Subsurface lithofacies mapping from geophysical logs in Kansas

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Abstract

Stratigraphic tops picked from geophysical logs are basic data in the preparation of regional subsurface maps of structure and thickness. These maps are topological—they are restricted to the display of the shape and size of stratigraphic units. However, the quantitative variation of logs with depth can be analyzed in terms of mineralogy and porosity which express the internal composition of these units. Use of computer-mapping packages in a novel way allows this information to be interpolated from available well control in the generation of lithofacies maps. As a practical example, the composition of the Viola Limestone was mapped in a four-county area in southern Kansas through transformation of data from neutron, density, and sonic logs into estimations of calcite, dolomite, chert, and pore volume. Available cuttings and core information were used both to monitor the result and to provide detailed meaning to observed variation. The map shows facies patterns which are readily related to depositional, diagenetic, and erosional trends. In a second example, the statistical moments of the gamma-ray log were used by a computer program to generate three-dimensional trend maps and cross section slices of shale-sand variation in the Simpson Group of the same area. The results give an immediate picture of the shapes and dispositions of major sandstone and sandy carbonate bodies, as well as outlining the areal pattern of a basal transgressive sand.

Introduction

The major use of geophysical logs is in the location of the depths of key subsurface formations for purposes of correlation and mapping. Interpolation of stratigraphic tops between well control maps structure as continuous surfaces which express the shape of the mapped unit. By contrast, when the differences in elevation between two marker horizons are interpolated, the result traces variations in thickness across an area, which is a measure of relative size. Both structural and isopach maps can be thought of as topological, since they are restrictive descriptions of the external geometry of subsurface units with no explicit information on unit composition.

Conventional lithofacies maps display areal compositional variation based on drill-cuttings descriptions and core analysis. Although cuttings generally provide the only direct samples of the subsurface, skillful work is required to differentiate contamination of caving material and the selective bias in description by different geologists. Core data are obviously preferable but are relatively rare in occurrence and have a limited role in mapping. As a further consideration, both cuttings and core information are qualitative and must be converted into quantitative estimates for interpolation between well control.

Although the older geophysical logs are primarily sensitive to shale content, pore volumes, and the nature of the pore fluid, combinations of more recent logs can be transformed to estimates of mineral compositions of formations within borehole sequences. Computer processing of responses from several logs generates profiles of compositional variation which show satisfactory agreement with the "ground truth" of cuttings and core (Doveton and Cable, 1979).

A research project at the Kansas Geological Survey evaluated the feasibility of extending these methods to regional lithofacies mapping. The test area is a four-county region in south-central Kansas which straddles the Pratt anticline, a southern extension of the Central Kansas uplift (fig. 1). The project was subdivided into two case studies which are the subject of the paper. In the first, log-analysis functions were incorporated into the operations of a computer-mapping package to map lithofacies variation in the Viola Limestone. In the second, mathematical algorithms were devised to map the position and shape of sandstone bodies within the Simpson Group in the three dimensions of depth and geographic space. The case studies of these two Ordovician units are examples of the application of borehole geophysics to subsurface-lithofacies mapping.

Case study 1: Viola Limestone

The Viola Limestone is a cherty, dolomitic limestone of Middle and Late Ordovician age which subcrops immediately north of the study area, against the flanks of the Central Kansas uplift. The basal unit consists of a distinctive crinoidal limestone that can be traced across the entire area

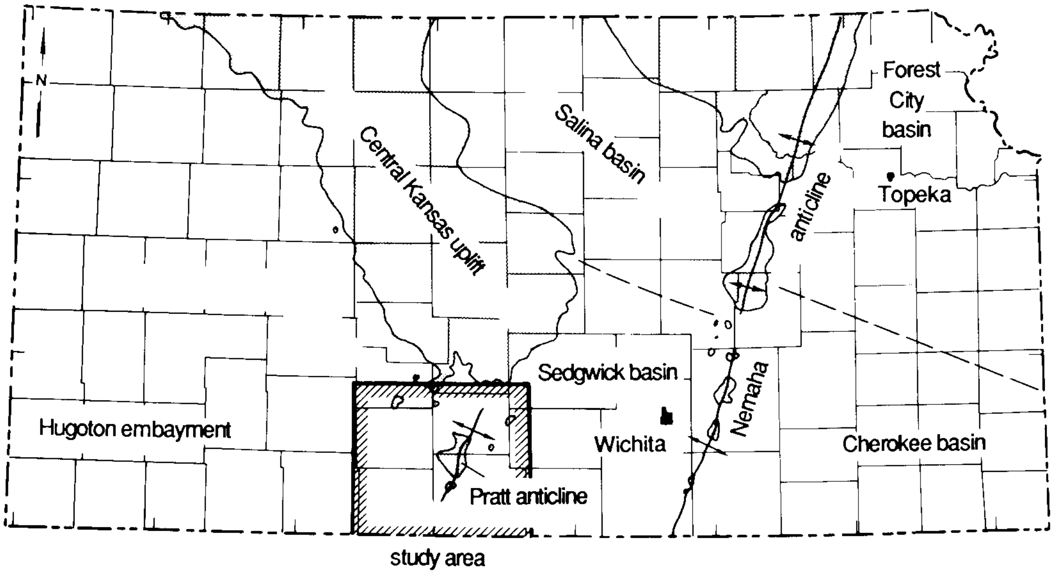

FIGURE 1—Location of study area in Kansas.

and makes a good stratigraphic marker because its relatively low porosity causes an easily recognized "tight lime" signature on resistivity logs. The remainder of the Viola consists of cherty dolomites and limestones and the entire unit ranges between 50 and 230 ft (15–69 m) in thickness. Patchy regolithic developments of residual chert occur in the northern part of the area as a broad peripheral rim to the subcrop margin.

Neutron, density, and sonic logs were digitized from 254 wells in the area. At any depth within a well, the measured log responses may be partitioned between contributions made by the component minerals and pore fluids of the logged formation. The result is a set of three simultaneous equations which relate the log measurements to the component proportions as unknowns. For the Viola Limestone, the basic components can be identified as calcite, dolomite, chert, and porosity. A fourth "unity equation" is introduced in which the four unknown properties will collectively sum to unity. The solution of this simultaneous equation set is a simple application of matrix algebra and is the basis for computer processing of a log-combination profile (Doveton and Cable, 1979). An example of a processed Viola Limestone section is shown in fig. 2. The presentation differs from a conventional lithologic log in showing a set of fluctuating traces rather than a sequence of discrete lithologies. A major reason for this difference is the vertical resolution of the porosity-log combination which is in the order of a few feet, and which results in a smoothed moving average of compositional variation. In this example, the gamma-ray log also was used to discriminate shale content, while the porosity difference between the sonic log and neutron-density combination was used to partition the pore volume between primary porosity (fine pore) and secondary porosity (coarse grade).

Mapping changes in lithology across an area requires an extension of the methodology developed for individual well profiles for techniques suitable for lateral interpolation. A more challenging problem to be resolved prior to mapping is the isolation and removal of errors caused by tool malfunctions, miscalibrations, and other inconsistencies. The removal of random measurement error from logs is often known as normalization. As described by Doveton and Bornemann (1981), trend-surface analysis was applied as a statistical technique to the mapping of the basal crinoidal limestone unit as a calibration unit. By these means, the measurement error associated with every log in the area was calculated, and used to correct the raw average log responses of each Viola section to estimates of their true values.

The corrected Viola average log responses were used as input to an automated contouring program in the generation of grids for neutron, density, and sonic values. The matrix algebra method described for the analysis of vertical variation was extended to the transformation of these log response grids to compositional grids of calcite, dolomite, chert, and porosity proportions. Rather than convert a sequence of depth-zone log responses to compositional profiles, the procedure was modified as a grid-to-grid operation in which corresponding grid nodes were successively transformed.

Grid-node proportions were plotted with reference to a calcite-dolomite-chert composition triangle (fig. 3). This

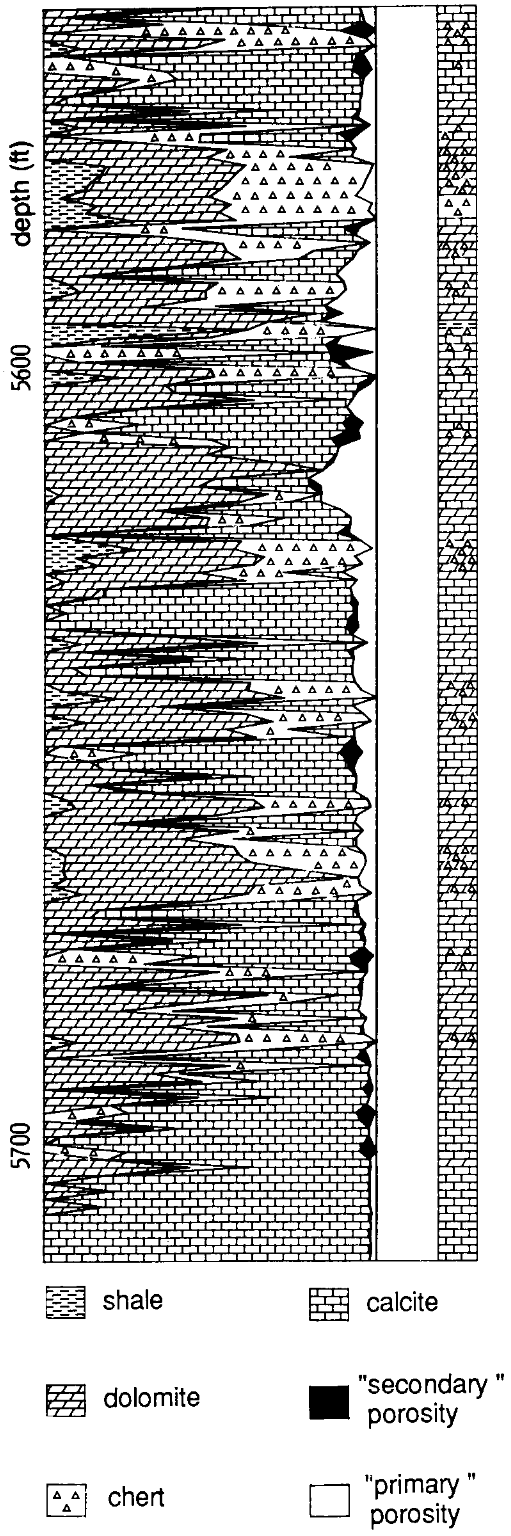

FIGURE 2 (LEFT)—MINERALOGIC PROFILE OF VIOLA LIMESTONE IN A STUDY-AREA WELL COMPUTED FROM LOGS USING MATRIX ALGEBRA.

ternary diagram is highly unconventional because many of the nodes are associated with negative component fractions. Points which lie above the calcite end member indicate systematic coarse-grade porosity which is generally associated with residual chert and weathered carbonate. Points below the dolomite-chert line suggest the influence of minor amounts of shale as an additional component. Following this line of interpretation, the diagram was subdivided into six lithofacies types. The fundamental calcite-dolomite-chert triangle was allocated between three facies of limestone, dolomite, and chert as determined by the dominance of one of the end members. The remainder of the diagram was divided into three lithofacies based on residual chert with carbonate, carbonate with residual chert, and shaly carbonate.

The lithofacies subdivision of the diagram allowed the four grids of compositional variation to be fused in a single lithofacies grid presentation, where each set of four grid nodes could be allocated to one or another of the six lithofacies. The result is shown in fig. 4, where the size of the grid cells conforms approximately to the density of well control in the area.

A facies interpreted as residual chert forms a belt which borders the Central Kansas uplift to the north and parallels the subcrop of the Viola. The extension of this facies to the south, together with isolated outliers, picks up the trend of the Pratt anticline feature. This petrophysical interpretation shows strong concordance with a map of residual chert thickness determined from cuttings logs by Adkison (1972). The facies designated as carbonate with subsidary residual chert is located mainly in the center of the area in close association with the residual chert facies. Several sample logs in this area report thin developments of shale and sandstone which are very similar to those of overlying Kinderhook rocks. Adkison (1972) has suggested that "some of the non-carbonate clastic deposits are probably misidentified cavern fillings of post-Viola age." If this interpretation is correct, then the two residual facies are paleogeomorphic, the former representing a detritus regolith and the latter karstic solution-weathered carbonates.

As a consequence of detailed core studies, St. Clair (1981) concluded that the Viola in this region could be subdivided into thick alternating units of limestone and cherty dolomitic limestone which appeared to be tilted westward. In tracing lateral facies variations within these units, she was able to detect a fundamental arrangement of facies belts paralleling the margin of the ancient Central Kansas arch that existed to the north. Bornemann and Doveton (1983) suggested that the combined effects of depositional facies patterns and subsequent erosional bevelling of the Viola were the key to explaining the regional disposition of the dolomite and limestone facies of the log-analysis map.

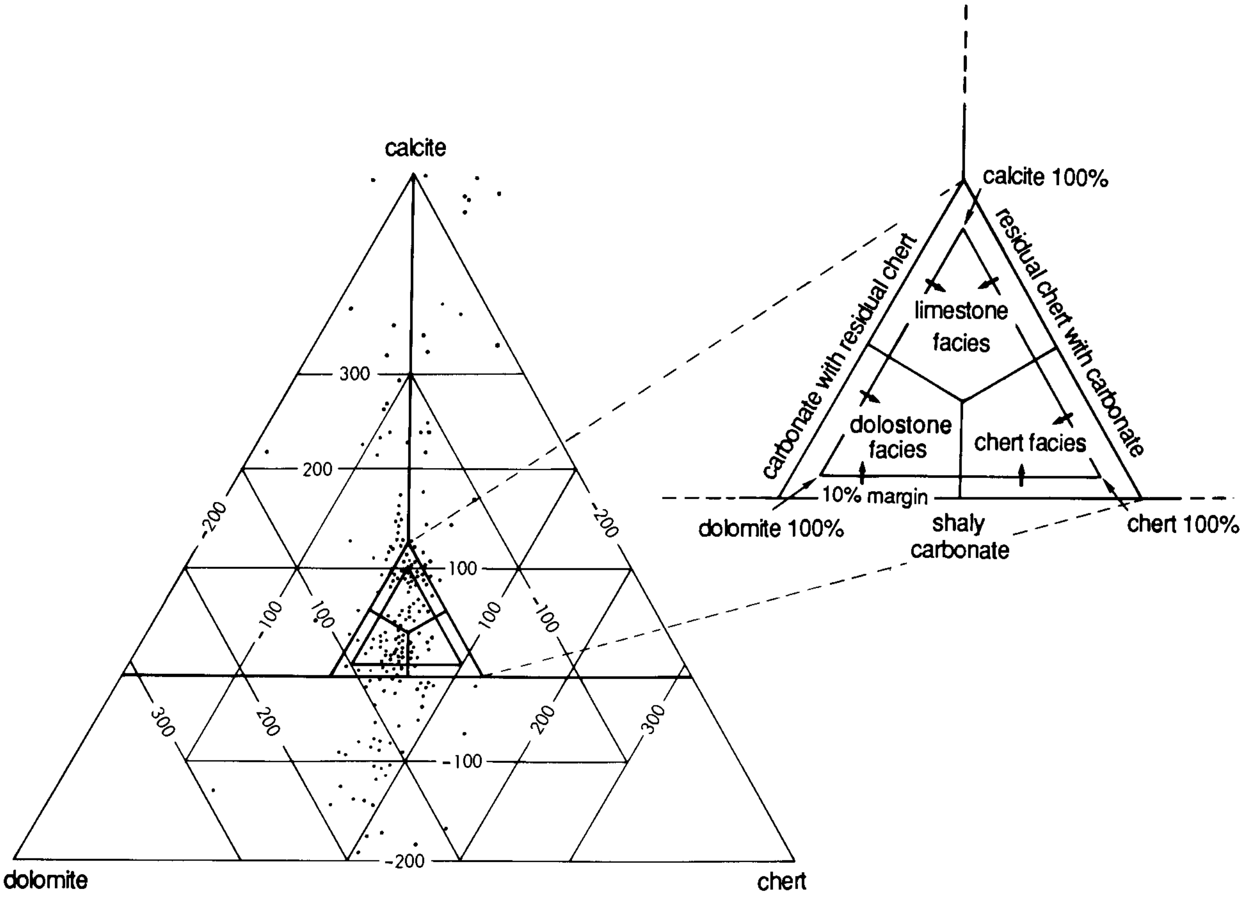

FIGURE 3—Ternary diagram of computed mineral percentages at map grid nodes, indexed with lithofacies subdivisions.

Of particular interest on the petrophysical-facies map is the marked grain, whose lineaments strike approximately north-northeast–south-southwest and northwest-southeast and can be related to features of both structure and thickness. These lineaments were observed by both Rich (1935) and Brewer (1959) who ascribed these to fault lines and fractures. The same pattern is discriminated by second-derivative maps from the recent aeromagnetic survey of Kansas (Yarger, 1981) and may represent block faulting and possible dike intrusion as a southerly continuation of features associated with the Proterozoic Central North American rift system.

Case study 2: Simpson Group

The Simpson Group in the study area consists of sandstones, shales, and sandy carbonates in deposits which have complex lenticular geometry, particularly in the upper part of the section. A satisfactory understanding of lithofacies relationships requires an analysis which extends beyond mapping in the two dimensions of geographic space to the incorporation of variability in the third dimension of depth. The limitation of conventional lithofacies maps for this purpose was recognized by Krumbein and Libby (1957). They introduced a new concept in the production of "vertical variability maps" based on statistical moments. The moments of the vertical distribution of any given lithology within a section can be calculated at well control and interpolated across a region as maps which trace geometrical changes of the lithology in three dimensions. Their ideas were used as the basis for a new method to map shale variability (and by implication, sandstone and carbonate geometry) of the Simpson Group in three dimensions from computer processing of gamma-ray logs from wells in the area.

A gamma-ray log of the Simpson Group is shown from a representative well in fig. 5. The gamma-ray log is a measure of the natural radioactivity of the section and makes a basic distinction between radioactive shales and less radioactive sandstones and carbonates. Baselines which typify sandstones or carbonates at one extreme and shales at the

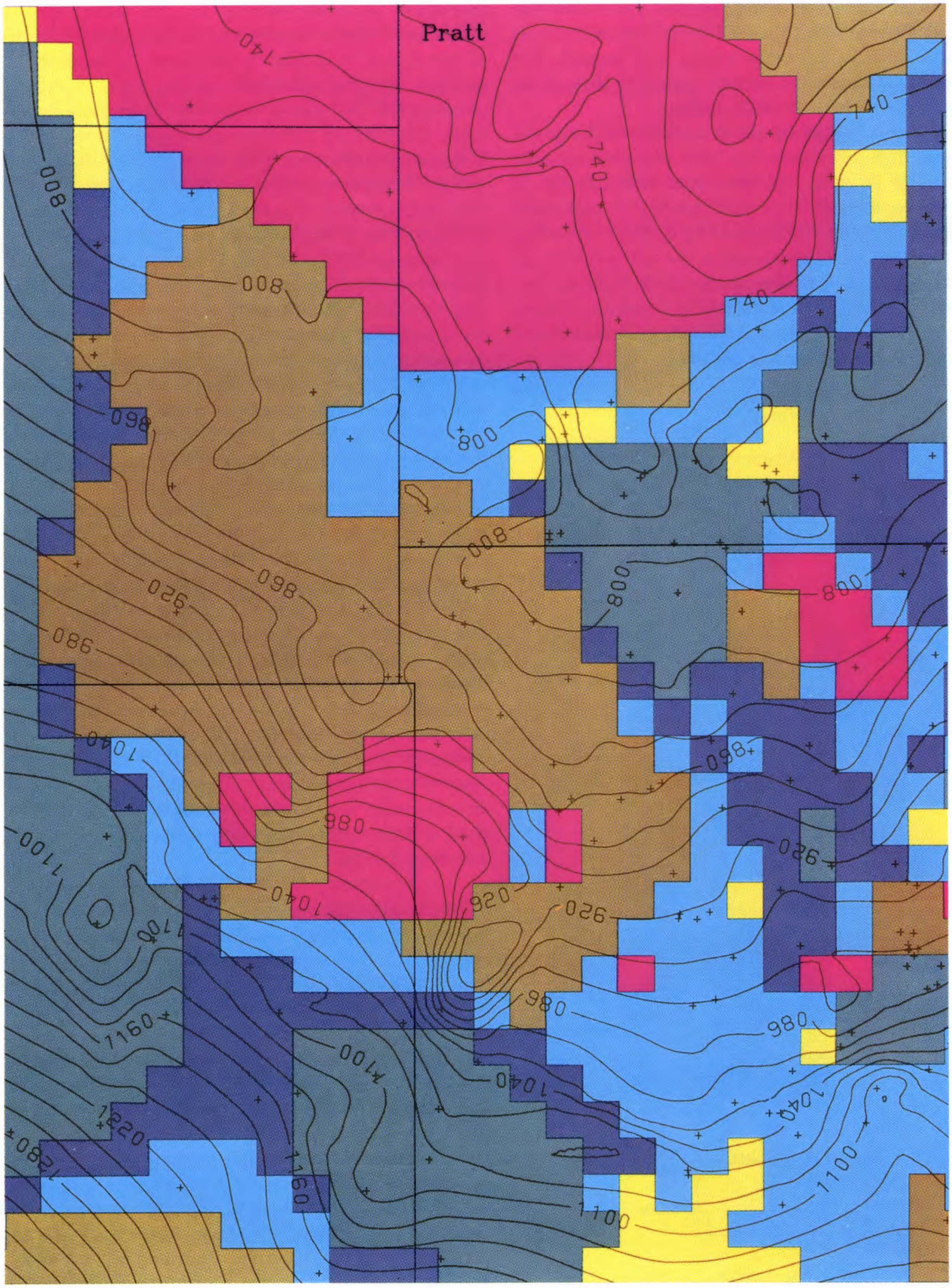

FIGURE 4—Petrophysical lithofacies map of the Viola Limestone.

other provide a new scale of reference (see fig. 5). Through these means, the radioactive count scale may be transformed to a proportional scale which is a semiquantitative measure of shale content used widely by log analysts. The rescaled log expresses the vertical variation in shale content, which must be condensed in some manner in order to be mapped. The most basic measure is the average amount of shale in the section, or the mean of the shale reading.

The mean shale content of the Simpson Group was calculated from gamma-ray logs from 148 wells and contoured across the area. The mean shale ratio map (fig. 6) contains three broad belts arranged in a general north-south orientation. Regions characterized by relatively low-shale (high-sand/carbonate) proportions to the east and west are broken by a high-shale trend centered over the Pratt anticline. This map expresses shale variability as a function of depth within the section. The moment method of Krumbein and Libby (1957) provides the necessary key.

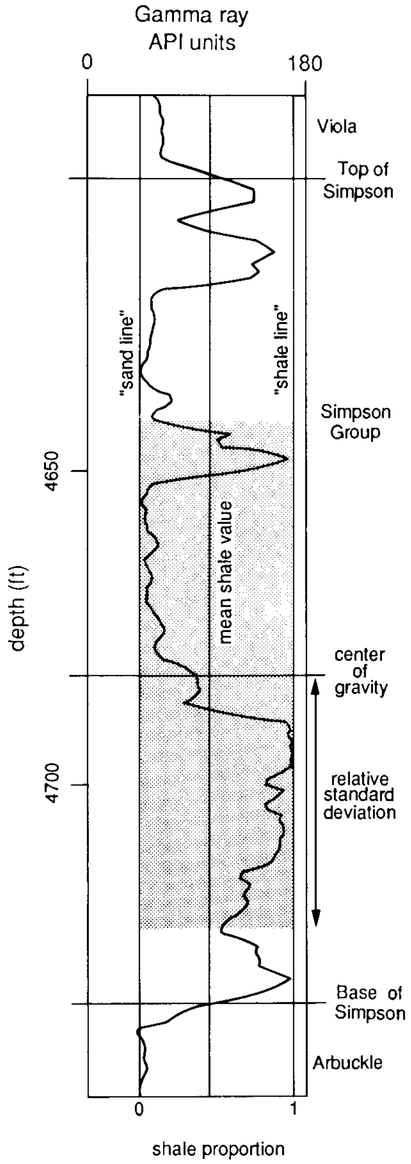

FIGURE 5—GAMMA-RAY LOG OF THE SIMPSON GROUP IN A STUDY-AREA WELL.

The first statistical moment corresponds to the center of gravity and can be calculated from a gamma-ray shale profile as a measure of the center of the shale distribution within the section (see fig. 5). The second moment expresses the relative dispersion of the shale about the center of gravity and is defined in mechanics as the radius of gyration. The third and fourth moments define the relative skewness and "peakedness" of the shale distribution, respectively. Doveton et al. (1984) computed the first two moments of the shale distribution in the Simpson Group section at each well and mapped these quantities across the region. Although these supplementary maps were legitimate measures of vertical variability in shale content, their collective interpretation was conceptually difficult. In order to arrive at a three-dimensional visualization, at least three maps were required to be considered simultaneously and in detail. This mentally taxing problem was resolved by a novel treatment of moment data which utilized the properties of polynomial curves.

A hierarchy of polynomial curves may be computed as a sequence of best-fit regression trends to any gamma-ray shale profile. So, for example, a first-order polynomial is a straight line function which describes a simple trend of shale variability with depth. Higher-order polynomials show increasing complexity of form in the development of curvature, peaks, and troughs, and are progressively closer approximations to the full variability of the shale profile. The coefficients of an m^{th} order polynomial equation are defined by the values of the first in moments. This property is the key to the direct display of variability in three dimensions. Moments of shale vertical variability may be estimated at any undrilled location by interpolation of their calculated values from logs at neighboring wells. By solving the polynomial equation coefficients from these moments, a trend curve of shale variability with depth may be generated. If this procedure is repeated over a grid network of locations which cover the area, the result is a three-dimensional model in which the trend of shale content is estimated both geographically and with respect to depth.

A hierarchy of models will match the different orders of polynomials and number of moments utilized, ranging from simple to more complex representations. Higher order models are successively closer approximations to the total variability expressed by the original gamma-ray logs. Although an increase in resolution is desirable, it is important to realize that extremely high order moments will account for localized features on the logs which cannot be correlated between wells and should not be interpolated. Therefore, an intermediate-level model is appropriate to absorb systematic trends of areal significance for realistic mapping.

As an example of this procedure, a fourth-order trend profile of shale content is shown as a north-south section in fig. 7. The geographic traces of these profiles are marked as lines in fig. 6. These sections are oriented at approximately right angles to the regional depositional strike. A basal sandstone unit occurs at the southern end, whose presence is confirmed by cuttings reports in the area. This represents either a basal transgressive sand facies of the

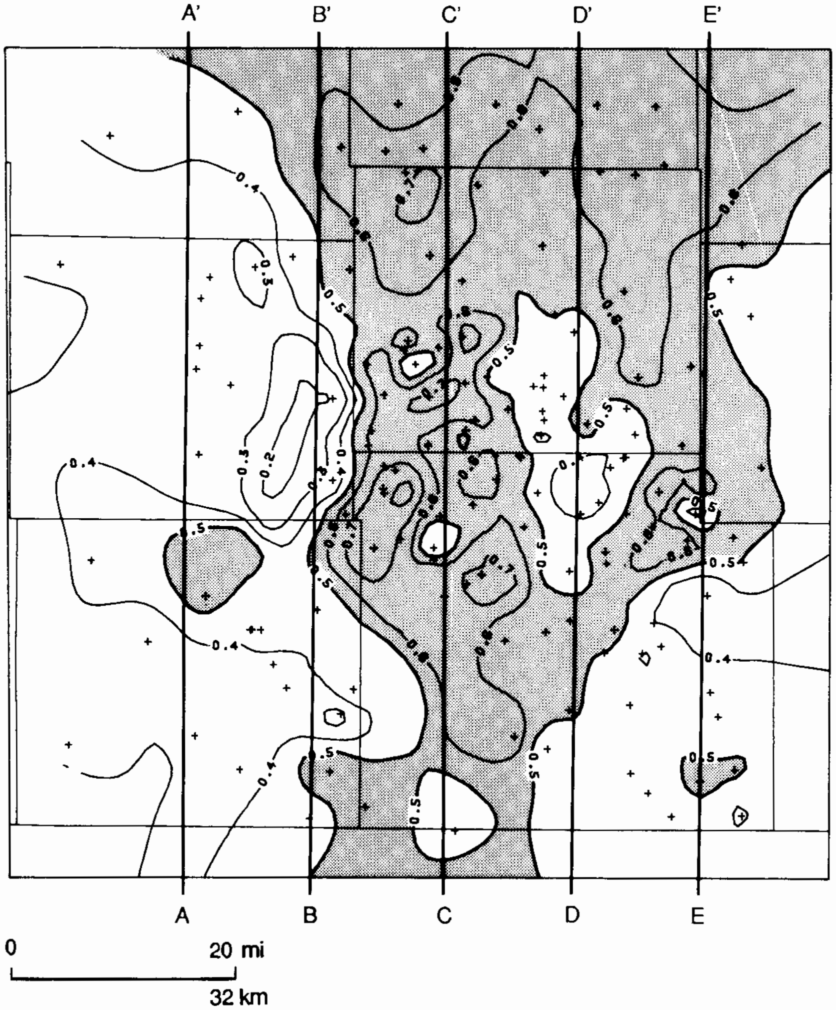

FIGURE 6—MEAN SHALE RATIO MAP OF SIMPSON GROUP. Ratios higher than 0.5 are shaded. Lines locate cross section of fig. 7.

McLish Formation or the extreme northern edge of the Oil Creek Formation. Features with low shale content in the upper bromide unit are elongated sandstone bodies that contain small localized oil fields, generally with thin pay zones near the top of the sandstone.

Both Doveton et al. (1984) and Doveton (1986) described the results of computing trend profiles oriented east-west and the generation of a horizontal slice map which expresses the trend of shale at the base of the Simpson Group across the area. In addition, they discussed the application of polynomial-curve properties in the definition of the depths of shale minima and maxima as well as inflection point boundaries. The location of curve-inflection points were used as a device of "polynomial stratigraphy" in the spatial definition of lithofacies boundaries in three dimensions.

Summary

The two case studies of this paper demonstrate the application of computer processing to borehole geophysics data in the generation of lithofacies maps in both two and three dimensions. Information drawn from cuttings, core, and other sources obviously is crucial to both monitor the basic validity of well-log maps and to provide meaning to any patterns which emerge. In this sense, logging information can be thought of as remotely sensed data and conventional geological samples as "ground truth."

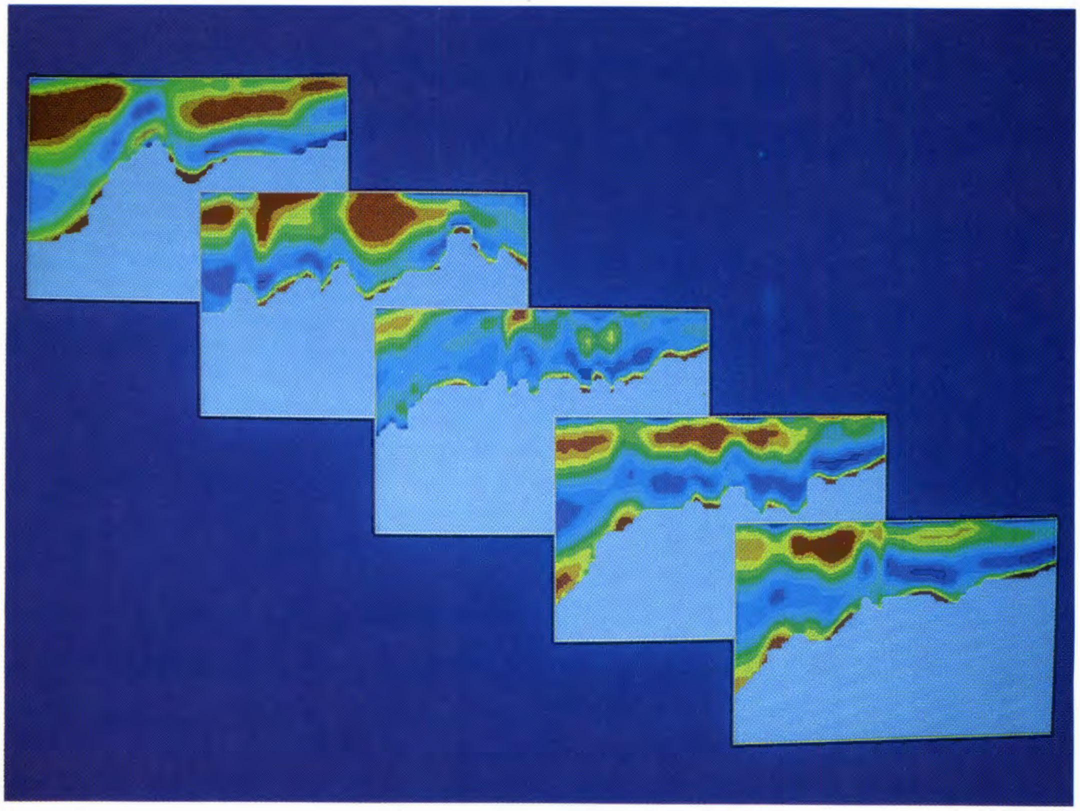

FIGURE 7—QUARTIC SHALE PROPORTION-TREND PROFILE OF NORTH-SOUTH CROSS SECTION (lines shown in fig. 6).

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