurface templates for sedimentary modeling

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Abstract The use of wire-line logs in subsurface studies is all too often restricted to the correlation of selected stratigraphic horizons. There is an increasing content of valuable geologic information in modern wire-line logs that can be extracted by simple computer processing. The resulting log transformations provide lengthy and continuous records of sections of interest. Examples of these methods, as applied to Cretaceous and Permian stratigraphic case studies, are described here. The log data can be incorporated in either forward- or reverse-modeling modes in the simulation and analysis of sedimentary sequences. In addition to their geologic information content, wire-line logs are quantitative, and so their data can be entered easily into numerical modeling programs. Analysis can be made in either the stratigraphic time or frequency domain. The power spectra of logs give key insights into the nature and scale of sedimentary depositional mechanisms.

The length of stratigraphic successions penetrated by the typical borehole easily surpasses that of outcrops, even those of exposures in deep canyon walls. Myriad boreholes have been drilled in the sedimentary basins of the world, and their records provide an extraordinary data resource for sedimentary modeling. However, the accessibility of deep stratigraphic units for detailed geologic observation is considerably more restricted than that of surface exposures. Core is costly to recover; drill cuttings are fragmentary, can become contaminated with cavings, and are sampled over coarse depth intervals. By contrast, wire-line logs are the standard reference material for subsurface stratigraphic correlation, but their geologic information content is generally underutilized by geologists. The correlation of stratigraphic units using logs from boreholes defines three-dimensional surfaces that express the large-scale geometry of sedimentation units. However, a set of correlation surfaces is purely a *geometric* skeleton framework because it is based entirely on depths and geographic coordinates. Explicit *geologic* information linked with the magnitudes of the log measurements can be used to fill in the body of the framework.

The traces of most logs reflect primarily shale content and pore volume and provide crude but effective indicators of gross geologic variation. For example, the waxing and waning of coarse clastic sediment supply is often indicated by spontaneous potential (SP) and gamma-ray log shapes and trends. These shapes can also aid in the recognition of specific sedimentary environments [see, for example, Selley (1976) and Garcia (1981)]. Porosity logs of carbonate sections can discriminate lithofacies whose history of genesis and diagenesis is reflected in pore volume characteristics (Doveton, 1986). These qualitative log features have been used by generations of petroleum geologists to assess potential plays and reservoir architectures. Geologic data and interpretations are commonly annotated on logs, which are widely used as the standard graphic base for subsurface cross sections.

The increasing demands on reservoir engineering have stimulated the development of new wire-line tools. Measurements obtained with these tools are sensitive to mineral and elemental compositions in clastic rocks, carbonate rocks, and shales. The economic benefits include better estimations of porosity and permeability of "complex" carbonates, recognition of clay mineral species in sandstone pore networks, and improved ability to analyze reservoir zones in exotic rock types. These nuclear tools are now commonly used, and their logs can be transformed into continuous and quantitative profiles of interpreted mineral composition and geochemistry. The log transforms are useful for studies of sequence stratigraphy but are particularly valuable for computer modeling because log data are both numerical and numerous. They can be analyzed statistically to extract trends and periods, which can be keyed to specific geologic properties rather than to vague log character. The results of such analyses should provide explicit input for realistic computer modeling. Alternatively, the output from such models can be used to evaluate the degree to which the data match the spatial distribution of diagnostic log features.

I discuss two case studies that apply natural spectral gamma-ray and lithodensity-neutron logs to the analysis of geochemistry and mineralogy. Both these log combinations have been run increasingly frequently since their introduction in the 1970's and can be found in boreholes from most basins of the world. They should be viewed as the forerunners of a new generation of logging tools that measure properties with a high geologic information content. One example is induced spectral gamma-ray sondes, which provide logs of a variety of elements and have been used extensively in the Deep Sea Drilling Program [e.g., Brewer et al. (1990)]. The case studies give some examples of transformations of nuclear logs to profiles of variables keyed to properties of sedimen-

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tary facies. The profiles can be thought of as templates to be matched critically with the results from computer-simulation modeling. In addition to their sedimentologic information content, the profiles have the particular advantages of being lengthy, continuous, and numerical and so can be readily compared with the output of simulation computer runs.

Geochemical facies analysis of a Permian–Cretaceous section based on spectral gamma-ray logs

The record of the conventional gamma-ray log is a summation of counts from all radioactive sources. The log is referenced to a scale of consistent (but arbitrary) API (American Petroleum Institute) units, where a value of 100 represents a typical midcontinent shale and corresponds to a calibration standard in a test pit at the University of Houston. The radioactive isotopes that account for the bulk of natural gamma radiation in rocks are restricted to potassium-40 and the daughter products of the uranium and thorium series. The gamma rays from different isotopes have characteristic energies that can be used to partition measured gamma rays in terms of their source isotope. Counting within the spectral gamma-ray tool is subdivided according to energy range, and the results are processed by computer to estimate the quantities of the three major sources of radioactivity (Serra et al., 1980). The spectral gamma-ray log is displayed as three parallel curves of thorium, uranium, and potassium. Thorium and uranium are recorded in parts per million, whereas potassium is reported as a fraction or a percentage. In common with the conventional gamma-ray log, the log quantities are stochastic because they are the product of probabilistic atomic decay. The reliability of the estimates is therefore partly controlled by the size of the sample count and the logging speed.

Sedimentary thorium is almost exclusively associated with aluminosilicates, and thus the thorium log curve is a good indicator of the volume of clay minerals in logged sections (Hassan et al., 1976). The thorium/potassium ratio (Th/K) is a broad index of relative potassium richness that has proved useful in distinguishing between types of radioactive minerals. For example, low-ratio (high-potassium) feldspars and micas are contrasted with higher-ratio illite, smectite, kaolinite, and chlorite (ordered by increasing ratio). The variability in composition of clay minerals is reflected by expected ranges in ratio rather than by precise values; empirical numbers are reported by Hassan et al. (1976) and in *Schlumberger Log Interpretation Charts* (1988). Also, shales generally contain mixtures of clay minerals, so that the ratio serves as a generalized facies indicator.

The thorium/uranium ratio (Th/U) has been used successfully in the evaluation of geochemical facies, following the extensive studies of Adams and Weaver (1958). The ratio is a useful indicator of the redox potential of the original sedimentary environment and/or subsequent diagenetic processes. Uranium and thorium are closely associated geochemically but have distinctive valency properties. Under reducing conditions uranium has an insoluble tetravalent state, which is fixed, commonly by organic matter. The soluble hexavalent state of uranium is formed under oxidation and can be mobilized into solution, typically by leaching processes. By contrast, thorium is restricted to an insoluble tetravalent state and thus functions as a reference for assessment of the degree of relative uranium paucity or enrichment. Adams and Weaver (1958) suggested that ratios less than 2 are indicative of reducing conditions and those greater than 7 are associated with oxidation, based on the geologic history of their large analytical sample. The conversion of the thorium, uranium, and potassium logs into Th/K and Th/U ratios therefore has great potential in the elucidation of both clay mineral facies and redox potential.

A spectral gamma-ray log was run in a hydrologic observation borehole that penetrated Cretaceous and Permian sediments in central Kansas (KGS Braun No. 1, NENENE sec. 30, T. 12 S., R. 18 W.). The location of the borehole on the eastern side of the Cretaceous western interior seaway together with the relative sophistication of the logging suite promised useful insights into the basin history and paleogeography. On a broader level the data would be valuable as detailed stratigraphic records to be emulated by computer modeling. The initial log analysis results have been reported by Macfarlane et al. (1989).

The cross-plot of the Th/U and Th/K ratios of the logs from this borehole are shown in fig. 1. The cluster of points from the Permian Cedar Hills Sandstone is clearly distinguished from the Cretaceous as relatively enriched in potassium. This aspect conforms with the lithology of these eolian sandstones, which range from quartzarenite to lithic subarkose (Holdoway, 1978). The sources of potassium are contained in a mix of feldspars, rock fragments, and illite. The Lower Cretaceous units (Cheyenne Sandstone, Kiowa Shale, and Dakota Sandstone) are deltaic clastic rocks from freshwater and paralic regimes of sedimentation. The clay mineralogy is a mix of kaolinite and illite with subsidiary amounts of chlorite, smectite, and mixed-layer clays (Merriam et al., 1959). This mixed character is reflected by the broad, diffuse cloud of ratio cross-plot points. However, the location of the cloud within the interpretive range of the kaolinite-smectite-illite assemblage shows good concordance with known lithology. Cross-plotted points from the marine sequence of the Upper Cretaceous (Graneros Shale, Greenhorn Limestone, Fairport Chalk Member, Blue Hill Shale Member, Fort Hays Limestone Member) fall in the illite-smectite range of ratios. With respect to the Th/U ratio, there is a basic differentiation that appears to be linked directly with the redox potential of the sedimentary environment. Uranium-poor Permian eolian sandstones and Lower Cretaceous deltaic sandstones and shales are contrasted with relatively uranium-enriched marine shales and limestones of the Upper Cretaceous.

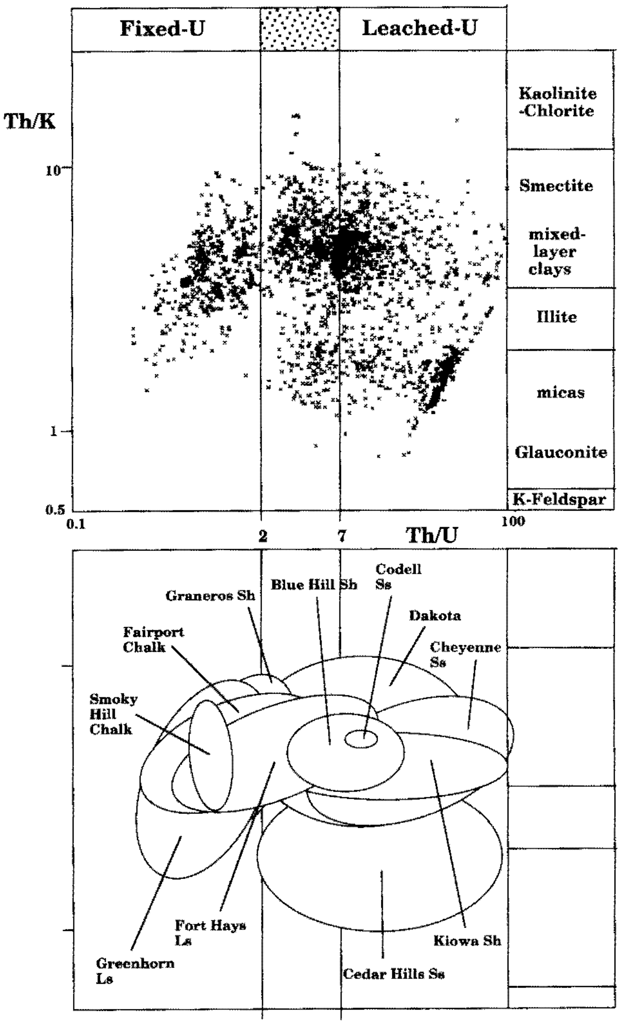

Figure 1. Thorium-uranium-potassium cross-plot of Cretaceous and Permian rocks from a spectral gamma-ray log run in a borehole in central Kansas.

These observations are clarified further when the spectral ratios are plotted as logs (fig. 2), which function as stratigraphic time signals of compositional and redox potential changes. The basal Cretaceous unconformity is clearly shown by the abrupt shift in the Th/K ratio, caused by the switch from the potassium-rich feldspars of the Permian to the illite-kaolinite deltaic shales of the Lower Cretaceous. Fluctuations in the Upper Cretaceous appear to represent responses to proportional volumetric changes in clay mineralogy. For example, the high-amplitude oscillations in the Graneros Shale and Greenhorn Limestone are probably caused by bentonites (seen in the drill cuttings) interbedded with normal illitic marine shales. These bentonites are altered ash layers deposited by explosive volcanic events in western states (Kauffman, 1985).

To aid in the interpretation of depositional environment through the use of an oxidation potential indicator, I reference the Th/U ratio log with the diagnostic values of 2 and 7, as suggested by Adams and Weaver (1958). The ratio indicates an oxidizing environment for much of the Permian Cedar Hills Sandstone, which would be expected from its postulated origin as eolian sand (Holdoway, 1978). Stacked repetitions of high and medium Th/U ratios characterize the Cheyenne, Kiowa, and Dakota formations. These probably reflect high lateral variability in clastic facies and interplay between mostly brackish and freshwater regimes of distributary channels, bays, and marginal marine deposits, which would be expected to typify a delta complex.

The relatively smooth, long-term cyclic pattern of the Th/U ratio in the marine sequence of the Upper Cretaceous is in stark contrast to the high-frequency character of the ratio in the deltaic deposits below and is an excellent indicator of a broad transgression-regression couplet on an open-marine shelf. The broad sine-wave feature conforms precisely with the outcrop interpretation of the Greenhorn cycle as a classic example of a symmetric third-order tectonoeustatic cycle (Glenister and Kauffman, 1985). Hattin (1985) was able to demonstrate the correlation of time-parallel beds in the Greenhorn from outcrops in Kansas to locations in Colorado and New Mexico. He concluded that the exceedingly widespread deposition of relatively thin units implied a regionally flat, gently sloping seafloor. The model would account for the strong simple transgression-regression signal in the ratio log from the top of the Dakota to the base of the Fort Hays Limestone Member. The transgressive phase of the cycle was initiated in the uppermost part of the Dakota Formation, continued through the Graneros Shale, and reached maximum development in the Greenhorn Limestone. The regressive hemicyclothem started at the top of the Greenhorn and continued through the Fairport Chalk Member and Blue Hill Shale Member, to terminate in the Codell Sandstone Member.

There is an abrupt break in the Th/U ratio log at the boundary between the Codell Member and the overlying Fort Hays Member. This contact is thought to represent a long period of nondeposition followed by a major transgression (Hattin and Siemers, 1987). The ratio log shows this transgression clearly but also indicates a distinctive regressive event at the top of the Fort Hays. This anomaly coincides closely with a similar peak on a Th/U log from a Colorado well that was attributed to a regional warm water pulse or low-salinity event from oxygen isotope studies in the carbonate phase (Zelt, 1985). The Smoky Hill Chalk Member at the top of the borehole succession is marked by a log ratio feature that indicates renewed transgression.

Mineral compositional analysis of a Permian section based on lithodensity and neutron logs

It is now common practice to run a gamma-ray–lithodensity–neutron wire-line log combination to provide volumetric estimations of porosity and indications of lithology. Whereas

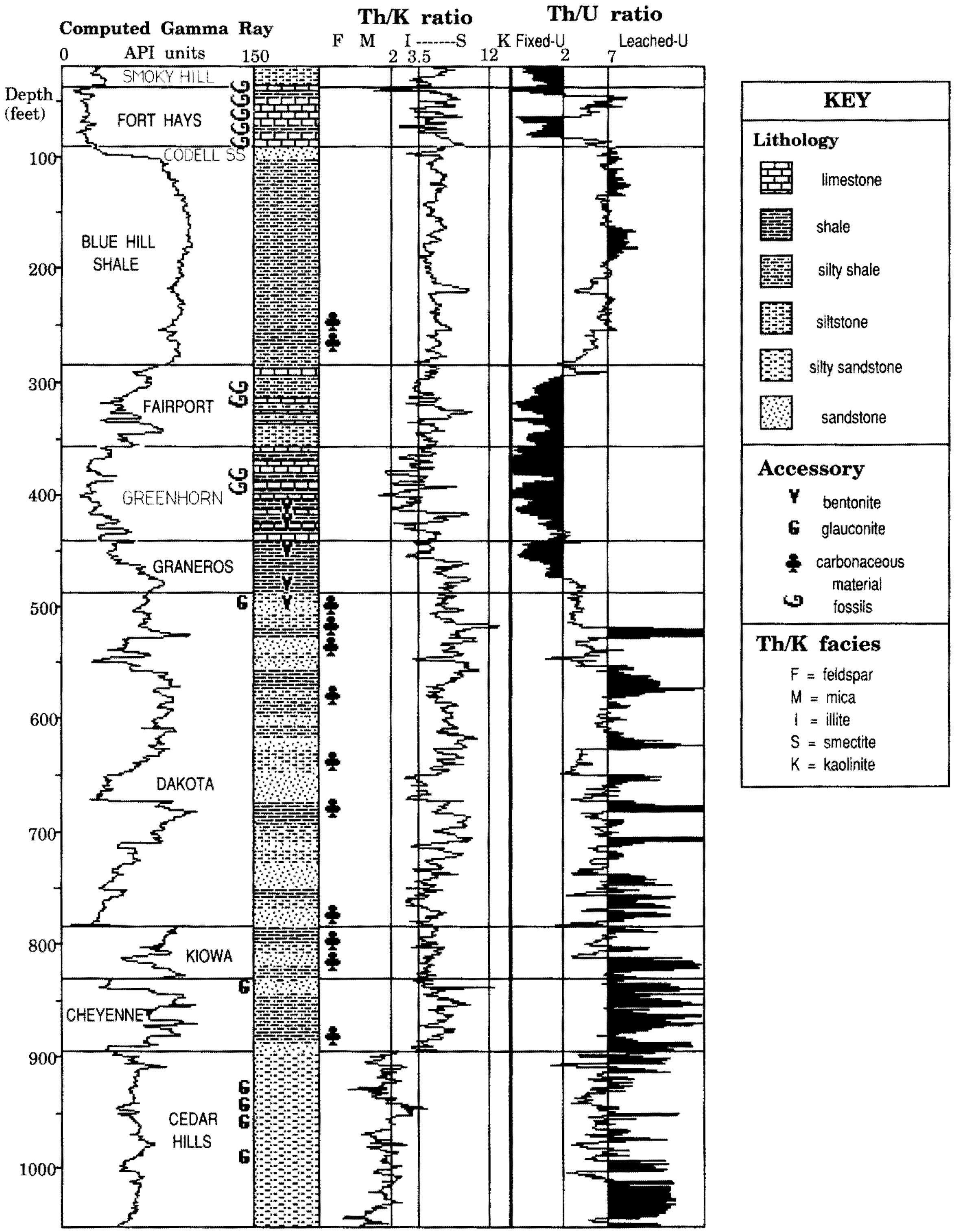

Figure 2. Spectral gamma-ray ratio logs and drill-cuttings sample log of the Permian–Cretaceous subsurface section in central Kansas.

the gamma-ray log differentiates shales from other rock types, the relative disposition of the neutron and density curves is affected systematically by changes in mineralogy. These properties can be used for both qualitative recognition of rock types and quantitative calculation of mineral composition. Logging measurements of the photoelectric cross section have proved to be especially useful in mineral identification work. The photoelectric index is a supplementary measurement obtained by the modern density logging tool, which records the absorption of low-energy gamma rays by the formation in units of barns per electron. The logged value is a direct function of the aggregate atomic number (Z) of the elements in the formation and therefore is a sensitive indicator of mineralogy (Gardner and Dumanoir, 1980). The collective use of gamma-ray, density, neutron, and photoelectric absorption data in cross-plots and computer processing is a powerful method to identify and estimate mineralogies in mixed lithologies, as demonstrated in the following case study.

Numerous production wells have been logged in the Hugoton gas field in southwestern Kansas. A lithodensity-neutron log combination was selected from a typical well (Mobil Brown No. 1–2, center of NW sec. 11, T. 35 S., R. 37 W.) run through the Permian Chase Group. The sequence is an alternating succession of shales and carbonates deposited mainly in a tidal flat setting with sedimentary environments ranging from supratidal to shallow marine. Red and green shales show desiccation features and other evidence of intertidal and supratidal origin. Fossil and petrographic criteria indicate that the carbonates were deposited in subtidal, lagoonal, and shallow marine regimes (Almouslli, 1987). The carbonates are limestones that are often cherty and dolomites that tend to be more common higher in the group. Nodular anhydrite occurs commonly, particularly in the upper parts of the regressive carbonates. The wide range of mineral compositions makes this sequence a good subject for nuclear log analysis, with useful implications for sedimentary modeling work.

The influence of pore fluid on the logging measurements can be screened out in the estimation of the hypothetical properties of the rock matrix framework. The grain density, ρ_{maa}, is estimated by a porosity correction to the measured bulk density, which removes the contribution of the pore fluid density. Similarly, U_{maa} is computed as the estimated composite photoelectric absorption of the minerals in the formation. A ρ_{maa}-U_{maa} cross-plot of logged zones provides an excellent medium for mineral recognition and lithofacies analysis (McCall and Gardner, 1982). The cross-plot for the Chase Group (fig. 3) is indexed with quartz, calcite, dolomite, and anhydrite values, which serve as reference points to characterize logged zones. Most points fall within the quartz-calcite-dolomite triangle, corresponding to limestones, dolomites, and cherty carbonates. The points drawn below the quartz-dolomite line are shale zones whose location is determined by the silt content and types of clay minerals. Ellis (1987) has pointed out that the aggregate atomic number of aluminosilicates should be similar to quartz and that higher photoelectric absorption can be attributed primarily to the iron content of clay minerals. The points to the right of the dolomite-calcite line reflect the occurrence of anhydrite. The plot was rescaled with the dolomite-calcite line as a zero isocontour to estimate implied proportions of anhydrite associated with any zone. A log plot of these estimates (fig. 4) related to depth shows a striking tendency for anhydritic zones to occur in the upper part of regressive carbonates, immediately below supratidal and intertidal shales. This is the location of nodular anhydrite commonly observed in Chase Group cores.

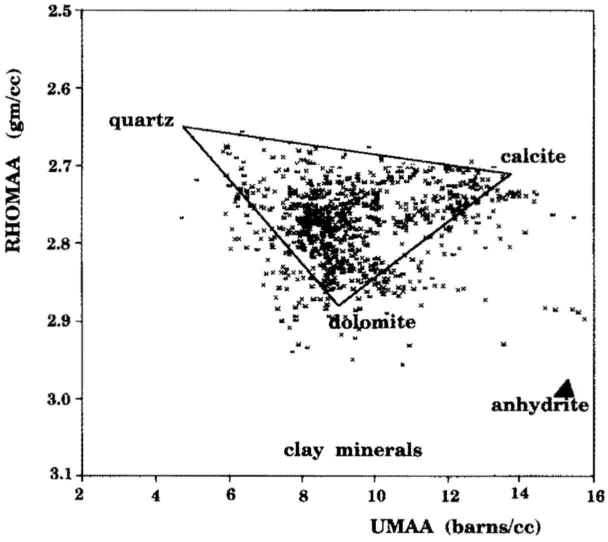

Figure 3. Cross-plot of apparent matrix density (RHOMAA) and apparent matrix volumetric photoelectric absorption (UMAA) from logs of the Chase Group (Permian) in a well in southern Kansas.

The graphic advantage of the anhydrite log over the cross-plot is that it is referenced to depth and therefore is put within a framework of stratigraphic time. The basic idea can be extended to the estimation of multiple components (minerals and fluid). A series of simultaneous equations that relate component log properties to observed log responses provides the solution for component proportions. In matrix algebra these equations take the form

$$C\mathbf{V} = \mathbf{L}, \tag{1}$$

where C is a matrix of component log properties, $\mathbf{V}$ is a vector of component proportions, and $\mathbf{L}$ is a vector of zone log responses. If the equation set is linear and determined, the unknown vector $\mathbf{V}$ can be solved by

$$\mathbf{V} = C^{-1}\mathbf{L}, \tag{2}$$

where C^{-1} is the inverse of the C matrix. When programmed

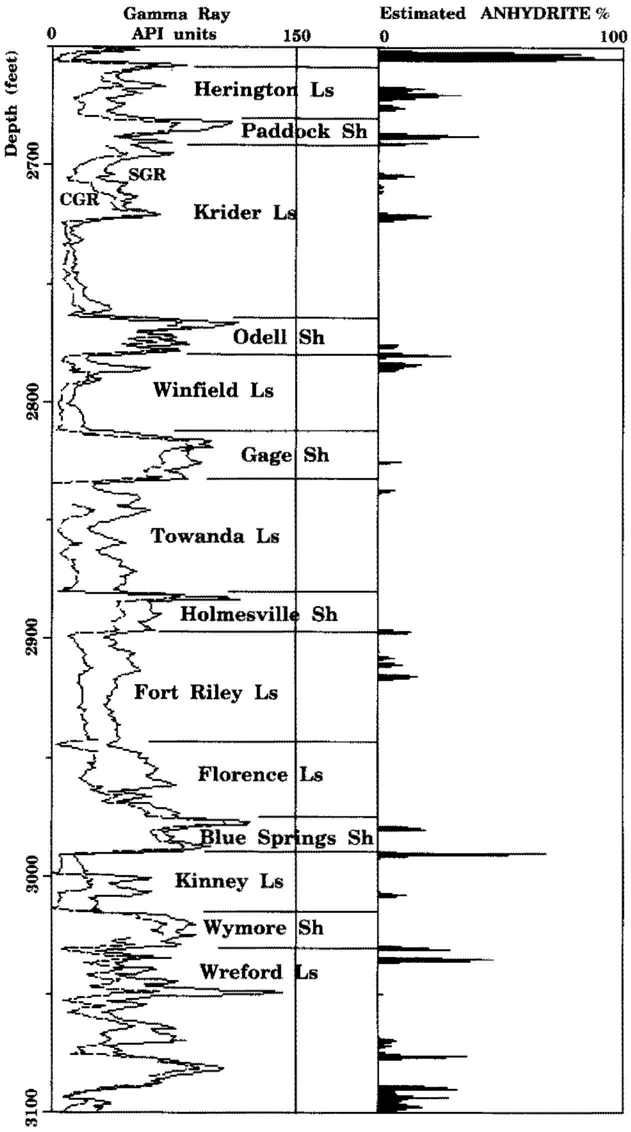

Figure 4. Log of anhydrite proportion in the Chase Group section, estimated from the RHOMAA-UMAA cross-plot and the gamma-ray log SGR = Th + K + U. CGR = Th + K.

for a computer, the method generates continuous vertical profiles of estimated mineral composition, as described by Doveton (1986). The results should be thought of as normative rather than modal estimates because the composition is *implied* by the logging measurements rather than actually observed. However, arguably unlike igneous norms, there is a strong desire to emulate real (modal) compositions, and information from core or cuttings is therefore useful.

Computer processing of gamma-ray, density, neutron, and photoelectric absorption logs of the Chase Group resulted in the profiles of shale, anhydrite, dolomite, chert, calcite, and porosity shown in fig. 5. There is good concordance between the character of the compositional profile and the rock types observed in cores and cuttings of the Chase Group in this area. Cherty limestones are more prominent in the lower part, grading upward to more dolomitic carbonates. Anhydrite occurs locally but typically at upper levels of the regressive phase of the carbonate units. The shales appear to vary both with regard to their volumetric silt content and according to whether the shales are calcareous, dolomitic, or quartzose. The vertical resolution of the profile traces is of the order of 1 m (3 ft), as dictated by the tool combination characteristics. This accounts for the fluctuating character of the traces as representing 1-m (3-ft) moving averages of real variation.

Frequency analysis of geologic log transforms

When wire-line logs are transformed into profiles that are keyed to useful geologic properties, the results are immediately accessible to sequence stratigraphic studies. In addition, the profile traces are *quantitative* geologic signals in the stratigraphic time domain. Statistics estimated from these profiles can be used to dictate parameter values as input to computer sedimentary models or as expectations for output results of these same models. The time scale of the logs is only a monotonic function of real time but can be converted to temporal units if credible estimates of sedimentation rates and hiatus times are available.

The numerical form of logging data is particularly useful because it allows easy transformation from the time domain of stratigraphic depth to the frequency domain. The presence of cyclic components can be detected and characterized through the computation of the Fourier transform. This transform decomposes the total signal into a spectrum of sine waves of differing frequencies, analogous to the way a prism breaks white light into its color components. The frequency characteristics of any computer sedimentation simulation are the fingerprint of the process model algorithm and should emulate those of the real-world subject. The match may take the form of periodicities of common wavelength, caused by a variety of mechanisms ranging from astronomical to small-scale, localized phenomena. Even in cases where the cumulative sedimentary record is essentially random, this should be evidenced by a nondescript white noise power spectrum, both in observed and simulated data.

The frequency characteristics of the Th/U ratio in the sections of the two case studies were analyzed to give some examples of this concept. As discussed earlier, the ratio is a useful indicator of ancient redox potentials, and its fluctuation with respect to depth should indicate both the nature and the scale of sedimentary processes. The discrete Fourier power (squared amplitude) spectra are shown for the Greenhorn cyclothem and Dakota aquifer formations and the Chase Group in fig. 6. In each case the log ratio data were standardized to allow useful comparisons to be made.

The Greenhorn cyclothem spectrum is dominated by a single harmonic with a wavelength of 400 ft (120 m), and

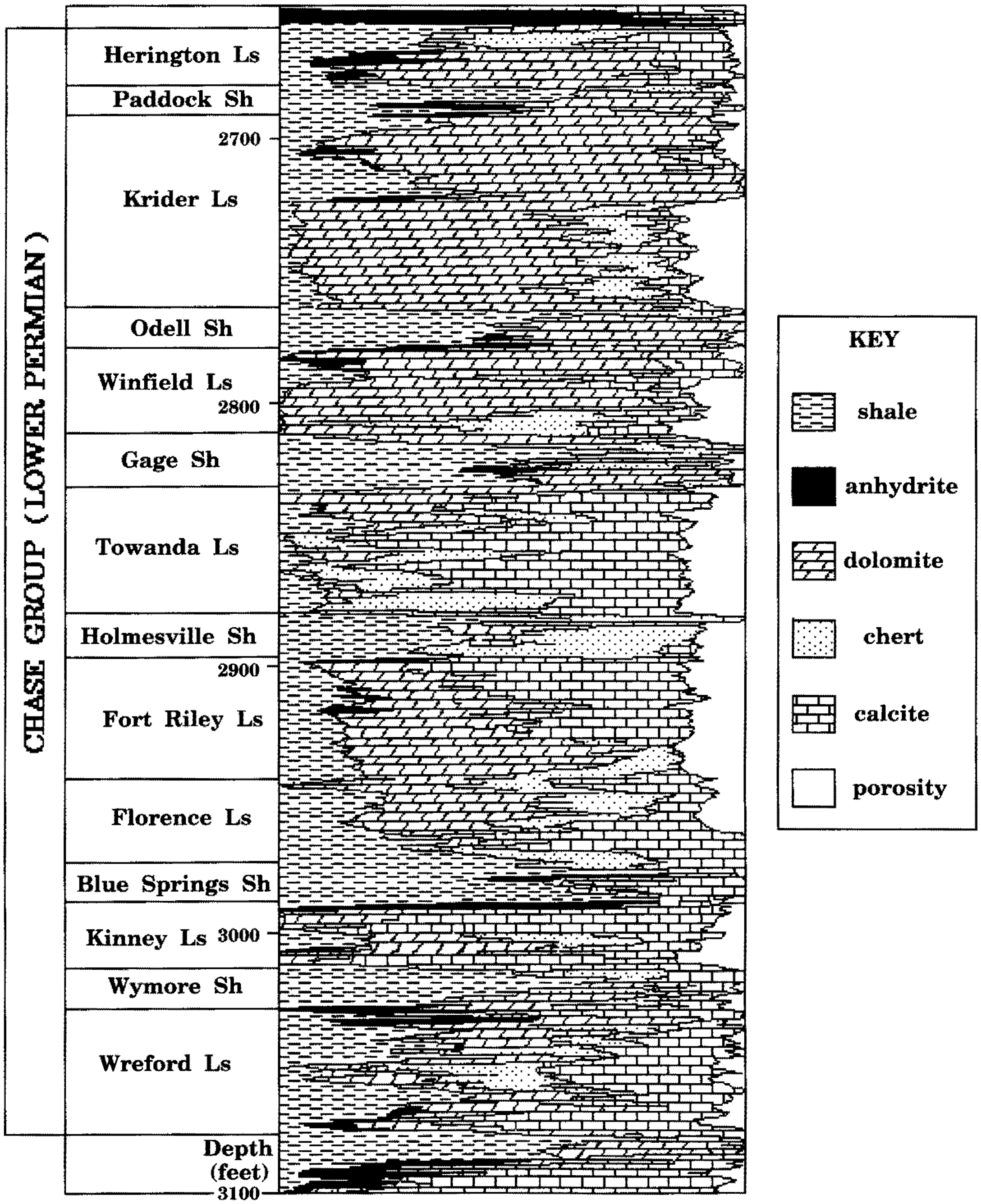

Figure 5. Compositional solution of the Chase Group section in terms of shale, anhydrite, dolomite, quartz, calcite, and porosity computed from gamma-ray, lithodensity, and neutron logs.

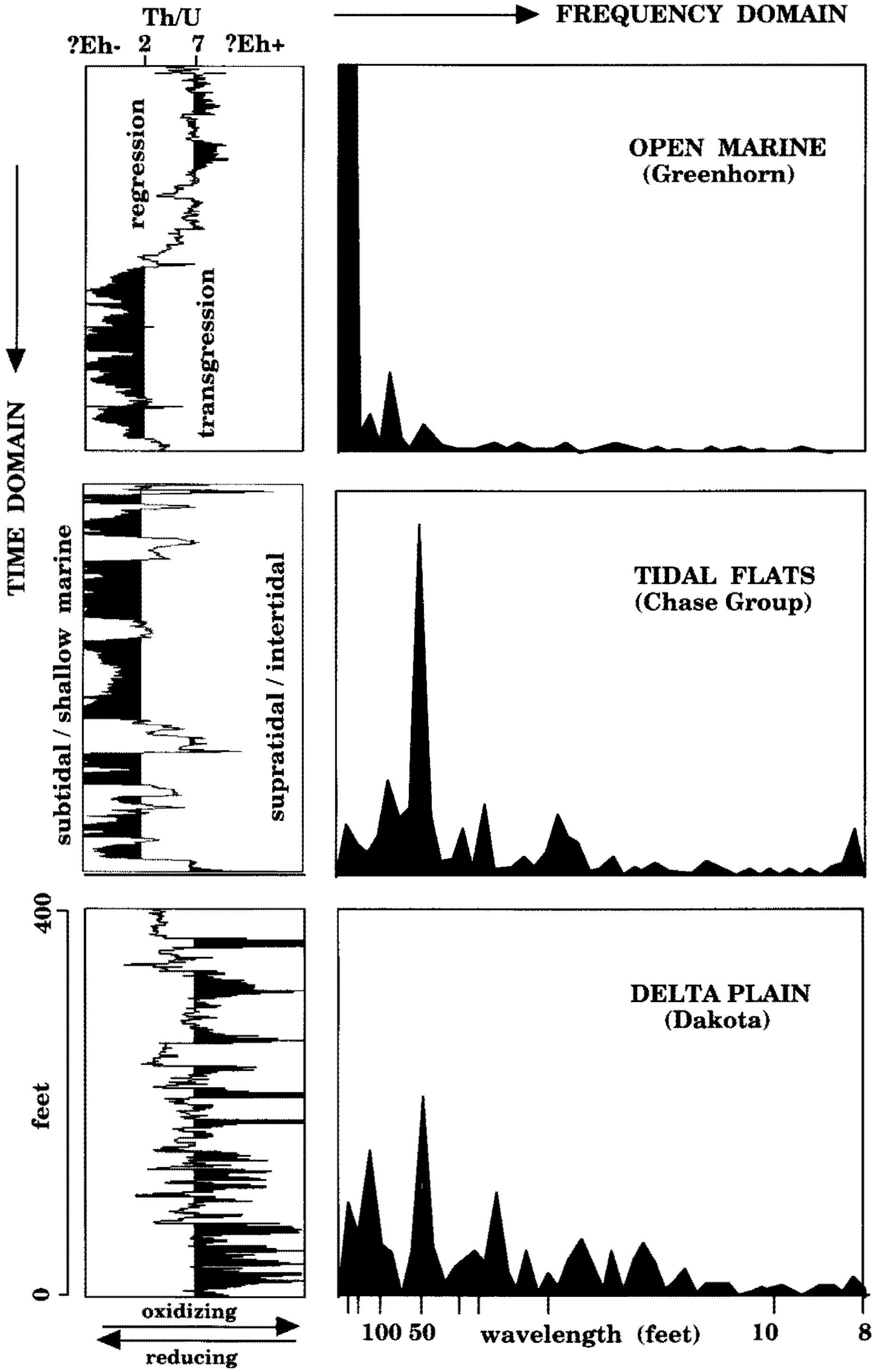

Figure 6. Logs and discrete Fourier power spectra of the Th/U ratio in the Greenhorn cyclothem, Chase Group, and Dakota aquifer formations. The power is squared amplitude and has dimensionless units.

contributions by other frequencies are trivial. The dominant harmonic picks up the major transgression-regression couplet described from an outcrop in Colorado as a symmetric third-order tectonoeustatic cycle (Glenister and Kauffman, 1985). The simple character of the spectrum may characterize major cycles on a broad open-marine shelf.

By contrast, the power spectrum of the Lower Cretaceous formations in the same borehole exhibits a ragged train of all frequencies. The poor coherency of the spectrum is attributed easily to the origin of these sediments in the mosaic of deltaic depositional environments. Oxidizing and reducing conditions would be expected to be highly variable between marine and nonmarine regimes and between localized environments on the delta plain. The partly chaotic result would confound processes in a smearing of frequencies in the power spectrum. Notice, however, that a wavelength of 50 ft (15 m) is discriminated by the harmonic with the highest power. This same wavelength is shown more strikingly on a power spectrum of the gamma-ray log and probably reflects a basinwide periodic component of clastic sediment supply.

Finally, the power spectrum of the Chase Group section has characteristics that are intermediate between the open-marine and the deltaic spectra of the Cretaceous section. The intertidal depositional setting of these rocks is recorded by a basic interbedding of supra- and intertidal shales with subtidal and shallow marine carbonates. This basic alternation is shown strikingly by a harmonic whose period is 50 ft (15 m). Otherwise, the spectrum is relatively undistinguished, and the subsidiary peaks do not appear to show any systematic pattern.

Conclusions

Modern wire-line logs have an intrinsic geologic information content that has not yet been fully utilized but is especially valuable for the computer simulation of depositional sequences. Spectral gamma-ray logs allow useful characterizations of clay mineralogy and ancient redox potentials. Computer processing of the lithodensity-neutron log combination resolves porosity and mineral suites as continuous quantitative estimates of lithology. The extended length of logged sequences and the numerical character of the logging data are a great asset to the estimation of model input parameter values and the comparison of model outputs. Comparative analysis can be made both in the stratigraphic time and frequency domains, which can give useful insights to the nature and scale of sedimentation mechanisms.

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