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**WELL LOG ANALYSIS AS A TOOL FOR LITHOFACIES
DETERMINATION IN THE VIOLA LIMESTONE (ORDOVICIAN) OF
SOUTH-CENTRAL KANSAS**

by

Erhard Bornemann

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ERHARD BORNEMANN

Diplom-Geologe, Technische Universität Hannover, 1974
M.A., Syracuse University, 1978

ABSTRACT OF DISSERTATION

Submitted to the Graduate School of Syracuse University
in partial fulfillment of the requirement for the degree
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Date

Advisor

For the Department of Geology

ABSTRACT

A technique for lithofacies analysis based on geophysical well logs is developed and applied to the Viola Limestone (Ordovician) of south-central Kansas.

The computation of porosity and a suite of three mineralogical components from the neutron, density, and sonic log ("porosity logs") is a well established procedure in well log analysis, but has been under the constraint that all three logs had to be available in an individual well. This condition is seldom met in the majority of wells needed as control points for a lithofacies analysis.

The advanced approach is based on the average log responses calculated individually for each porosity log available at a control point over a given stratigraphic interval. Errors in log measurements were normalized by spatial regression analysis applied to the log responses of a "calibration unit" within the Viola. Each set of corrected average log responses is used to calculate a grid which provides an estimate of the spatial variation of the physical parameter measured by the neutron, density, or sonic log. The grids are contiguous and allow the calculation of porosity and three mineralogical constituents at grid nodes which correspond to geographical locations. The computed mineral fractions were classified into lithologies and a suite of lithofacies maps was constructed. The lithofacies maps in conjunction with a set of structure maps were interpreted with regard to the Viola's structural history and speculations on depositional and diagenetic processes are put forward.

This method taps data resources commonly not employed in lithofacies studies and allows a speedy analysis as the procedure utilizes digitized log traces and interactive computer programs for well log analysis and automated mapping. Keywords: Lithofacies analysis, Ordovician, Viola Limestone, Kansas, log analysis, automated mapping.

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I. INTRODUCTION

Purpose of Study

The main task set for this research is to develop a new method for lithofacies analysis based on geophysical well logs. This involves the utilization of numerical data processing techniques employing interactive computer programs. The Viola Limestone (Upper and Middle Ordovician) in the subsurface of south-central Kansas was chosen as a test example. The evaluation of the areal variation of the Viola Limestone in terms of geometry, principal mineral constituents, and porosity is the aim of the new approach. Studies with similar objectives, but employing traditional subsurface techniques, are common in the academic literature and are routine procedures in oil company exploration programs.

In recent years, simple mathematical models have been devised which relate geophysical log responses to the lithology and pore volume of stratigraphic units. This work has provided the essential impetus for the present study (Savre, 1963; Burke and others, 1967; Harris and McCammon, 1971; Doveton and Cable, 1979). In planning the research, a sequence of four objectives was defined:

- (1) Evaluate mineralogical/porosity variation in logged Viola sections of individual wells of the study area by application of an interactive well log analysis system, KOALA (Kansas On-Line Automated Log Analysis).
- (2) Subdivide the Viola sections into lithological units which are mappable with respect to rock type and unit geometry.
- (3) Generate structural, isopach, and lithofacies maps.

- (4) Interpret the results with regard to the depositional and diagenetic history of the Viola. In addition, attempt to link areal variations of these characteristics with known occurrences of hydrocarbons in the Viola Limestone.

In assembling the data base it became apparent that the first objective could not be met in the vast majority of wells, since the typical log suite was inadequate to evaluate the mineral composition of the Viola. Three "porosity" logs (neutron, density, and sonic) are required to calculate both porosity and three mineral constituents for a desired interval of a well. A modified strategy was needed which would resolve this problem as suggested by the following considerations.

Although only two individual wells had a complete suite of porosity logs, the entire sample of "porosity" logs was adequate to estimate the areal variation of log responses as continuous surfaces. Consequently, the dilemma of insufficient data could be resolved by the use of spatial coordinates in the log analysis phase. Objectives one and two were redefined as follows:

- (1) Compute the average log response of the Viola Limestone for each of the "porosity" logs at every well location. Calculate a grid from the average responses for each of the three "porosity" logs.
- (2) Use the grids which contain the neutron, density, and sonic log responses to calculate porosity and three principal mineral constituents of the Viola Limestone as a whole.

The crucial operations of log normalization and mineralogical/porosity solutions from log responses were transferred from KOALA (the log analysis package) to Terraplot (the automated contouring package). The functions could be programmed within Terraplot by use of trend surface analysis, grid-to-grid operations, and data retrieval utility routines. All these procedures will be explained in detail in a later chapter.

The fusion of spatial and geophysical log analysis in a single operative module is an approach which could have wide applicability. Its strengths and drawbacks are critically examined in the production of the Viola lithofacies synthesis.

Previous Work

Combinations of structure, isopach, and facies maps have been used over the years as aids for interpretation of the geologic history of a stratigraphic interval over an area of investigation (King, 1942; Krumbein, 1948; Wengerd, 1948; Schramm, 1964; Adkison, 1972). Work on a unit that occurs entirely in the subsurface over the area studied, is generally limited to the preparation of facies maps representing its major lithological components. These maps are termed lithofacies maps and may be constructed in a variety of ways. Common methods are to contour the percentage of one component (isofacies map) or the ratio of one lithology to another (lithologic ratio map).

A map representing a combination of lithologies is constructed usually with the aid of a compositional triangle. The triangle vertices generally represent 100 percent of either a combination of components or of a single constituent, while the area of the triangle is divided into fields that are defined by limiting percentage values between the end members (Krumbein and Sloss, 1951). The choice of endmembers and of the "limiting percentage values" should result in a suite of combinations of components, which are diagnostic for the problem to be solved. In most cases, combinations are sought which can be interpreted with regard to the environment of deposition.

A somewhat different approach was advanced by Pelto (1954), who conceived the "classifying function" as a means of mapping a multi-component

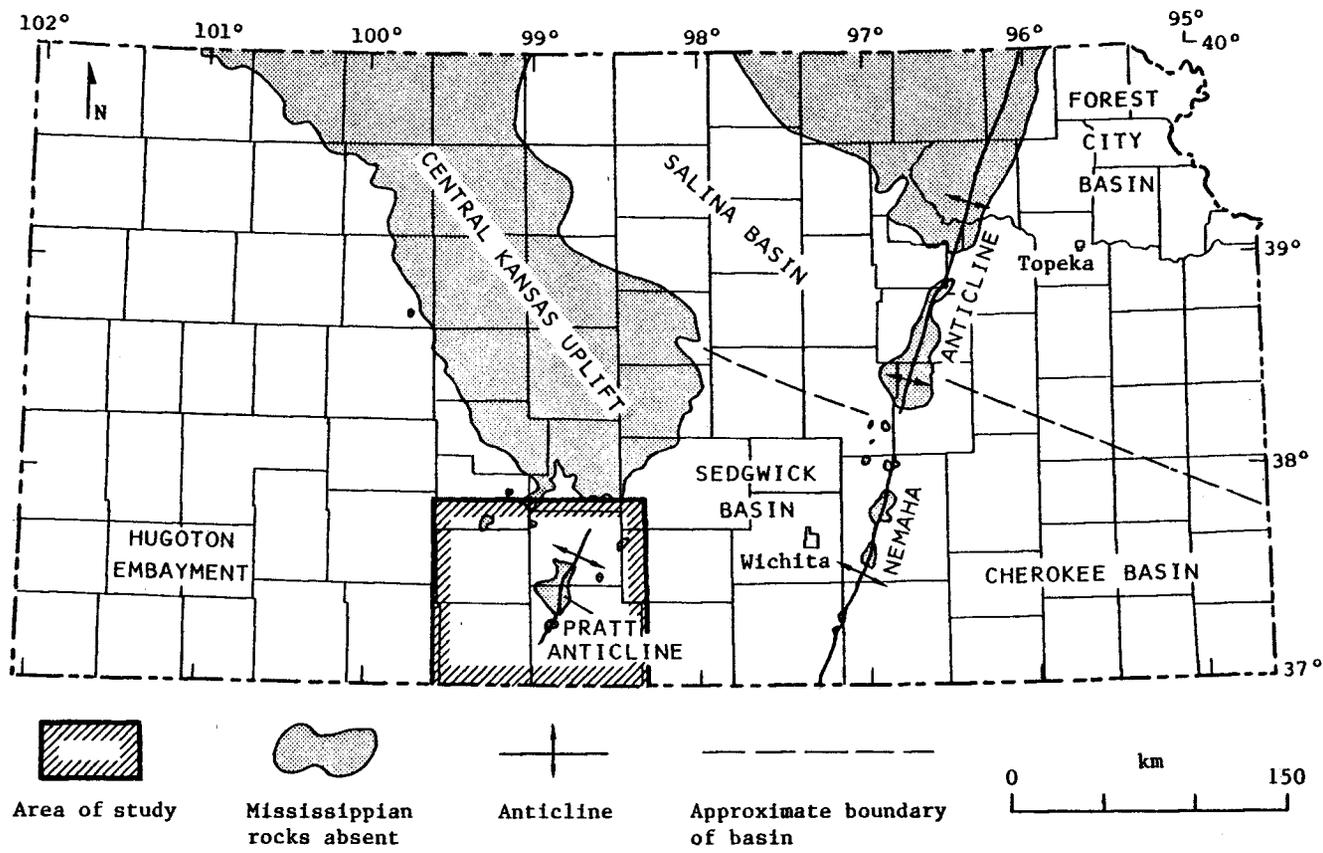


Figure 1. Map showing major structural features in the subsurface of Kansas and location of study area (after Merriam, 1963).

system. A compositional triangle is divided into seven sectors, each subdivided by classifying function lines which express the distance of a control point to a sector endmember. In the production of lithofacies maps, each sector is assigned a color or pattern indicating the main lithology, with the values of the classifying function contoured on top, giving the amount of mixture of the main lithology with some other lithologic component.

Wengerd (1948) published a lithofacies study on the Viola Limestone and the overlying Fernvale Limestone of south-central Oklahoma. Although he collected some of his samples from surface sections, including the Viola Limestone type section on the flanks of the Arbuckle Mountains, most of his data were derived from well-cuttings. The Viola of this area is composed primarily of cherty limestone with some dolomite, the latter being the dominant lithology in one area only. Wengerd subdivided the Viola into four principal members on the basis of chert content, insoluble residue percentage, texture, and color. Structure, isopach, and two isofacies maps, showing chert and insoluble residue content, were constructed and used to divide the Viola geographically into a platform facies and a platform slope facies, as well as into six provinces having a distinct lithologic character. Wengerd's main conclusions regarding the Viola are summarized below:

- (1) Only modest epeirogenic movements affected the Viola basin of deposition.
- (2) No correlation could be established between amount of chert or dolomite and areas that were exposed to erosion several times throughout geologic history.
- (3) Areas favorable to hydrocarbon accumulations are not those dominated by porous dolomite, but those that developed secondary porosity associated with faulting and intraformational unconformities.

A report by Adkison (1972) on Middle and Upper Ordovician rocks of south-central Kansas, covering the eastern half of the area analyzed in this thesis, includes a chert isofacies map of the Viola Limestone. Data for this map are based on sample logs from description of well-cuttings. Adkison notes the correlation of residual chert with structural highs and concludes:

The Viola was subjected to postdepositional alterations, such as dolomitization and solution, at several times before final burial, and the alterations probably improved the permeability and porosity of the formation in many places. . . (Adkison, 1972).

Lithofacies determination in subsurface carbonate sequences relies traditionally on a quantitative or semi-quantitative description of well-cuttings, i.e., the direct observation of rock samples. The method applied in this research can be described best as a remote-sensing type of approach, where lithologies are derived from traces recorded by geophysical well logs. Most commonly used are logs which record the acoustic travel time, density, and neutron response characteristics of a formation as a continuous function of depth. The latter approach was first described by Savre (1963), who devised charts for a graphical solution of porosity and three mineral constituents from the three logs mentioned above. Based on Savre's work, Burke and others (1967), Harris and McCammon (1971), and Doveton and Cable (1979) transformed the graphical solution into a numerical algorithm, employing matrix algebra. In addition, Doveton and Cable (1979) describe the advantages of an interactive well log analysis system for the solution of complex lithologies.

Location and Geomorphic Setting

The area studied covers approximately 10,000 square kilometers in south-central Kansas, including Kiowa, Pratt, Comanche, and Barber

counties, as well as portions of adjacent counties (Fig. 2). It is located 170 kilometers west of Wichita, the largest city in Kansas and the center of the State's oil industry.

With regard to the major physical division of the United States, Kansas is part of the Interior Plains, of which two subdivisions, the Great Plains and the Central Lowland, are represented in the State (Schoewe, 1949) and likewise in the study area (Fig. 2). In the north, the Central Lowland province is represented by the Arkansas River Lowlands which also constitutes the southwest corner of Barber County. The southern two-thirds belong to the Great Plains. The latter province is subdivided in Kansas into High Plains and Dissected High Plains. Topographic elevation averages 600 meters (1968 ft).

The Arkansas River Lowland is a relatively low lying area which follows the valley of the Arkansas River. It is covered by unconsolidated gravels, silts, and clays of Tertiary and Quaternary age. Inactive Quaternary dune fields are frequent.

The High Plains constitute a rather featureless belt with negligible local relief. Cretaceous and Tertiary rocks are covered by a thin veneer of soil, but are found directly at the surface over wide areas.

The Dissected High Plains form a striking contrast to the physiographic units to the north. They exhibit a local relief of 90 m (300 ft) due to extensive erosion of Permian shales, sandstones, and evaporites, primarily by the Medicine Lodge River and its tributaries, creating a mesa and butte topography (Wilson, 1978). This area, now named the "Red Hills," was known to the Indians as "Medicine Hills" because of the healing qualities of the water of its springs.

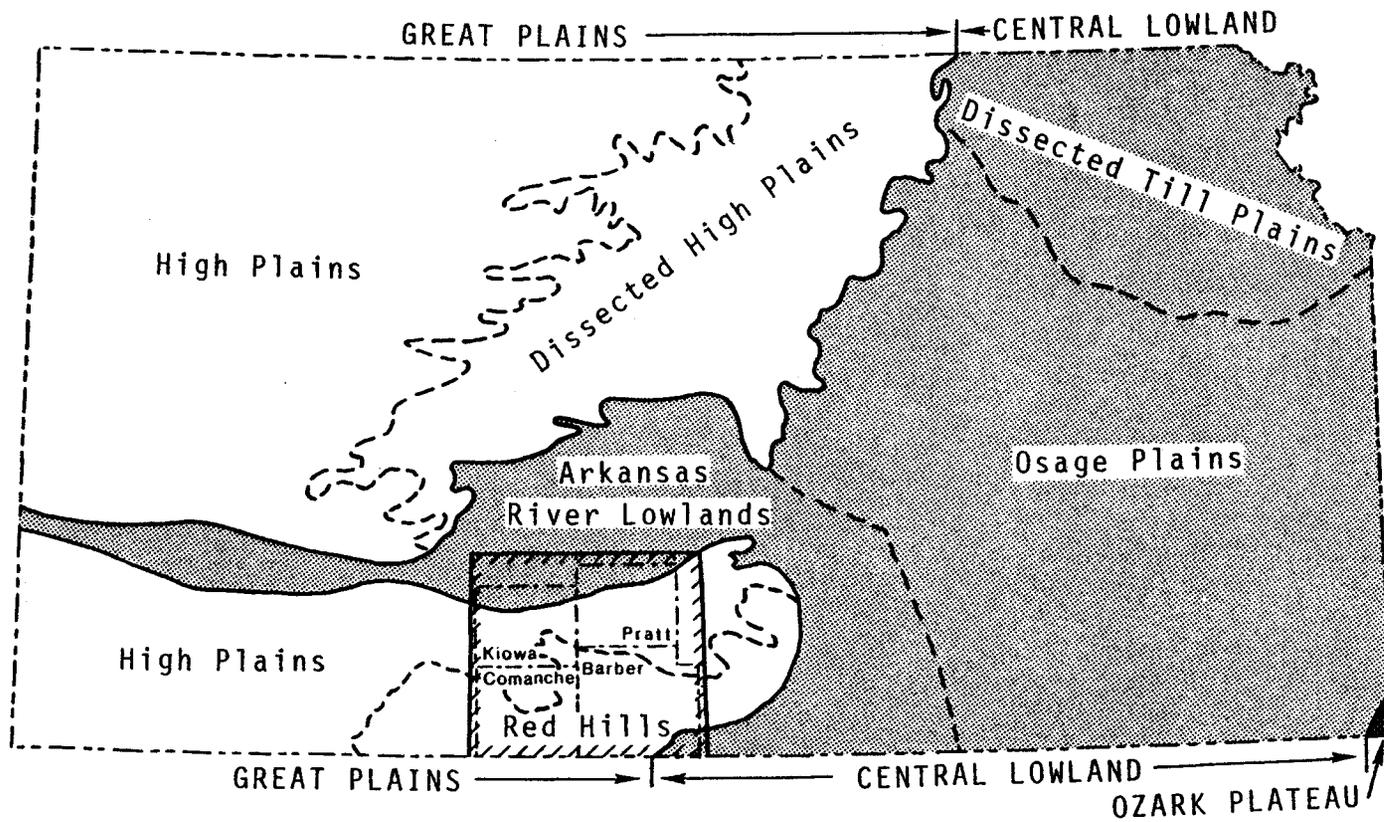


Figure 2. Major geomorphic division of Kansas (simplified from Schoewe, 1949).

II. GEOLOGIC SETTING

Stratigraphy

Ordovician rocks are encountered in the subsurface over almost the entire area of the State of Kansas and are absent only over parts that experienced regional uplift at various times throughout geologic history. The Central Kansas Uplift, the Nemaha Anticline, and the Chautauqua Arch represent major structural features where Ordovician rocks are absent or reduced considerably in thickness (Merriam, 1963).

Petroleum geologists established four divisions of Ordovician rocks in Kansas (Leatherock, 1945 Fig. 3). Names for these units were borrowed from surface sections in neighboring states, (Taylor, 1947). The uppermost formation is the Maquoketa or Sylvan Shale (Upper Ordovician) which is correlated with sections in Iowa (Maquoketa Shale) and Oklahoma (Sylvan Shale). This unit consists of a dolomitic shale at the top, grading into shale towards the base.

The underlying Viola or Kimmswick Limestone (Upper and Middle Ordovician) is separated from the Maquoketa by an unconformity. This formation is referred to as Kimmswick in central and northeastern Kansas, where it is tentatively correlated with the Kimmswick formation of Missouri (Lee, 1943) and the Galena Group in Iowa. In south-central and western Kansas the name Viola is preferred with reference to the Viola Formation of Oklahoma.

The Simpson Group (Middle and upper Lower Ordovician) underlies the Viola over most of Kansas. This group is divided into two formations. The upper unit is the Platteville Formation, which is primarily limestone and dolostone with shale and sandstone interbeds. The

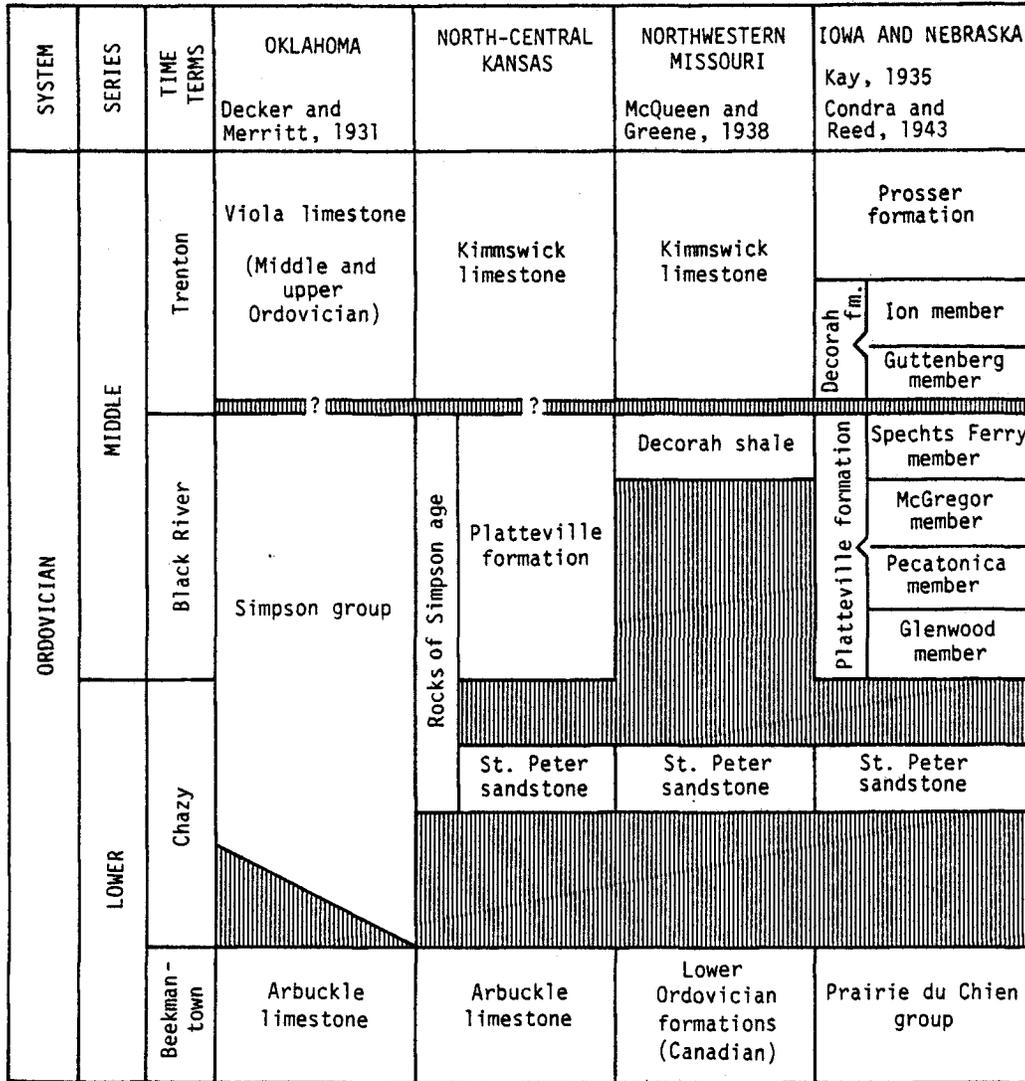


Figure 3. Stratigraphic nomenclature used for Ordovician rocks of the Midcontinent (after Leatherock, 1945).

lower unit, the St. Peter Sandstone, consists of two sandstone units separated by a shale (Merriam, 1963), of which the latter unit comprises the main lithology of the St. Peter in the study area. The oldest Ordovician rocks in Kansas are limestones and dolostones of the Arbuckle Group, which underlies the Simpson Group and is separated from it by a major unconformity.

The stratigraphic nomenclature of the Ordovician system in Kansas and neighboring states is reproduced in Figure 4. Leatherock (1945) published this compilation, and although stratigraphic terminology has been modified since then, based primarily on conodont biostratigraphy by Sweet and Bergstrom (1976), the terms used by Leatherock (1945) are still used today by subsurface geologists.

The Viola Limestone was first described by Taff (1902) from an outcrop near the village of Viola in Johnston County, Oklahoma (Wengerd, 1948). Subsequent studies (Decker, 1930; Decker and Merritt, 1933; Wengerd, 1948) modified Taff's original definition of the Viola. Two members, the Fernvale at the top and the Bromide at the bottom were given formational rank, although arguments regarding the rank of the Fernvale formation continue (Alberstadt, 1973; Amsden, 1979).

The Bromide constitutes the upper formation of the Simpson Group and is encountered in the thick miogeosynclinal sediments of the Quachita facies in Oklahoma (Ireland, 1966), which do not extend into Kansas. The Fernvale of Oklahoma has never been correlated with a rock unit in Kansas and, if ever present, was removed by erosion which affected the Viola as a whole in Kansas before final burial (Lyons, 1966). The Viola was considered by Lee (1956) to be difficult to subdivide because of lateral facies variation, although he did recognize four lithologic zones (Lee, 1949) in the Salina Basin. Taylor (1947) and Ver Wiebe

(1948) divided the Viola into six lithologic zones, mainly on the basis of amount of chert present. Adkison (1972) described three lithologic zones in the Viola Limestone of south-central Kansas. The basal unit consists of a medium to coarse crystalline crinoidal limestone with a thickness of 5-30 ft containing little or no chert. This zone is overlain by a cherty, dolomitic limestone with a thickness of about 15 to 60 ft. Cherty, medium crystalline limestone and dolostone beds make up the upper 20-60 ft of the Viola.

Sedimentation and Paleogeography

Throughout the Ordovician, paleogeography and sedimentation of the cratonic areas of the Midcontinent region were controlled primarily by the Transcontinental Arch and by the position of the North American plate with respect to the earth's latitudinal belts (Ross, 1975). Evidence of late Ordovician glaciation (Sheehan, 1973) as well as latitudinal biotope variations (Berry and Boucot, 1970) supports the hypothesis that extensive polar ice-caps created a more pronounced climatic zonation than that postulated for the Cambrian and Late Silurian (Spjeldnaen, 1976). The Transcontinental Arch represented a nearly continuous land bridge in the Early Ordovician, but became inundated over wide areas at the close of the period. Its known extension covered an area ranging from New Mexico to Minnesota across the Midcontinent (Fig. 4).

Depth of water and the extent to which epicontinental seas covered the Transcontinental Arch and the Canadian Shield determined the nature of marine sediments deposited on the Midcontinent region. During Simpson time, the Transcontinental Arch and the Canadian Shield were exposed over a wide area to erosion and supplied detritus for the

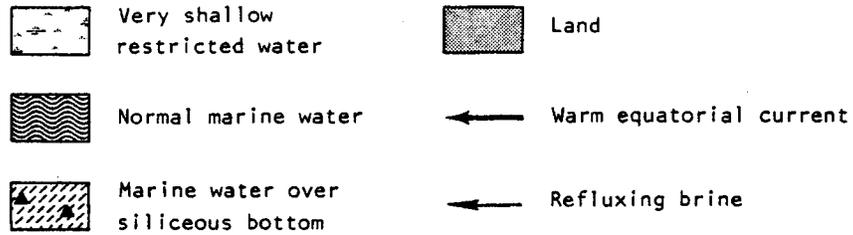
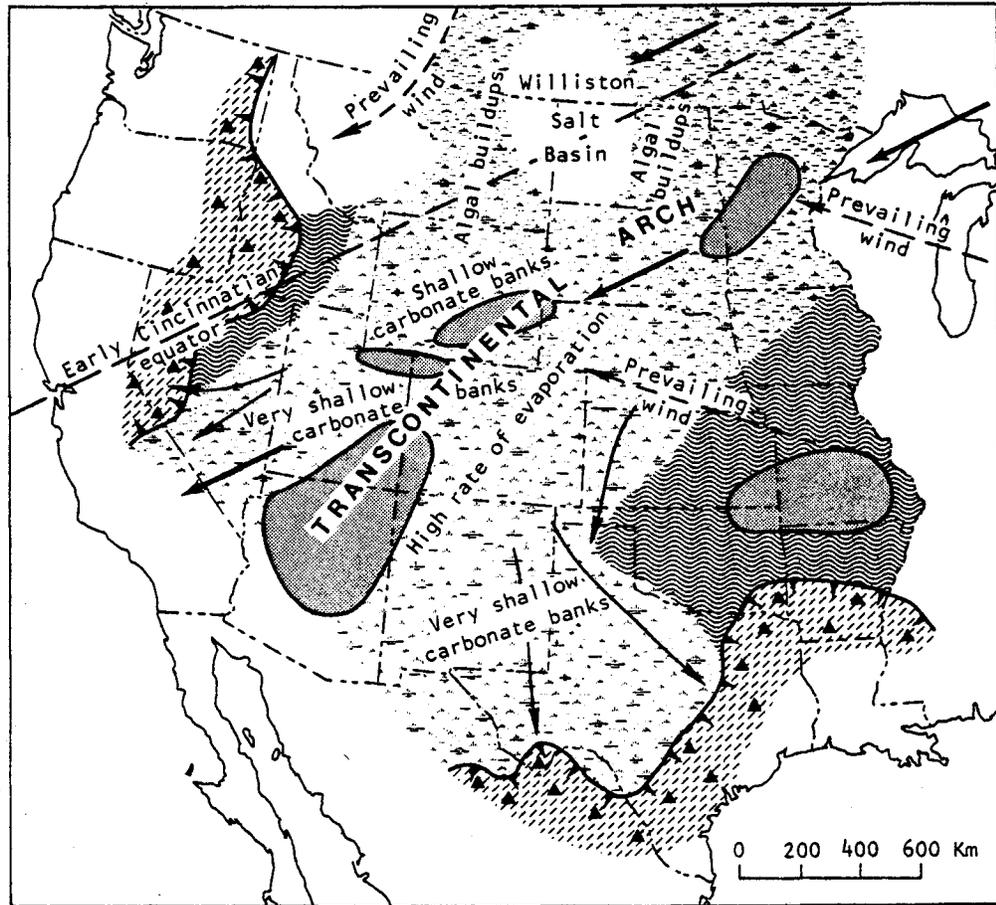


Figure 4. Paleogeography and large scale sedimentary environments of the Midcontinent in late Upper Ordovician time (from Ross, 1976).

shales and sandstones of the Simpson Group. The St. Peter Sandstone was deposited by longshore currents (Amaral and Pryor, 1977) that were driven by the tradewinds. In Viola time, the intracontinental land masses became largely inundated and marine sedimentation on both sides of the Transcontinental Arch was dominated by carbonates. The carbonate sediments of the Viola Limestone and its equivalents, were laid down over areas where normal marine conditions prevailed.

Towards the close of the Ordovician, the epicontinental seas covering the Midcontinent experienced a decrease in water depth accompanied by a restriction of water circulation. This process culminated with the deposition of the dolomitic Maquoketa Shale, which in Iowa contains a dwarf fauna of low diversity indicative of hypersaline water conditions (Agnew and others, 1956).

Structure

Three deformational events occurred in Kansas during the Paleozoic Era (Lee, Leatherock, and Bottinelly, 1948). They influenced the lithology and the final geographic distribution of Paleozoic rocks. Uplifted blocks provided clastic material sources for depositional basins which were covered by carbonate producing shallow seas, while oscillation of coastlines led to erosion of previously deposited strata. Overall, the structural geology of Kansas is not complex when compared with that found in orogenic belts.

Precambrian igneous and metamorphic rocks form the basement. They are part of the nucleus of the North American plate exposed as the Canadian Shield in the northern regions of the continent. These rigid basement rocks are covered by a thin veneer, generally less than 2900 meters (9500 ft), of sedimentary strata (Merriam, 1963). Vertical

movement of basement blocks dominated (Clark, 1932) and created the regional structural elements that control the subsurface geology of Kansas and caused folding of the sedimentary cover. These anticlinal structures contain the most important hydrocarbon producing reservoirs in the State of Kansas. The size of the long axes of these anticlines range in most cases between one and five kilometers (one and three miles), as deduced from oil field contour maps (Merriam, 1963).

The Paleozoic sediments of Kansas were first affected by a tectonic event occurring in Early Paleozoic time, prior to the deposition of the Simpson Group. As shown by the convergence map between the top of the Precambrian and the top of the Arbuckle Group, a structural high, the Southeast Nebraska Arch, was formed accompanied by a broad structural low, the Southwest Kansas Basin (Fig. 6A). An early ancestor of the Central Kansas Uplift began its structural history as suggested by the 250 foot contour in the northwestern area of the map (Merriam, 1963). The Southeast Nebraska Arch was below sea level during most of the period of Arbuckle sedimentation, as indicated by a complete section of the Arbuckle Group on its flanks. These rocks were stripped off the arch by erosion before Simpson time (Lee, Leatherock, and Bottinelly, 1948).

Structural development continued with the formation of the Chautauqua Arch, an early phase of the Ozark Uplift, and the Ancestral Central Kansas Uplift, separating two subsiding basins, the North Kansas Basin and the Southwest Kansas Basin (Fig. 6B). Rich (1933) coined the term Central Kansas Arch, in which he included the Ancestral Kansas Uplift, the Chautauqua Arch and a structural high area connecting the two. Extensive post-Mississippian erosion of older strata from the uplifted areas makes it difficult to define the phases of uplift. Adkison (1972) believes that deposition of the Simpson Group was

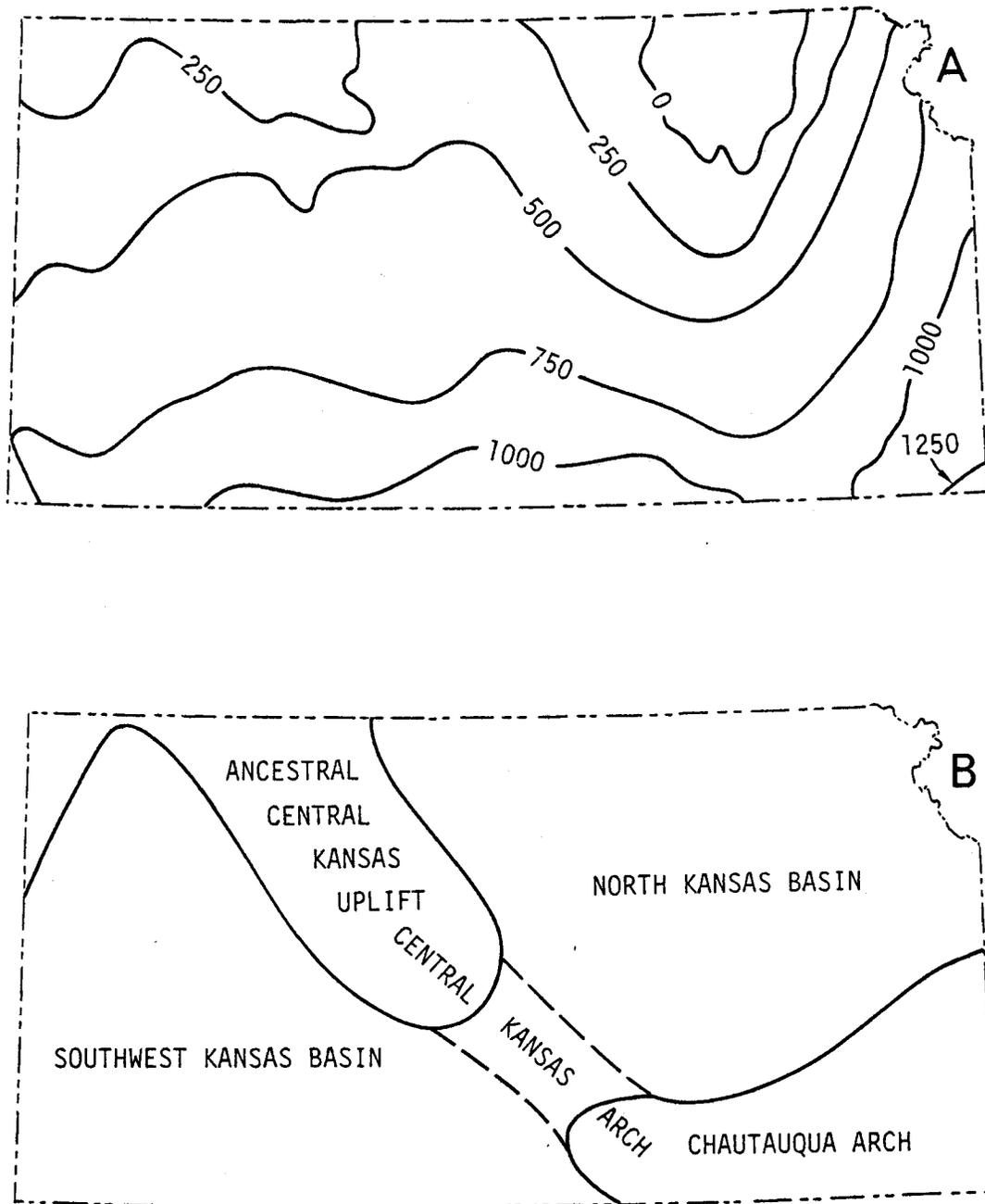


Figure 5. A: Isopach map between top of Precambrian and top of Arbuckle Group (after Merriam, 1963).

B: Pre-Mississippian structures (after Merriam, 1963).

influenced, as indicated by its general thinning along the flanks of the uplifts. During much of late Simpson time parts of the Chautauqua Arch became a source of terrigenous sediments, manifested in the scarcity or absence of carbonate sediments in the Upper Simpson Group surrounding it (Adkison, 1972).

Deposition of the Viola Limestone followed the same pattern with continuing subsidence of the basins and uplift of the structural blocks. This unit once covered the whole of Kansas with the exception of the higher parts of the Chautauqua Arch which constituted a broad land mass during late Viola time. It is shown in Figure 4 as the unnamed land mass stretching over the southeast corner of Kansas, northeast Oklahoma, and much of southern Missouri.

The last and most important structural event in Paleozoic time began its final phase at the close of the Mississippian Period and culminated in Early Pennsylvanian time. Initial movements, that started the Nemaha Anticline, are recognized in Early Mississippian time and structural activity did not cease until Early Permian time (Lee, 1943). Widespread uplift that included basinal areas, followed by erosion, created a major unconformity which was buried by Pennsylvanian sediments. In the Early Pennsylvanian, the Central Kansas Uplift, the Nemaha Anticline, and the Pratt Anticline became established as the dominant structural highs separated by the basinal areas shown in Figure 1. The Chautauqua Arch became inactive as a high land and formed the Cherokee Basin.

The Viola Limestone was affected in Late Silurian and Early Pennsylvanian time by widespread erosion that removed this unit from the Central Kansas Uplift, the Chautauqua Arch, and parts of the Nemaha

Anticline. Strata recognized as Viola consist largely of residual chert on the flanks of the Central Kansas Uplift and over the Pratt Anticline. The final structural configuration of the Kansas subsurface was shaped by this event. Post-Paleozoic tectonic activity had little influence on these structures although it caused regional warping and some local folding (Adkison, 1972).

III. GEOPHYSICAL WELL LOGS

Well logging is the collection and analysis of borehole measurements that are recorded as a function of depth and are used to determine the physical properties of geologic formations surrounding a borehole. Often used synonyms for well logging are geophysical or petrophysical logging formation evaluation, and electrical logging. The first well log ever recorded was a resistivity trace measured by the brothers Schlumberger in France in 1927. Of the logs used in this research, the gamma ray log was introduced in the late thirties and the neutron, density, and sonic log (the so called "porosity" logs) were introduced in the late forties and early fifties. The gamma ray log and the "porosity" logs provided most of the data used in the lithofacies analysis of the Viola Limestone. Their operational theory, as well as possibilities of application, are examined in the following paragraphs, which to a large extent are based on information contained in well logging manuals published by service companies such as Schlumberger, Dresser Atlas, and Welex.

The Gamma Ray Log

A majority of the chemical elements consist of a mixture of two or more isotopes, which are atoms of the same element but of different mass. Many of the natural occurring isotopes are unstable and decay into a stable state emitting radiation known as alpha rays (Helium nuclei), beta rays (electrons) and gamma rays (electromagnetic waves). In practice, only the gamma rays are measured in a borehole, since alpha and beta rays are easily absorbed and do not reach the detectors in gamma ray logging tools. Unstable isotopes of the uranium-radium

series, the thorium series, and the potassium-40 isotope provide most of the radiation measured by the gamma log, since only they occur in appreciable quantities in nature. Although gamma rays have a higher penetration depth than alpha and beta rays, they too are absorbed by material such as geologic formations and borehole mud. Ninety percent of the radiation reaching the detector are estimated to originate within the first 15 centimeters (6 inches) of a formation surrounding a borehole, which prescribes a radius of investigation for the tool.

Gamma ray emission is a random process and varies in quantity with time. The radioactive count is therefore a statistical quantity whose fluctuations are smoothed by an averaging (time constant) circuit. Additional smoothing of the count rate is dependent on the logging speed at which the tool is raised through the borehole. The time constant (i.e., length of time radiation is measured before it is recorded) and logging speed have to be selected in a way that statistical noise is minimized but systematic minor variations in radiation intensity are not lost in the averaging process. Measurement of the statistical background radiation is made during each logging operation by holding the tool stationary for several minutes. A record of this measurement is included with the log, and is used to differentiate noise from minor systematic variation.

Two types of measurement techniques are commonly used in gamma log tool design. The first is the Geiger-Mueller counter based on the ionization of gas by incident gamma rays. This tool is fairly insensitive to borehole temperatures and is used to log boreholes with a small diameter as it does not require insulation. The other technique is based on the scintillation principle. Certain crystals when bombarded

with gamma rays, produce tiny flashes of light which are converted to electrical pulses. These pulses are proportional to the amount of incident gamma rays. Tools designed with this physical principal are very efficient, i.e., a higher logging speed can be used for the same time constant. On the other hand, they require extensive insulation from borehole temperatures which restricts their use to wide diameter holes.

Calibration of the tool in the field is performed prior to every logging run by exposing the tool to a standard calibrator. All modern logs are recorded in API gamma ray units which are scaled so that an average Midcontinent shale registers about 100 units. Limestone, dolostone and non-shaly sandstones register approximately 20 to 30 API units.

Clay minerals are the principal source of radioactive isotopes. Chemical analysis of shales combined with gamma ray measurements led to the generalized conclusion that up to 20 percent of the radiation emitted is caused by potassium-40. The remainder is largely due to isotopes of the thorium-series and uranium, while the latter is a dominant radiation source in shales that were deposited under reducing conditions. These shales are commonly called "black radioactive shales" due to their excessive gamma log readings which make them excellent marker beds in stratigraphic applications.

Differing borehole conditions introduce minor errors into gamma log readings. Factors such as mud type, cement, and casing increase the absorption of gamma rays but do not eliminate the intensity differences of "radioactive" versus "non-radioactive" formations.

The use of the gamma log for stratigraphic correlation is widely practiced. In addition, it is applied to detect and evaluate mineral deposits containing uranium or potash (Tixier and Alger, 1967), although

its main application lies in the exploration and evaluation of hydrocarbon reservoirs, where it is used primarily as a "shale" log to distinguish shales from "clean formations." "Clean formations" are sandstones, limestones and dolostones which in general do not contain a large amount of radioactive isotopes. The left trace of Figure 9 is a gamma log with "clean" formations registered to the left of the log track and shales to the right. The division of a gamma log trace into "clean" units and shale units is often used in lithofacies studies of sandstone/shale formations (Krumbein, 1948). The thickness of shales and sandstones of a given interval are measured and percentages or a ratio between the two lithologies is calculated. Results are then displayed in form of a contour map. This technique of quantitative lithofacies analysis is restricted to sandstone/shale sections, since the gamma log characteristics of stratigraphic sequences that consist of limestones and dolostones generally do not allow the two carbonate types to be distinguished.

Another application of the gamma log as a "shale" log is as an aid in formation evaluation. This procedure includes the calculation of the pore volume of a formation as well as of the water and hydrocarbon saturation from "porosity" and resistivity logs. The readings of both log types are influenced by the shale content of a formation (Poupon and Gaynard, 1970). Reasonable results can only be obtained if a reliable estimate of the shale content of a formation is available, and this is calculated from the gamma log by a simple method. Two parallel vertical lines are drawn on the log, one representing the average reading of "clean" formations (zero percent shale) while the other typifies the average response of shales. Gamma log readings that fall between these two lines are then related by an empirical curve to the percentage of clay minerals present in the formation.

A different application of the gamma log is demonstrated by Selley (1976), who advocates a "cowboy geology" approach to the interpretation of sedimentary environments in sand/shale sediments of the North Sea. He uses the gamma log in conjunction with traditional geological data such as presence of glauconite and carbonaceous matter obtained from well cuttings. The shape of the gamma log "kicks" reflects sharp or gradational contacts between shaly and "clean" formations. Gradational positive or negative slope changes can be interpreted either as upward fining or upward coarsening grain size profiles. Selley (1976) was able to distinguish a total of eight environments ranging from submarine fan sediments to deltaic distributary channels. He repeatedly stresses the point that all available information should be used to aid and check on the interpretation of sedimentary environments derived from the analysis of gamma log traces.

The Neutron Log

The neutron logging device represents the only "porosity" tool that was developed directly for the purpose of measuring formation porosity. It contains a source element from which high energy neutrons radiate spherically into the surrounding formation. The neutrons collide with nuclei in the formation and experience a progressive reduction in energy. The greatest energy losses occur when a neutron strikes a nucleus of similar mass. Primary reduction in energy, therefore, occurs in the collision of neutrons with hydrogen nuclei. Eventually, each neutron is reduced to thermal velocity and captured by a nucleus which emits capture gamma rays. Depending on the tool, one or two detector elements measure either the amount of slowed-down neutrons or the capture gamma rays.

In typical reservoir rocks such as sandstones and carbonates which are free of any considerable amount of shale, the reduction of neutron flux is a function of the amount of hydrogen present, and consequently is a measure of the amount of fluid contained in the pore space. Formations with a high porosity result in a low count rate, as most neutrons are captured close to the source element, and slow neutrons and capture gamma rays are absorbed before reaching the receiver. Conversely, a low porosity results in a high count rate as proportionally more neutrons survive the distance to the receiver. This consideration also determines the resolution of the neutron tool which is largely controlled by porosity, and can range from several inches to several feet.

In modern neutron tools (Tittman and others, 1966), source and receiver elements are mounted on a pad which is pressed against the borehole wall by springloaded arms. This design largely eliminates the influence of the borehole diameter and mud on the neutron readings. The recording device is linked with a small computer that continuously converts neutron counts into porosity units. The neutron log of more recent tool designs is arithmetically scaled in limestone porosity units which are calibrated with reference to a variety of limestones with aqueous pore fluid and differing porosities. Porosities recorded in lithologies other than limestone need to be corrected to true porosities by applying charts supplied by the service companies.

Older neutron tools were centered in the borehole and the measurements were recorded as neutron counts. An exponential relation that includes factors as lithology, borehole diameter and hardware characteristics, is applied to relate neutron counts to porosity. This relationship is approximated by a logarithmic equation of the form:

$$\log \phi = C - KN \quad [1]$$

where ϕ = porosity

N = neutron counts

K, C = factors related to lithology, borehole diameter
and tool design

Almost the entire sample of neutron logs available in this study are recorded in counts, and the equation above was applied to convert them into porosities. In order to relate the measured neutron counts to porosity, the constants K and C need to be calculated, which requires at least two points of definition. In the absence of core analyses that would allow a systematic match of neutron counts with measured core porosities, the so called "40 to 1 method" was applied in deriving the two constants. A shale and a tight carbonate zone, both recognizable on all logs, were selected on each log and porosity values of 35 percent and two percent, respectively, were assigned to them. These percentage values are not entirely artificial, as they are averages based on porosity estimates from density and sonic logs as well as from neutron logs that are recorded in porosity units. With these two points, two equations could be set and solved for K and C, which when inserted in the logarithmic equation, provided the relation to compute porosities from neutron counts.

Although the neutron device is mainly used to estimate formation porosity, it should be kept in mind that neutron collisions with hydrogen nuclei make no distinction as to the molecular form of the hydrogen present in the formation. The neutron log, therefore, is primarily a measure of hydrocarbon concentration and its use as a porosity tool is justified only in formations where the vast majority of hydrogen atoms is concentrated in the pore fluid, unless appropriate

corrections are applied. This feature is of advantage in distinguishing certain lithologies. In evaporite sequences, for example, the neutron log can be used to distinguish gypsum from anhydrite due to the crystallization water associated with gypsum. When the neutron log encounters porosities with a high gas saturation, it records extremely low porosities due to the low hydrogen concentration in the pore space.

As already indicated, the neutron log response is related to the hydrogen concentration of the materials measured. This concentration is expressed as the hydrogen index (HI) which can be calculated for any substance by applying simple molecular theory. The hydrogen density (HD) of water is calculated as the ratio of the atomic weight of the hydrogen atoms to the molecular weight of water times the density of water. Using 1 and 16 as the atomic weights for hydrogen and oxygen, the hydrogen density can be expressed as:

$$HD_{H_2O} = \frac{2H}{(2H + O)} * \rho_{H_2O} = 1/9 \quad [2]$$

where ρ_{H_2O} = density of water in grams per cubic centimeter

As the hydrogen index of water is set to one, and serves as standard, the hydrogen index of any compound can be calculated by multiplying its hydrogen density by the factor nine. As an example of how fluids with different hydrocarbon indices can influence porosity readings, the hydrocarbon indices of oil and methane are derived. The chemical composition of oil can be approximated by the formula $n(CH_2)$ where n reflects the molecular complexity of the average hydrocarbon within the oil. For an oil with density of .85, the hydrocarbon index is calculated as:

$$HI_{oil} = \frac{2}{14} \times .85 \times 9 = 1.09 \quad [3]$$

For methane (CH_4) that has a density of .1 at given formation pressures and temperatures the hydrogen index is calculated as:

$$\text{HI}_{\text{methane}} = \frac{4}{16} \times .1 \times 9 = .225 \quad [4]$$

As the more recent neutron tools are calibrated in terms of fresh water fluid, a neutron porosity reading of 100 percent corresponds to the reading of a component with a hydrogen index of one. The computed hydrogen indices for oil and methane indicate porosities of 109 and 22.5 percent respectively. The comparison of these two values with that for water illustrates that in general only residual gas saturation has a significant influence on neutron porosity readings.

By using the hydrogen index formula, apparent neutron porosities can be calculated for various hydrated minerals from their molecular composition and atomic weights. These values are extremely helpful when applying the neutron log to the search for certain salts within evaporite sequences, as a salt with a high hydrogen index will give a high neutron porosity reading and vice versa.

The hydrogen index of shales generally cannot be calculated due to their complex mineralogy. The neutron response of shales is variable and depends on the quantity of hydrogen associated with the lattices of the various clay minerals and the proportion of bound water. As a result, neutron porosity values for shales are derived from the neutron log from zones identified as shales with the help of the gamma log (Poupon and others, 1971). Typical values for Midcontinent shales range from 30 to 40 percent neutron porosity. Reservoir rocks that contain a certain amount of shale are corrected by the following empirical formula.

$$\phi = \phi_a - V\phi_{Nsh} \quad [5]$$

ϕ = true neutron porosity

where ϕ_a = apparent neutron porosity

V = fraction of shale

ϕ_{Nsh} = neutron porosity of shale fraction

In addition to porosity determination and the identification of gas-rich zones and certain minerals, the neutron log is applied in conjunction with the density and sonic log to resolve complex lithologies into their fractions of mineral constituents and pore volume.

The Density Log

Density devices were introduced to estimate bulk density of geologic formations to aid in the interpretation of gravity surveys. Their applicability as a "porosity" tool was soon recognized and its main use today is for the estimation of formation porosity. The bulk density measurement incorporates the grain density of a formation and the fluid density contained in the pore space. The relationship of these two contributions is the basis for porosity calculations.

A density tool consists of a source of gamma rays which is mounted in a rubber pad and pressed against the borehole wall by spring-loaded arms. The leading edge of the pad is plow-shaped in order to furrow through the mudcake on the sides of the borehole and minimize its influence on the density readings. The constant flow of gamma rays emitted from the source element interacts with the electron clouds of the atoms encountered in the surrounding formations. This process leads to scattering and annihilation of gamma rays. The reduction of gamma ray flux is measured by one or two detectors (Wahl, Tittman, and Johnstone, 1964), and is

proportional to the average electron density of the formation. "Apparent bulk density" is derived from electron density measurements by considerations applying simple atomic theory.

Atoms consist of a nucleus which virtually represents the total mass of an atom with approximately equal numbers of protons and neutrons. The nucleus is surrounded by an electron cloud and the number of electrons matches the number of protons. A measurement of electron density, therefore, is related to the "apparent bulk density" of the formation. The distinction between the term "apparent bulk density" and "true bulk density" is necessary because elements are made up of isotopes that differ in the number of neutrons present in the atomic nucleus. In general, the number of neutrons matches very closely the number of protons, thus a factor of two is applied in the estimation of apparent bulk densities from electron density measurements. True bulk density would require a factor that takes the isotopic composition of elements into account. In the context of well logging, true and apparent density are almost identical for the molecules that characterize the most common lithologies. Quartz, calcite, and dolomite for example have a ratio of molecular weight to their sum of atomic numbers of 2.0028, 2.0016, and 2.0024. This ratio, however, amounts to 2.0838 for halite resulting in an apparent density value of 2.03 calculated with a factor two while the true density of halite is 2.16 grams per cubic centimeter. As all calculations are done in terms of apparent density, corrections are not required unless real densities derived from core analyses are applied for log recalibration. Terms such as density, bulk density always refer to "apparent bulk density" unless otherwise noted.

Original calibration of density tools is made by service companies who use a variety of limestones with different densities as standards of reference. Calibration can be checked after a logging run by comparing the measured densities with the matrix densities of a known tight quartzite or carbonate zone in the logged well. Modern density tools employ two gamma ray detectors and the measured density values are automatically corrected for borehole conditions. Readings of older, single detector type tools are corrected for mud cake applying charts made available from service companies.

The main application of formation density measurements is the estimation of formation porosity. This procedure employs a mass balance equation where the bulk density of a zone equals the sum of the densities of the pore and grain fractions.

$$\rho_b = \phi \rho_f + (1 - \phi) \rho_{ma} \quad [6]$$

ϕ = the pore fraction

where ρ_b = the apparent bulk density

ρ_f = the density of the pore fluid

ρ_{ma} = the density of the matrix material

Since bulk density is the measured quantity and pore fraction is the unknown to be solved, density values for matrix and pore fluids are inserted into the operation according to the lithology and type of pore fluid present in a particular zone. Lithology can be deduced from the gamma log in conjunction with well cuttings, and the following values represent apparent bulk densities of some major mineralogical components expressed in grams per cubic centimeter.

Quartz = 2.65

Calcite = 2.71

Dolomite = 2.87

As the radius of investigation of the density tool is limited, the pore fluid is generally mud filtrate which replaces formation brine and hydrocarbons during the drilling process. The density of fresh mud filtrate is close to unity and will not be influenced markedly by minor residual oil saturations. The presence of significant residual gas saturations, however, will result in an extremely low density reading, the so-called "hydrocarbon effect."

The above equation applies only to zones that consist essentially of one mineralogical component. The presence of shales in a zone tends to reduce the density reading resulting in exaggerated porosity values. In order to correct for the amount of shale, the basic equation is expanded to:

$$\rho_b = \phi \rho_f + V \rho_{sh} + (1 - \phi - V) \rho_{ma} \quad [7]$$

where ρ_{sh} = the density of shale

V = the volume fraction of shale

The shale volume can be calculated from the gamma log and the shale density is generally drawn from the density log itself by selecting (with the aid of the gamma log) a shale unit in the vicinity of the formation undergoing evaluation. This approach is necessary due to the variable nature of shales that do not allow the definition of universally valid physical parameters.

Another expansion of the basic equation takes a mixture of different mineralogical components into account. This expanded equation is the

basis for porosity and lithology derivations as applied in this research in conjunction with equivalent equations based on neutron and sonic log responses. The basic equation assumes the form:

$$\rho_b = \phi \rho_f + (1 - \phi) \sum_{i=1}^n X_i \rho_i \quad [8]$$

where X_i = the fraction of component i

ρ_i = the density of component i

The density log by itself is a valuable aid in the identification of certain lithologies and minerals which have a high density contrast compared with sandstones, limestones, and dolostones. These include coals with a density in the range of 1.6; salt beds with a density of about 2.03; and anhydrite beds with a high density of 2.96.

Another application of the density log is the detection of over-pressured zones during the drilling of a well (Fertl and Timko, 1970). Density logs are run several times during the drilling operation and shale zones are selected with the aid of the gamma log. Particularly in younger sediments, a plot of shale bulk density shows a gradual increase with increasing depth. This trend is reversed when an over-pressured zone is approached, and appropriate measures such as increasing the mud weight can be taken.

The Sonic Log

The Sonic Log was originally developed to provide information on the variation of acoustic velocities versus depth to aid in the interpretation of seismic data. Although it is still used for this purpose, its major application today is for determination of formation porosity, as it was soon recognized that a strong relationship exists between lithology, porosity and the velocity of acoustic waves.

The sonic device operates with compressional waves in the low ultrasonic frequency range, and its basic concept of operation is the measurement of the transit time of an acoustic wave over a certain length of rock. An acoustic impulse is generated at brief intervals by a transmitting element and the arrival of the first signal at the receiving element triggers the recording of the transit time. The interval transit time, Δt , is expressed in microseconds per foot, and for most lithologies lies within a range from 40 to 200 $\mu\text{sec}/\text{foot}$. Modern tools employ two transmitters and two receivers to measure the transit time over differing path lengths in order to calculate a transit time value free from errors introduced by borehole conditions as thickness of mudcake, borehole diameter, and tilting of the tool within the hole. The spacing of transmitters and receivers determines the vertical resolution of the tool which is generally about two feet, and the measured value represents an average for that distance.

In a series of laboratory measurements Wyllie, Gregory, and Gardner (1956, 1958) demonstrated the existence of a relation between porosity and transit time which can be approximated by a linear interpolation from the transit time of the matrix material (zero percent porosity) and the transit time of the pore fluid (100 percent porosity). For a mono-mineralic zone this relation is expressed by the equation:

$$\Delta t = \phi \Delta t_f + (1 - \phi) \Delta t_{ma} \quad [9]$$

where Δt = the measured transit time of the zone

ϕ = the porosity of the zone

Δt_f = the transit time of the pore fluid

Δt_{ma} = the transit time of the matrix material

Solved for porosity, the equation is known as "Wyllie time average equation":

$$\phi = (\Delta t - \Delta t_{ma}) / (\Delta t_f - \Delta t_{ma}) \quad [10]$$

The transit times ($\mu\text{sec}/\text{foot}$) for some common minerals representing the framework of sandstones, limestones and dolostones are:

Quartz = 55.5

Calcite = 47.5

Dolomite = 43.5

The transit time of the pore fluid used to calculate porosity is generally that of mud filtrate with a value of about $189 \mu\text{sec}/\text{ft}$ for fresh muds. This value is chosen because the radius of investigation of the tool allows measurements only in the flushed zone. The radius of investigation is dictated by the fact that the first acoustic wave reaching the receiver of the tool travels the shortest distance, i.e., close to the borehole wall. Small residual oil saturations will not greatly modify this value as the transit time for oil ($238 \mu\text{sec}/\text{ft}$) is relatively close to that of mud filtrate. Residual gas saturations have a much more pronounced effect on the transit time as Δt of methane has a value of $626 \mu\text{sec}/\text{ft}$, resulting in a pronounced "hydrocarbon effect" expressed by an excessively high transit time reading on the sonic log.

As already indicated in the discussion of the density and neutron logs, shales consist of clay minerals with various proportions of other mineralogical constituents as quartz, dolomite, and calcite. Apart from the mixed mineralogical composition of shales, the velocity of acoustic waves is greatly influenced by the degree of shale compaction. In order to derive a reasonable transit time for shale beds, the same rationale is followed as in the derivation of shale densities from the density

log. With the aid of the gamma log a shale zone immediately above or below the unit of interest is selected and the transit time is directly read from the sonic log. The determination of shale transit times is important in the calculation of porosities in formations "contaminated" by shale.

To account for a shale fraction, the time average equation is expanded to:

$$\Delta t = \phi \Delta t_f + V \Delta t_{sh} + (1 - \phi - V) \Delta t_{ma} \quad [11]$$

where V = the volume fraction of shale

Δt_{sh} = the transit time of the shale fraction

For formations that include a variety of mineralogical components, the equation assumes the general form

$$\Delta t = \phi \Delta t_f + (1 - \phi) \sum_{i=1}^n X_i \Delta t_i \quad [12]$$

where X_i = the volume fraction of lithology i

Δt_i = the transit time of lithology i

This equation in combination with its equivalents based on the neutron and density log is the basis of porosity and lithology derivations from geophysical well logs.

Porosity values calculated with the time average equation compare favorably with porosities derived from core analyses (Wyllie, Gregory and Gardner, 1958). This equivalence is generally close in sandstones and carbonates which are free of vugs and fractures. The arrival of the first acoustic velocity wave at the receiver, will bypass large porosity features as vugs, cavities or fractures. As a result, the porosity estimate is the sum of intercrystalline and intergranular porosity, i.e., primary porosity in the context of well logging. This

apparent problem occurs frequently in carbonate sequences, but can be turned into an advantage if another porosity log is run in the same well. Since the neutron and density logs are both sensitive to the total porosity, the difference of the porosity estimates provided by either of these tools with that from the sonic device corresponds to secondary porosity, which is defined here as an estimate of the proportion of vugs and fractures.

The sonic log can also be used to detect overpressured zones in an analogous manner to that described for the density log.

IV. DATABASE

Data Source

All the following statements regarding the structure and lithology of the Viola Limestone as well as specific relations of geologic variables to hydrocarbon producing areas are based on data that were almost exclusively derived from geophysical well logs. The types of logs used were discussed in detail in the previous chapter. Core reports, scout tickets, and sample log descriptions of well cuttings, served as supplementary data to check formation boundaries picked from the geophysical logs and to monitor lithofacies interpretations. The paper logs are stored on file together with all additional data sources at the Kansas Geological Survey in Lawrence. Altogether, logs from 368 wells were examined, of which 254 were selected for the data base. Most of the logs that were discarded, either did not reach the Viola Limestone or were of low quality and unsuited for digitizing. Of the 254 wells used 194 had a neutron, 36 a density and 62 a sonic log. The geographical locations of the well are shown in Figure 6.

An arbitrary identification number was assigned to each well, and these are listed together with Land Office (spot) locations in Appendix 1. Spot locations approximate the geographical coordinates of a well site in terms of a township, range, section, and subsection hierarchy. In the case of four levels of section subdivision, no well is farther than 50 meter (165 ft) from its actual location. Wells were assumed to be drilled vertically so that the formation parameters measured in the subsurface are geographically located at the coordinates of the drill site. The spot locations were translated into

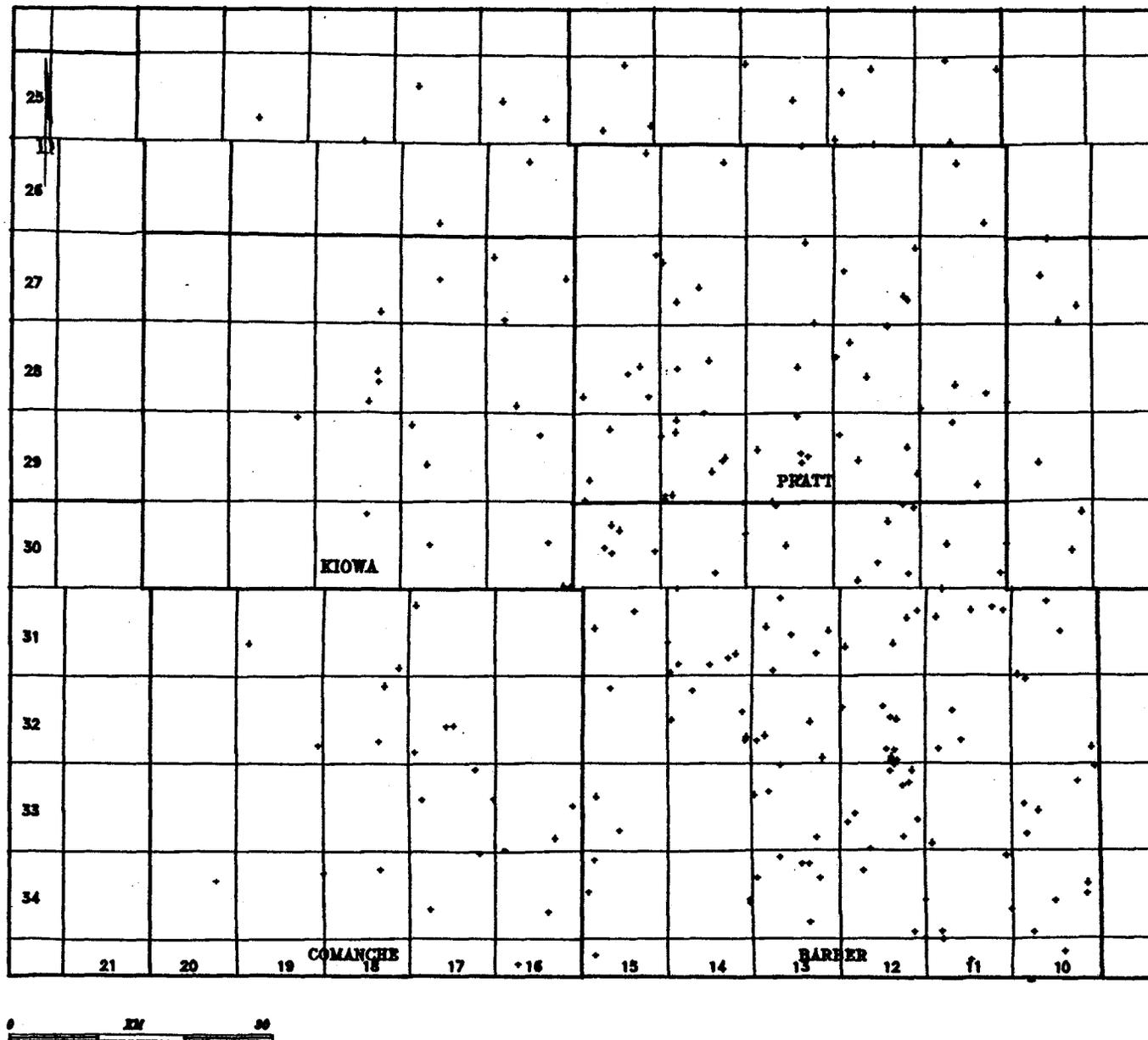


Figure 6. Distribution of wells that provided information for mapping lithologic and structural variation of the Viola Limestone.

latitude and longitude coordinates by an improved version of a computer program developed first by Morgan and McNellis (1969) for use in Kansas. A general map projection program (Cable, in preparation) transformed latitude and longitude coordinates into inches for plotting convenience.

The following paragraphs outline the steps performed in the production of the two data files which form the basis for the suite of maps that describe the areal variation of geologic variables in the Viola Limestone. The steps are illustrated in Figure 7.

Structural Data

The structural data are derived from geophysical well logs and consist of the base and top of the Viola Limestone and of the top of a "Lower Limestone" zone. The "Lower Limestone" unit is an informal lithologic zone that is readily recognized on all three porosity logs by a pronounced deflection or "kick" indicating porosity values of about two to three percent (Fig. 8). The base of the "Lower Limestone" unit is defined here as the base of the Viola Limestone, which is in agreement with the vast majority of sample logs and with the definition given by Adkison (1972). It is the only lithologic zone of the Viola that can be identified by the marked similarity of log traces in every well. The areal extent of this zone and its essentially uniform lithology, which is suggested by sample logs, make the "Lower Limestone" an ideal interval for correcting the log traces for measurement errors. This recalibration process is considered part of the data analysis and specific details of the computation will be described in the next chapter. Lacking the "Lower Limestone," separation of the Viola Limestone from the Platteville formation would be extremely uncertain in wells where the upper Platteville consists of carbonate beds rather than shale units as in Figure 8.

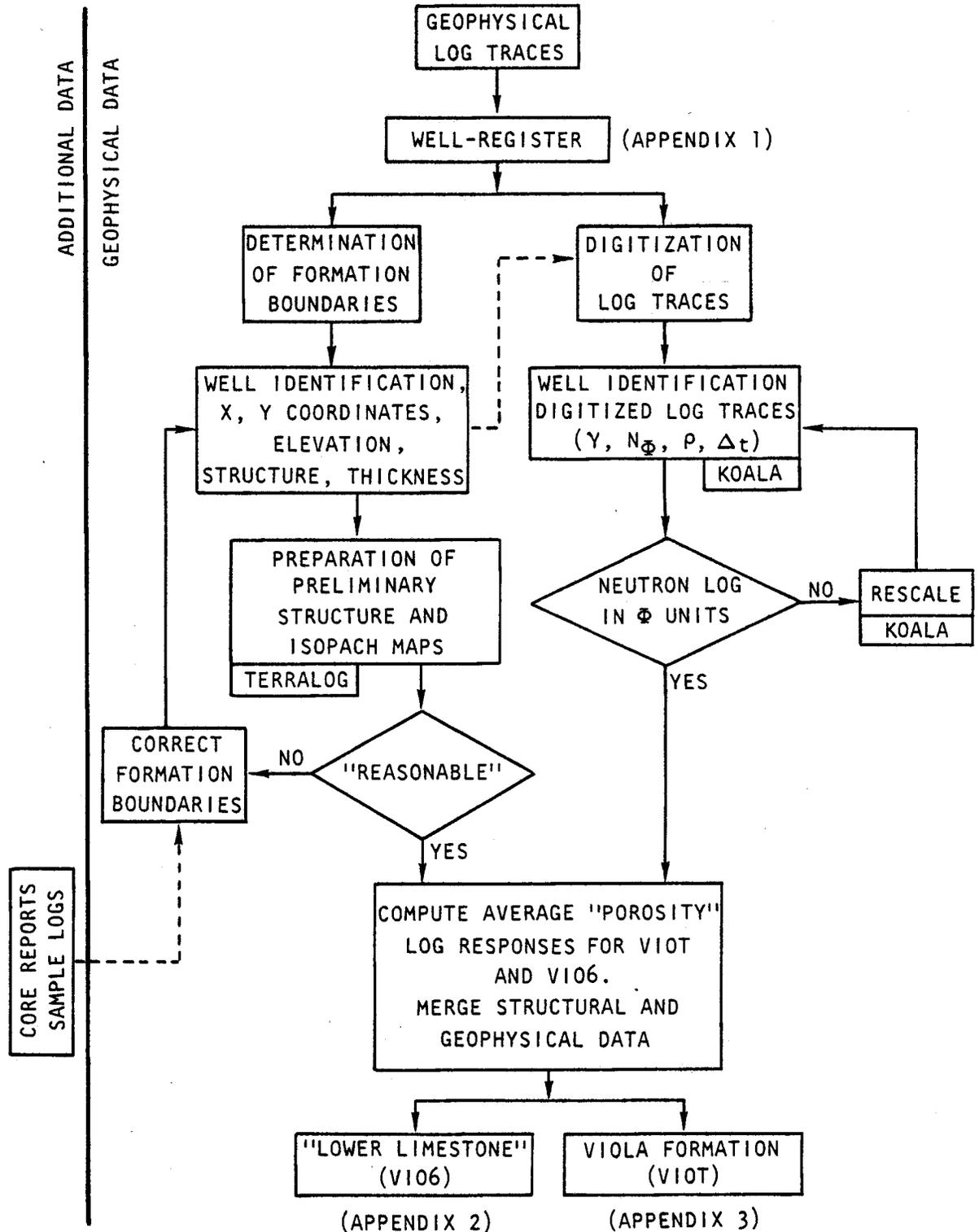


Figure 7. Flowchart illustrating the steps performed to establish a datafile for the Viola formation and the "Lower Limestone" unit that contain the information for lithofacies analysis. KOALA and Terralog are the names of the interactive well logging package and interactive mapping package, respectively.

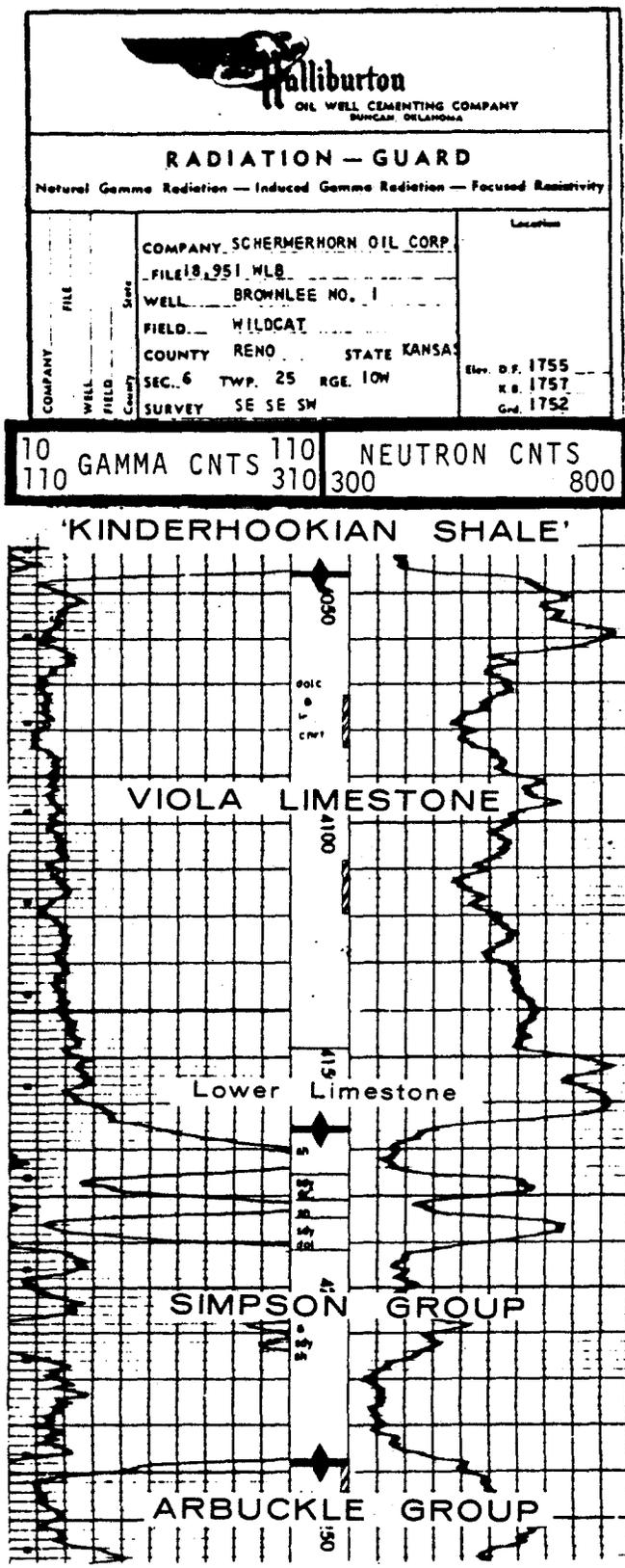


Figure 8. Gamma and neutron log traces of Brownless 1 well.

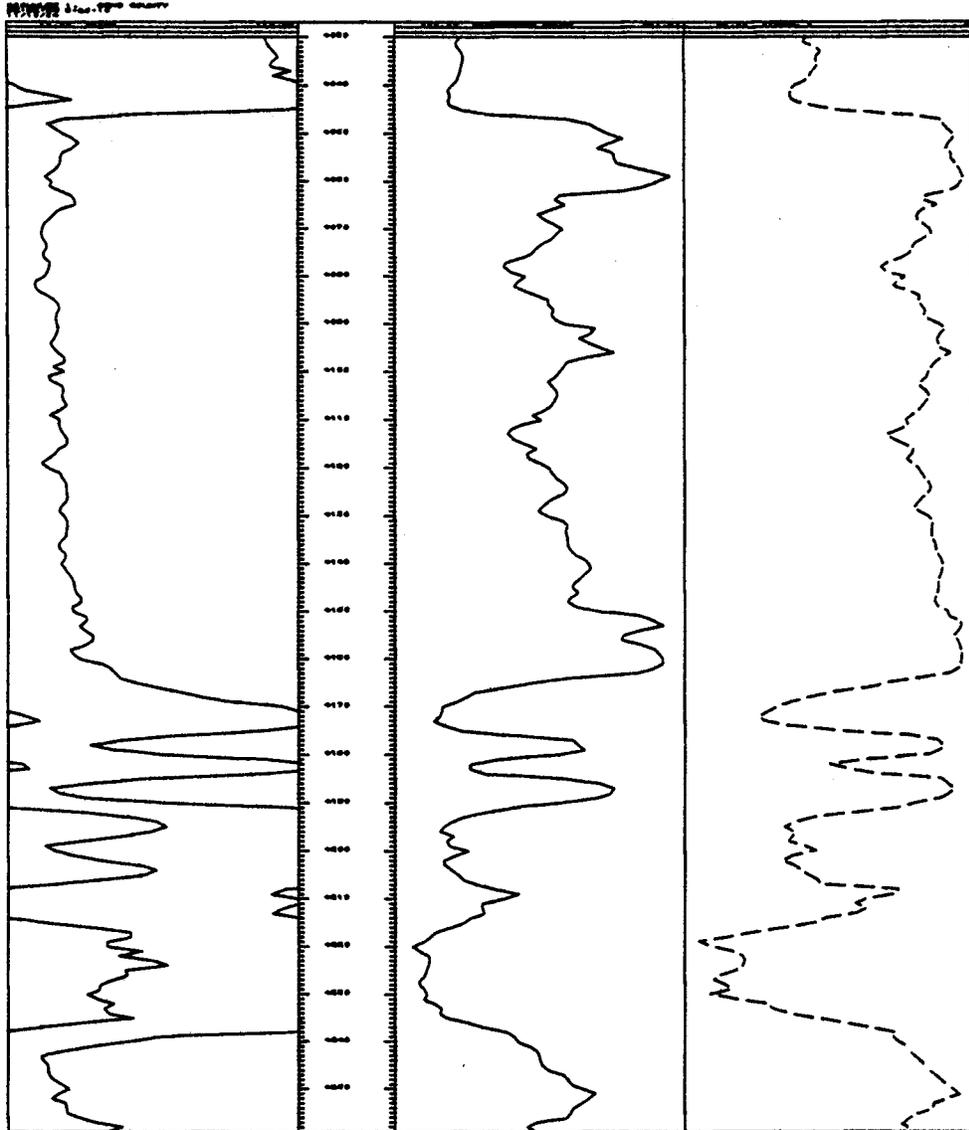


Figure 9. Digitized traces of gamma and neutron log of Brownless 1. Right trace contains formation porosity scaled in limestone porosity units computed from the neutron log.

The elevation of the top of the Viola was identified readily in more than two-thirds of the wells, where Devonian and Mississippian shales ("Kinderhookian" shales in the terminology of subsurface geologists) mark a striking lithology contrast as evident in the log traces of Figure 8. In structurally high areas, where the Viola is overlain by Mississippian carbonates, the identification of the formation top became problematic and constituted a common source of error in the initial structural data file.

The initial structural file was considered to contain three types of error. The first, simple measurement error, is associated with well site and formation boundary elevations and is considered negligible. This assumption is based on the difference in the magnitude of possible error compared with the magnitude of the variable measured. This error is introduced if a well site elevation is interpolated from a topographic map and is determined by the contour interval of the map used, but should not exceed three to six meters (10 to 20 ft). This error fraction amounts to approximately one half of a percent when the average depth drilled to the top of the Viola is used. The same type of error increases to about two percent for the isopach data if the cumulative error for upper and lower boundary does not exceed two feet. Measurement error, therefore, has negligible influence on the variable measured and no attempt was made to correct for it.

The two remaining types of errors consisted of "operator errors," that are introduced (1) when data values are entered incorrectly in the data preparation process, and (2) by misidentification of formation tops. Both errors were regarded of importance since their magnitude is more likely to exert significant influence on the spatial relations of

measured variables. In order to detect these errors, preliminary structure and isopach maps were contoured and examined using the following strategy.

- (1) Select control points that cause slope values to differ markedly from slopes portrayed by contour lines in the surrounding area.
- (2) Check well site location, as well as topographical and structural elevations for typing errors.
- (3) Compare formation tops with the information contained in other data sources such as sample logs and scout tickets.
- (4) Check whether spot location and elevation for a well site are in agreement when compared with a topographic map.

The above process was repeated twice and approximately 50 wells were reexamined. Thirty-three wells needed corrections. Three typing mistakes were detected readily, since they introduced an error that caused the contour lines to depict either holes or pinnacles of extremely high slope. All other errors consisted of misidentification of the upper formation boundary of the Viola. Regions of high slope which were supported by more than one control point, are considered to portray true variation of the geologic variable mapped. Two isolated control points were eliminated in this process because they had no support from neighboring data values. The concentric anomalies they caused had high positive values that excluded the interpretation as sinkholes. No information was available to suggest the presence of volcanic pipes or salt plugs affecting Viola rocks in this area (Merriam, 1963), and a horst with a geographical extension of these anomalies could not be related to structural features shown on the Precambrian basement map of Kansas.

At the end of this process, a data file was established containing well identification number, elevation of top of Viola limestone and

top of "Lower Limestone" as well as elevation of the base of the Viola. A number of wells did not penetrate the Viola completely and only the Viola top elevation is included in the file. All elevations are normalized with respect to sea level.

Digitized Well Logs

The second step in the process of establishing the data files used in the data analysis process consisted of digitizing well log traces associated with wells that penetrate the Viola Limestone in its entirety.

The original logs were xeroxed and care was taken to eliminate the effects of folds in the original blueprint copies by carefully stretching them during the process. Each log which contained scale changes was xeroxed twice. The reflected portion (Fig. 8) was cut from one copy and glued into the proper position on the other copy. This facilitated greatly the digitization process. Especially with gamma logs, the reflected portion of a log is generally recorded with a change of scale. Digitizing a well log, or for that matter any kind of data represented in graphical form, is limited by hardware design to the recording of x, y- coordinates in a linear fashion. For this reason a factor relating different scales of one log trace was calculated and the reflected portions were appropriately rescaled. They were then loaded into a data file that could be accessed by the KOALA log analysis package. The digitized neutron logs were generally recorded in API neutron counts and were converted into limestone porosity units by the "40 to 1" method, described in the previous chapter. Quality control of the digitizing process was maintained by plotting about every tenth log and comparing it with the original (Figs. 9 and 10).

Errors introduced by the logging process were described in the previous chapter. Their potential significance in the context of this research will be assessed in the chapter on "log normalization."

Final Data Files

The last step in the data preparation process consisted of merging the files containing structural data and those with the digitized log traces. This included the calculation of the average of the log responses for each digitized log for the "Lower Limestone" and the Viola Limestone as a whole. Two data files emerged as the result of the data retrieval and preparation process. One file contains well identification, geographic coordinates, structural elevation, and thickness, and average log response for the Viola Limestone (Appendix 2). The second file includes the same data for "Lower Limestone" (Appendix 3).

V. MINERAL AND POROSITY DETERMINATIONS FROM POROSITY LOGS

In the chapter on geophysical well logs, reference was made to the identification of certain lithologies based on individual well logs. These lithologies are generally characterized by the domination of one mineralogical component with physical characteristics which are markedly dissimilar from those associated with the more common sedimentary lithologies of sandstones and carbonates. As an example, coal, salt, and anhydrite zones can be identified easily on a density log, and shale units on a gamma ray log.

These strong diagnostics do not typify the common lithologies so that, for example, a single density reading may represent a limestone, a cherty dolomite, or some intermediate composite mixture. However, knowledge of the matrix composition is extremely important, since an incorrect specification of the mineralogy will result in erroneous porosity estimates. So, for example, a density log recording could yield porosity estimates of 10 percent if the zone was a limestone, 18 percent if a dolomite, and seven percent if a sandstone.

The gamma ray, neutron, sonic and density logs collectively provide the best data source for the derivation of both porosity and mineralogical composition from geophysical measurements (Savre, 1963). Common procedures for analysis are the overlay of two porosity logs on a compatible scale or the crossplot of raw responses of two porosity logs to identify zones of different mineralogical composition. Both methods aid in the identification of matrix minerals that will give better results in porosity calculations. These two techniques are used mainly if only two porosity logs are available in a well.

Porosity Log Overlay

A direct comparison of a combination of porosity logs (neutron, density, and sonic) can be done in a straightforward manner, when their drastically different measurement units (limestone porosity, grams per cubic centimeter, and microseconds per foot) are calibrated on a common reference scale. As most modern neutron logs are recorded in limestone porosity units, it is practical to transform the density and sonic log readings into limestone porosity units. This is accomplished by the use of a linear equation that is defined by a "matrix point" and a "porosity point." The equation for the density log, for example, is defined by setting the density of calcite (about 2.71) equal to zero porosity and the density of the pore fluid (about 1.0 for fresh-water muds) equal to 100 percent porosity. Limestone porosities for all intermediate densities can now be calculated by a linear equation. The same procedure is followed to convert transit times into porosity units. The "matrix point" has a transit time of 47.5 $\mu\text{sec}/\text{ft}$ corresponding to a porosity of zero percent, while the "fluid point" with a transit time of 189 $\mu\text{sec}/\text{ft}$ corresponds to a porosity of 100 percent.

An overlay of two porosity logs scaled in the same units enables a rapid evaluation of the main mineralogical components of a logged section, which is based on the different responses of the matrix minerals to the individual porosity logs. An overlay of a neutron log (solid line) and a density log (dashed line) is illustrated in track two of Plate 6b, accompanied by a gamma log to the left and a sonic log to the right. The disposition of the neutron and the density log track relative to each other together with the response of the gamma log identifies common sedimentary lithologies. Limestones have a low

gamma log reading and a more or less coincident density and neutron log reading, as the reference scale is scaled in limestone porosity units. Dolostones also have a low gamma log reading, but the density log has a lower (lower and higher refer in this context always to limestone porosity) reading than the neutron log. This is due to the higher grain density of dolomite as compared to that of calcite resulting in a lower porosity estimate. The inverse relationship is observed in sandstone zones, where the density log shows a higher reading than the neutron log, as quartz has a lower grain density than calcite, the standard of calibration. Shales are identified by a high gamma log reading and a high neutron reading accompanied by a low density reading.

Due to the composite lithology of the Viola Limestone, the neutron-density overlay of Plate 6b does not exactly represent a classic example for the functionality of porosity log overlays, but the relationships of log responses to matrix mineralogy can be reasonably demonstrated for a few zones. Incidentally, Plate 6a is a graphical display of the lithology computation of the same section utilizing three porosity logs simultaneously, a procedure discussed later. According to the principles of lithology-log response just described, the top of the section (5540 ft to 5553 ft) is interpreted as a shale. The intervals between 5592 feet and 5596 feet and between 5610 feet and 5618 feet correspond to a shaly dolostone. A dolostone is represented in three zones (5571 ft to 5581 ft, 5636 ft to 5647 ft, and 5654 ft to 5668 ft). The oscillation of the density log around the neutron log (5670 ft to 5714 ft) is interpreted as limestone. At least one (5557 ft) significant difference in neutron and density-log response could be caused by residual gas saturation, although no hydrocarbon production is reported from the Viola in this well.

The whole procedure of log overlays is basically a pattern recognition approach that identifies dominant lithologies, but fails to identify composite mixtures as cherty dolomites or dolomitic limestones. A somewhat more definitive approach to mineral identification is a crossplot of porosity log responses.

Porosity Log Crossplots

A cross plot of porosity log responses is constructed by plotting log readings of zones on a coordinate system whose horizontal and vertical axes correspond to two porosity logs, scaled arithmetically in their original measurement units (McFadzean, 1973). For each of the three porosity logs theoretical responses for any range of porosity can be calculated in monomineralic zones as pure sandstones, limestones, or dolostones. Porosity values derived in this fashion are displayed as trends on crossplots and define boundary endmembers. Figure 10 gives an example of a neutron density crossplot of the upper part of the Viola Limestone. Zone coordinates that fall between endmembers can be resolved in terms of mineralogy and true porosity. An example of such a solution is given for a zone shown circled in Figure 11. As this zone plots between the "endmember trends" of limestone and dolostone, its composition is considered a mixture of calcite and dolomite. The proportion of limestone to dolomite is about two to one, as expressed in the relative distance of that point from the limestone and dolomite trends. The respective porosities are 21 percent for limestone and 17.5 percent for dolomite. By multiplying these porosities with their volume fraction, a more accurate porosity value of 20 percent is calculated.

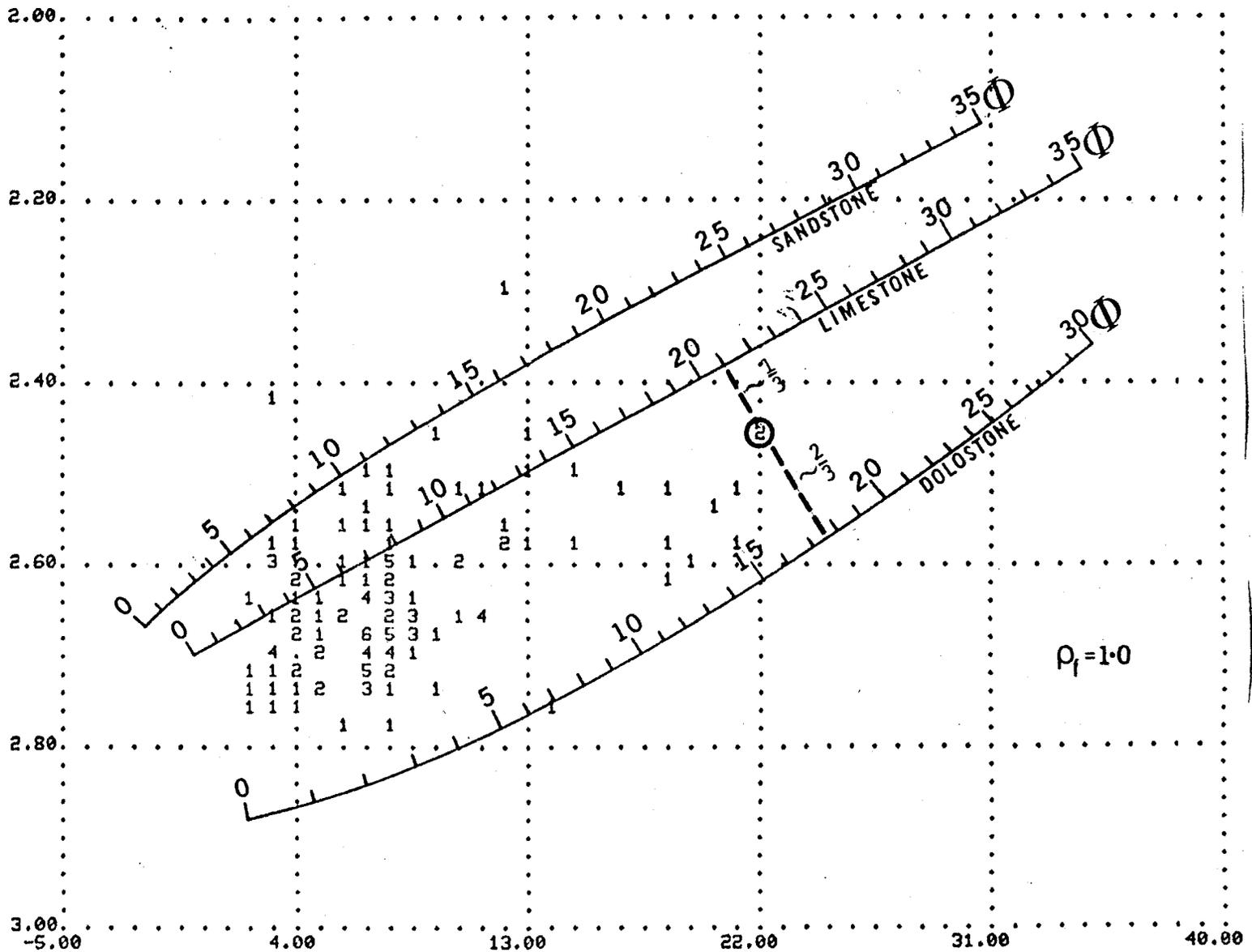


Figure 10. Crossplot of neutron and density log responses of upper Viola Limestone in the Belcher well (NE-NE 21-32-17).

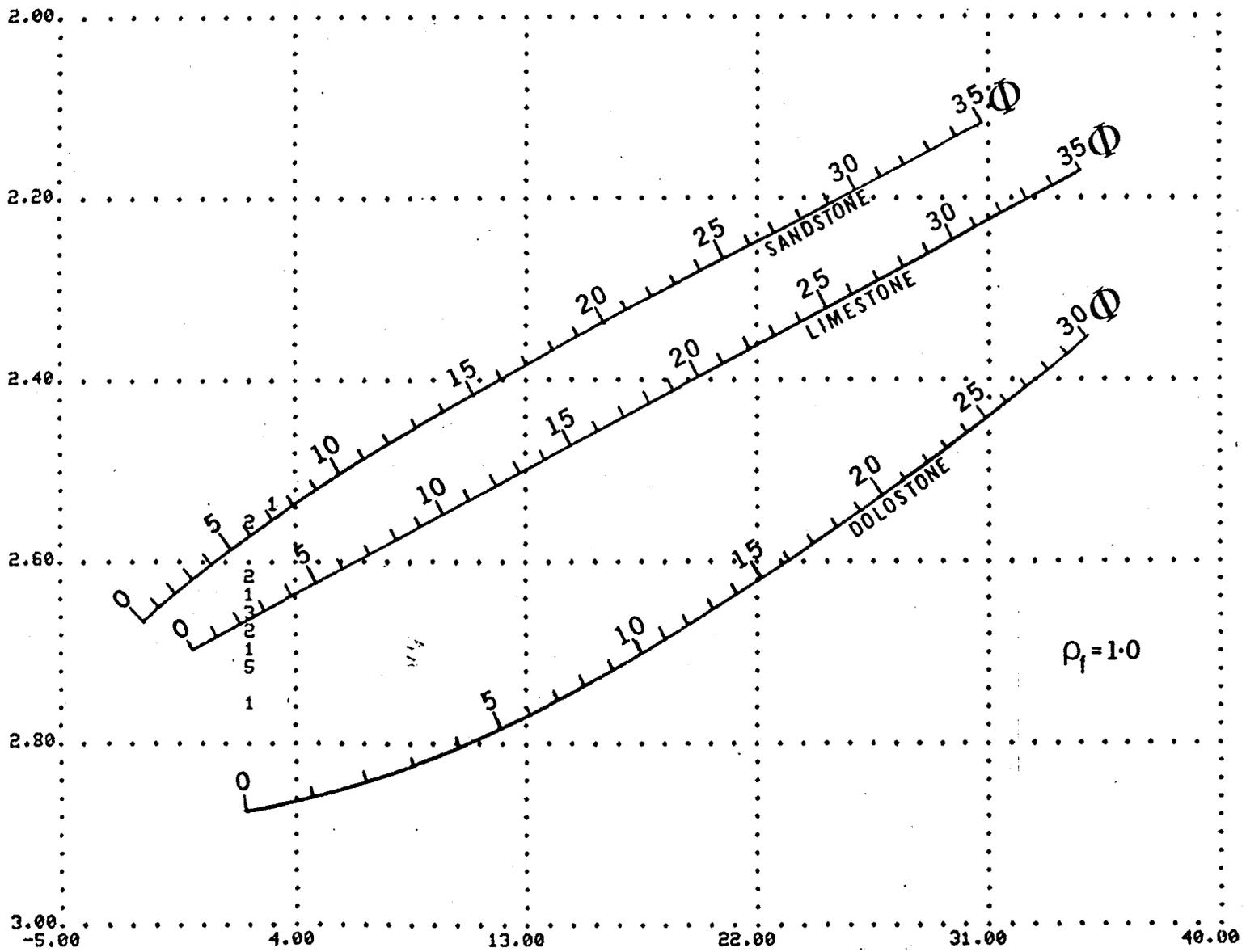


Figure 11. Crossplot of neutron and density log responses of "Lower Limestone" unit in the Belcher A1 well (NE-NE 21-32-17).

The two examples of neutron-density crossplots (Figs. 10 and 11) correspond to the upper part of the Viola and the "Lower Limestone" unit, respectively. The plotted zones correspond to log readings digitized at one foot intervals.

The lithologies of the upper Viola limestone according to Figure 11, consist of a few chert (quartz) zones, cherty limestone, limestone, and dolomitic limestones. A number of zones of a mixture of dominantly dolomite with calcite exhibits a trend towards higher porosities. Such a trend is expected if dolomitization of limestone occurred as this would result in a higher pore volume. The two zones plotting above the sandstone trend probably contain residual gas saturation, as already suggested for one zone from the log overlay.

The lithologies suggested by the crossplot of the "Lower Limestone" are predominantly limestone with varying, but relatively low proportions of dolomite or chert. Three zones consist entirely of chert. Porosity values for this unit tend to cluster around a value of approximately two percent, supporting the choice of a porosity value of two percent that was assigned to this unit in the conversion process of neutron logs from neutron counts to limestone porosity units.

In a practical application of the crossplot technique, zones characterized by approximately equal log responses would be selected and plotted as separate graphs. If these zones tend to cluster, the average mineralogical composition of that cluster would be used in the porosity determination for that zone. By successively decreasing the footage of selected portions of a well, clusters can generally be achieved, otherwise mineral composition and porosity have to be calculated for every zone picked from the log.

Although crossplots can be interpreted more precisely than log overlays, a reliable porosity estimate can be derived only if the lithology is a binary mixture of known minerals. The dolomitic limestone suggested by the crossplot of the upper Viola Limestone can very well include chert or consist solely of chert and dolomite. The log responses that position a zone on the crossplot are determined by the matrix material and its respective volume fraction. Differing volume fractions of various mineral combinations can result in identical log responses.

The reason for this ambiguity is the relationship between the number of "knowns" (porosity logs) and the number of "unknowns" (mineral components and porosity). Two logs can be solved for three unknowns (porosity and two mineral components) as two equations can be constructed from the log responses and the third equation sums the "unknowns" to unity as they represent volume fractions of a closed system. A graphical and a numerical method for solving for porosity and three mineral components from three porosity logs is the subject of the next two sections.

The M-N Plot

The M-N plot provides a graphical solution for mineralogical components defined by the responses of three porosity logs. This plot solves the dilemma of having to interpret simultaneously variation of zones defined in three dimensional space by the three porosity logs, all measured in entirely different units. The M-N plot reduces a three-dimensional problem to two dimensions by eliminating the porosity component, which becomes a redundant unknown as the plot is directed

to the identification of relative mineral proportions. This method can perhaps best be visualized as a form of conical projection. The base of a tetrahedron (Fig. 12) is defined by matrix points (zero percent porosity) of three minerals assumed to represent the lithology of the unit under investigation. The apex of the pyramid corresponds to a fluid point (100 percent porosity). Points on intersections of the pyramid's bounding planes represent one mineral constituent whose porosity fraction is determined by its position between the fluid and matrix point. Points that lie in one of the bounding planes represent a mixture of two minerals, whose proportions are determined by the distance of the point to the mono-mineralic "corner lines." Porosity is represented on a bounding plane by lines connecting equal porosity values between "corner lines." Points within the pyramid represent a mixture of three minerals and porosity. A projection of such a point onto the base triangle defines the mineral proportions of that point and eliminates porosity as the base triangle is defined by matrix points. Any point outside the tetrahedral space does not belong to the system and requires the definition of a tetrahedron based on a different choice of matrix points. The choice of matrix points should be based on previous knowledge of the overall lithology of the rock sequence under investigation.

In practice, the M-N plot is constructed by computing the composite variables M and N from the log responses of all three porosity logs by the following relations:

$$M = (\Delta t_f - \Delta t) / (\rho_b - \rho_f) \quad [13]$$

and

$$N = (\phi N_f - \phi N) / (\rho_b - \rho_f) \quad [14]$$

where Δt_f = the transit time of the pore fluid

Δt = the measured transit time

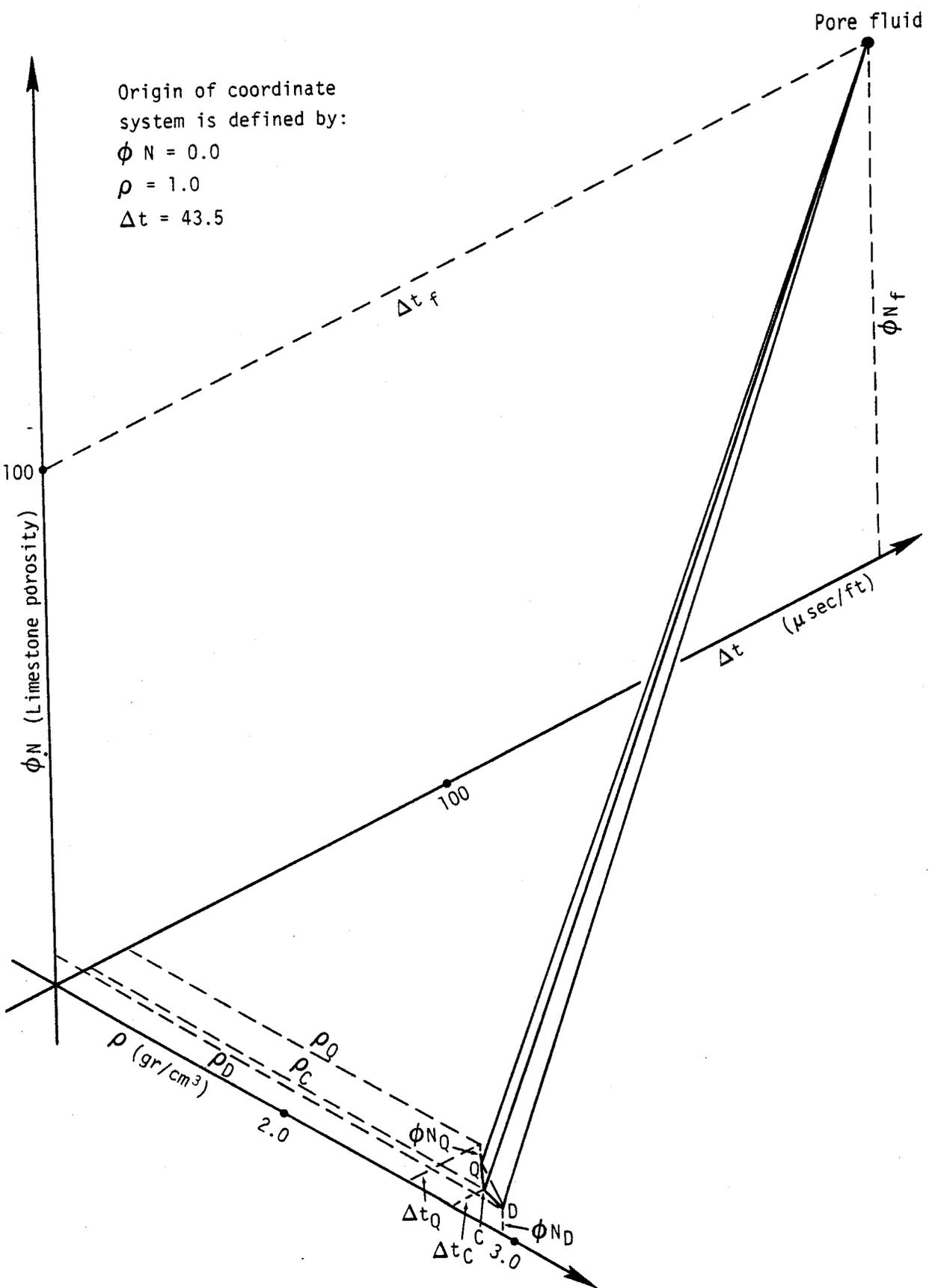


Figure 12. Tetrahedron containing valid solutions for zones that are composed of porosity, calcite, dolomite, and quartz. The three-dimensional space is defined by the physical parameters measured by the neutron, density, and sonic log.

ρ_f = the pore fluid density

ρ_b = the measured bulk density

ϕN_f = the neutron response of the pore fluid

ϕN = the measured neutron response

The values for the log responses for pore fluid are taken from tables in logging manuals and for freshwater mud correspond to:

Δt_f = 189.0 microseconds per foot

ρ_b = 1.0 grams per cubic centimeter

ϕN_f = 1.0 neutron response

The value of M is conventionally divided by 100 to give units of similar magnitude to those of N.

An example of a M-N plot is illustrated in Figure 13, where M and N values for the whole Viola Limestone of the Belcher A1 well are plotted. Although most zones fall between the points defined by the minerals calcite, dolomite, and quartz, a fair number of points plot outside the triangle. The actual density of points within the triangle is far larger than shown, as points with small variation of M-N values tend to coincide due to the computer algorithm that produced this plot. Points outside the triangle are determined by log responses that are influenced by lithology components other porosity, calcite, dolomite, and quartz. The only additional components mentioned in sample logs and core studies of the Viola (Biederman, 1966) are shale and secondary porosity. Zones plotting below the triangle base line are caused by log responses to a lithology mixture that includes a proportion of shale, as shale content tends to decrease the value of M. An approximate shale point for the Viola can be defined using the log responses ($\phi N = .3$; $\rho_b = 2.5$; $\Delta t = 95$) for the Simpson shale below the Viola. The M and N values for this shale compute as .63 and .47 respectively. A triangle

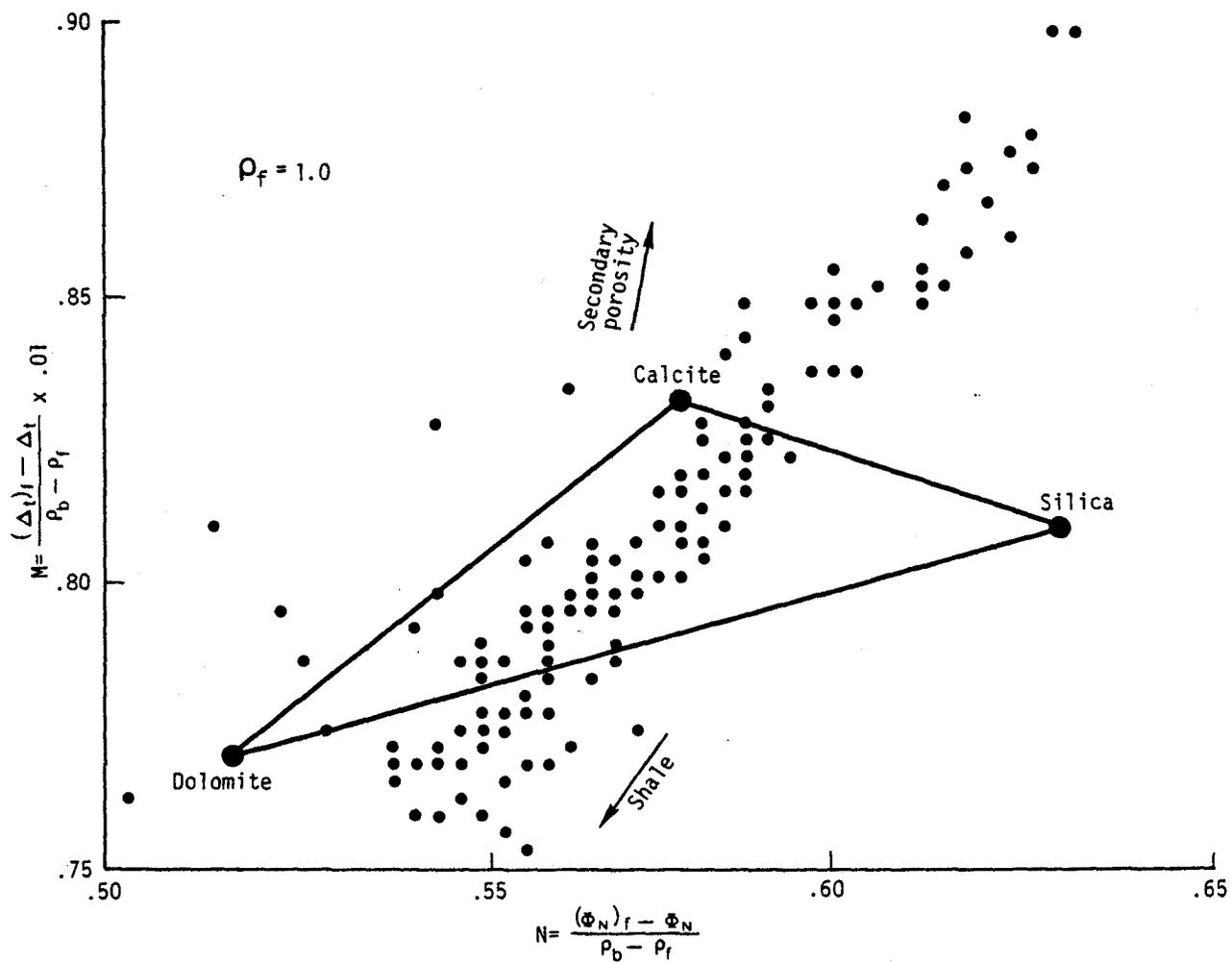


Figure 13. M-N plot of the Viola Limestone of the Belcher A1 well (NW-NW 21-32-17).

constructed with this shale point and the dolomite and quartz point results in an average shale content for these zones of about 10 percent, excluding calcite as a component. Points above the calcite-quartz and calcite-dolomite triangle side are caused by varying proportions of secondary porosity, such as fractures, vugs or both. Secondary porosity increases the value of M as the density log is sensitive to primary and secondary porosity, whereas the sonic log accounts for primary porosity only. This results in a lower reading of bulk density decreasing the denominator without changing the numerator, hence a higher value of M.

The M-N plot is primarily used as a reconnaissance procedure in the identification of mineral components. Its principle provided the insight for the interpretation of the lithology plot (Fig. 16) which is the basis for the lithology classification of the Viola Limestone.

Numerical Determination of Porosity and Mineral Components

In the chapter on geophysical well logs, equations were given for each porosity log relating measured log response to porosity and matrix mineral proportions. With the availability of three porosity logs, four simultaneous equations can be formulated. This system of equations consists of three log response equations that express the log reading of a tool as a function of the proportions of porosity and mineral endmembers multiplied by their respective pore fluid or mineral log response coefficient. A fourth equation expresses the fact that the proportions of all components will sum to unity. Consequently, four equations can be established and solved for four unknowns. The unknowns chosen for the Viola Limestone are porosity (ϕ) dolomite (D), quartz (Q), and calcite (C). This choice of the mineralogical components is

based on lithology descriptions from sample logs and supported by cross-plots and the M-N plot. The equations are written as:

$$\begin{aligned}
 \text{Neutron: } & 100.0\phi + 5.00D - 5.00Q + 0.00C = \phi N & [15] \\
 \text{Density: } & 1.00\phi + 2.87D + 2.65Q + 2.71C = \rho_b \\
 \text{Sonic: } & 189.0\phi + 43.5D + 55.1Q + 47.5C = \Delta t \\
 \text{Unity: } & 1.00\phi + 1.00D + 1.00Q + 1.00C = 1.0
 \end{aligned}$$

The coefficient values are taken from standard tables published in logging manuals. Although these equations can be solved by iterative solutions and substitutions, a more elegant and efficient method is provided by matrix algebra. Rewritten as matrices these equations assume the form:

$$\begin{bmatrix} 100.0 & 5.0 & -5.0 & 0.0 \\ 1.0 & 2.87 & 2.65 & 2.71 \\ 189.0 & 43.5 & 55.1 & 47.5 \\ 1.0 & 1.0 & 1.0 & 1.0 \end{bmatrix} \begin{bmatrix} \phi \\ D \\ Q \\ C \end{bmatrix} = \begin{bmatrix} \phi N \\ \rho_b \\ \Delta t \\ 1.0 \end{bmatrix} \quad [16]$$

In the case that the mineralogical composition of a unit does not consist of dolomite, quartz, and calcite, the column vectors of the coefficient matrix have to be replaced with the log response properties of appropriate minerals. The above matrix equation can be expressed in symbols used commonly for matrix notation as:

$$\underline{C} \underline{X} = \underline{R}$$

where \underline{C} = coefficient matrix

\underline{X} = matrix of unknown porosity and mineral proportions

\underline{R} = matrix of measured log responses

The solution for \underline{X} involves the calculation of the inverse matrix of \underline{C} and the multiplication of both sides of the equation by it.

$$\underline{C}^{-1} \underline{C} \underline{X} = \underline{C}^{-1} \underline{R}$$

$$\underline{X} = \underline{C}^{-1} \underline{R}$$

This equation is written out as:

$$\begin{bmatrix} \phi \\ D \\ Q \\ C \end{bmatrix} = \begin{bmatrix} 0.004 & -0.090 & 0.002 & 0.125 \\ 0.022 & 7.369 & 0.073 & -23.441 \\ -0.079 & 5.561 & 0.123 & -20.927 \\ 0.051 & -12.84 & -0.198 & 45.244 \end{bmatrix} \begin{bmatrix} \phi N \\ \rho_b \\ \Delta t \\ 1.0 \end{bmatrix} \quad [17]$$

Once the inverse matrix \underline{C}^{-1} is computed the proportions of porosity and minerals can be calculated very swiftly by matrix multiplication.

Plate 6a is a graphical representation of the lithology of the Viola Limestone in the Belcher A1 well. The proportion of porosity and mineral constituents were computed at one foot intervals which correspond to the interval used in digitizing the original log blue prints. The KOALA well logging package calculated the proportions and created the plotter file. A total of six components were calculated for the entire section, although no more than four could be derived for each zone as the system of equations described in the foregoing paragraph allows a simultaneous solution for four components only. The first track (white) to the left of Figure 6a represents primary porosity, whilst secondary porosity (white) is displayed in track two. Dolomite, quartz, calcite, and shale are represented by standard patterns for dolostone, sandstone, limestone, and shale.

The calculation of the various volume fractions with the KOALA system includes the computation of an error parameter. The meaning of this parameter and its usefulness in the lithology analysis of individual zones is perhaps best explained by the following geometrical considerations. Three coordinate axes representing neutron porosity, bulk density,

and transit time define a three-dimensional space (Fig. 12). As four unknowns can be solved for by the system of log response equations, a tetrahedron can be constructed whose vertices are defined by the coordinate values associated with pore fluid and lithological components that are assumed to represent the bulk composition of the section under investigation. Any solution that plots outside the tetrahedral space will result in the computation of a negative component fraction indicating that this point is not defined by the system chosen. As the M-N plot is a projection of the tetrahedral space onto its base triangle, Figure 13 provides an explanation of calculated negative components. A negative limestone fraction determines a lithology of dolomite, chert, and shale. Consequently, negative fractions of dolomite define a cherty limestone with vugs and possibly fractures in addition to intercrystalline porosity. Primary and secondary porosity also characterize a rocktype consisting of a mixture of dolomite and calcite, an interpretation based on a computed negative quartz fraction.

The process of lithology computation using the KOALA system is accomplished by solving the whole section first for the main mineralogical constituents and primary porosity. The solution is then investigated for negative component fractions and their respective depth intervals and mineralogy is marked. Recomputation of these zones follows after an appropriate column vector in the log response coefficient matrix is replaced with the coefficients of a different lithology component. So, for example, a negative calcite fraction would lead to the replacement of the calcite coefficients with those defining the log responses of shale. The interactive mode of the KOALA system enables the operator to perform these steps without interrupting his process of log analysis.

VI. LITHOLOGY DETERMINATION OF THE VIOLA LIMESTONE

The lithofacies analysis of the Viola Limestone as planned originally would have employed the approach demonstrated in the analysis of the Belcher A1 well which was discussed in the last chapter. In that approach, the lithological composition of the Viola in every well would be analyzed at one foot intervals and used as the basis for subdividing the formation into units characterized by a distinctive lithological character. These units would then be correlated, and maps prepared of their variation in terms of geometry and lithological composition. The available suite of porosity logs associated with each well, however, precluded this approach. A method was devised that allowed the computation of average proportions of porosity and mineralogical constituents of the entire Viola without requiring a complete suite of porosity logs at every well location.

Methodology

The new technique is based on log response averages calculated for each porosity log over a defined stratigraphic interval. An average log response for a formation is computed by summing the responses of a porosity log for each zone (zone = digitization interval) and dividing the sum by the number of zones. These average log responses can be viewed as points on surfaces which represent either variation in average neutron porosity, average bulk density, or average transit time of a particular stratigraphic interval over the mapped area. The surfaces can be approximated by grids whose z-values are calculated by interpolation from surrounding data points. The gridding technique used is based on a triangulation algorithm, as this approach retains the variation of the original data to a higher degree, than algorithms based on various search methods and distance

weighted averages (McCullagh, in preparation). The resulting three grids cover the area of study and are geographically congruent so that an estimated average log response of each porosity log is available at geographical locations corresponding to grid nodes. A grid cell surrounding a node covers an area of about 6.25 square kilometers in a square grid composed of 41 rows and 51 columns. The distance between rows as well as columns corresponds approximately to one half of the distance between well sites in areas with good control point coverage, which was determined by visual inspection of a posting of well sites. The average proportion of porosity and three mineralogical components for the formation can now be calculated at each node. The validity of this method is demonstrated by the following considerations.

The average proportions of components that make up a stratigraphic unit can be calculated by two different methods in a well that is logged with all three porosity tools. The first method is to compute the component fractions of every zone (zone = digitization interval) and then compute their averages by summing them over the interval and dividing the sum by the number of zones. This can be expressed mathematically in the following equation which, as an example, relates to the computation of one component fraction for one zone.

$$V_a = N\phi C_{a1} + \rho_b C_{a2} + \Delta t C_{a3} + C_{a4} \quad [18]$$

where V_a = volume fraction of component a

C_{a1} to C_{a4} = coefficients of inverse matrix \underline{C}^{-1} that relate measured porosity log responses to volume fraction a.

Calculation of the average of that particular volume fraction is expressed as:

$$\frac{1}{N} \sum_{i=1}^n (Va)_i = \frac{1}{N} \sum_{i=1}^n [(N\phi)_i C_a + (\rho_b)_i C_{a2} + (\Delta t)_i C_{a3} + C_{a4}] \quad [19]$$

where $i=1, 2 \dots n-1, n = \text{number of zones}$

The component average can also be expressed as:

$$\frac{1}{N} \sum_{i=1}^N (Va)_i = \frac{Ca_1}{N} \sum_{i=1}^N (N\phi)_i + \frac{Ca_2}{N} \sum_{i=1}^N (\rho_b)_i + \sum_{i=1}^N (\Delta t)_i + Ca_4 \quad [20]$$

which is the equivalent of the foregoing equation and states that an average fraction of a component can be calculated from the average porosity log responses.

The above considerations simplify the lithofacies analysis of the Viola Limestone to the formation as a whole, as porosity and mineralogical composition are calculated as formational averages from the average porosity log responses. However, this application does not restrict the general usefulness of the method in lithofacies analysis as any stratigraphic interval that can be identified on well logs over an area of study can be analyzed for its bulk compositional components. The method can be applied as long as a more or less even distribution of different porosity logs is available. The interpolation of the average log responses into grids frees the analysis from the restrictive condition of having all three porosity logs present in every well, as the vast majority of wells are logged with only one or two porosity tools. It is believed, therefore, that this approach can prove a helpful tool for lithofacies analysis in industrial as well as academic applications.

Log Normalization

Before grids could be interpolated the average log responses for the Viola Limestone needed to be normalized for an error component. The term "log normalization" describes a procedure that is designed

to correct log traces for errors caused by tool malfunction, inconsistent shop and field calibration, and operator error. It is estimated that more than 50 percent of all logs are erroneous and that all but 10 percent of those can be corrected because the error involved is largely systematic (Neinast and Knox, 1973). Errors that cannot be corrected are generally caused by sporadic and unsystematic tool malfunctions during a logging run. Systematic errors are caused by tool miscalibration and borehole conditions for which the measurements were insufficiently compensated and manifest themselves in a shift of the log trace relative to the scale of measurement. A density log, for example, may read consistently .1 grams per cubic centimeter less than it should. The correction of such errors is relatively straightforward if a core is available to serve as a standard of calibration. Measured grain densities can then be converted into apparent densities and compared with the readings recorded by the log.

In regional studies, it is general practice (Neinast and Knox, 1973) to select for the purpose of log calibration a stratigraphic unit that is "essentially uniform" in its physical characteristics, and does not contain any considerable amounts of hydrocarbons as this would cause anomalous log readings that are not related to the lithologies of the stratigraphic interval under investigation. Core measurements in a well serve as ground truth for the whole area and are compared with equivalent log responses measured over the cored section of the calibration unit in all wells. The deviation between core and log data is considered to be an error component associated with the log measurements and used to normalize the logs.

In the absence of core analyses, average log responses are calculated for a "calibration unit" in every well ("well average"). An "area-average"

is calculated from the well averages, and the well averages are then subtracted from the areal average and the deviation is added to the appropriate log trace.

The log normalization method applied in this research is similar to the approach just described, but includes one modification as trend surfaces are used to account for regional variation in the "essentially uniform" physical characteristics of the unit selected as calibration standard. The unit chosen is the "Lower Limestone" which fulfills the requirements demanded of a "calibration unit," as hydrocarbon shows are not reported from this unit in drilling reports. Although no cores were available as a definite check, the "Lower Limestone" is described by Adkison (1972) as a pure limestone with minor amounts of chert and dolomite which is in agreement with most of the sample logs investigated. As already mentioned in the discussion of the neutron log, the "Lower Limestone" is the only interval in the Viola section that can be identified beyond doubt in every well encountered. The log responses of every porosity log is consistently extreme, so that the assumption of essential uniform physical characteristics associated with this unit is considered justified.

Log normalization was accomplished by computing the average log responses for the "Lower Limestone" unit for every porosity log available at every well location. As top and bottom elevation of a unit are defined by the point of inflection of an analog log trace, only log responses two feet below the top and two feet above the base were used in the calculation of the average log response. This assures that the average log response is a measurement of the "Lower Limestone" and eliminates to a large extent any contribution from vertically adjacent beds. Trend surfaces of increasing order were fitted to the average

responses of the neutron, density, and sonic logs (Figs. 14a, 14b, and 15). An F-test (McCullagh, 1973) was used to determine if a trend surface of n th-order accounted for a significant increase in the explanation of variation over a trend surface of $(n-1)$ th-order. According to the F-test, first-order trend surfaces are a sufficient approximation of areal variation for the density and sonic average log responses, while a second order trend surface best accounts for the variation of the neutron porosity averages. The higher trend surface for the neutron responses is caused by the substantially larger number of control points as compared with the density and sonic responses. This allows a better definition of a regional trend.

A low order trend surface can be regarded as a reasonable representation of measurements that are essentially uniform as was assumed for the physical characteristics of the "Lower Limestone." An ideal unit used for log calibration would exhibit only random variation of its physical characters which would result in the computation of a trend surface of zero-order, i.e., a horizontal plane. The calculated residuals consist of random measurement error together with a component representing fine-scale geological variation. The residuals are subtracted from the average log responses computed for the Viola Limestone which decrease high log responses and increase low ones.

Unless log normalization is based on comparative core measurements in every well, all normalization techniques tend to smooth true variation of the measured variable together with variation introduced by logging tools. It is believed that the application of trend surfaces minimizes the suppression of geological variation present in the data, as compared to the use of an "areal average."

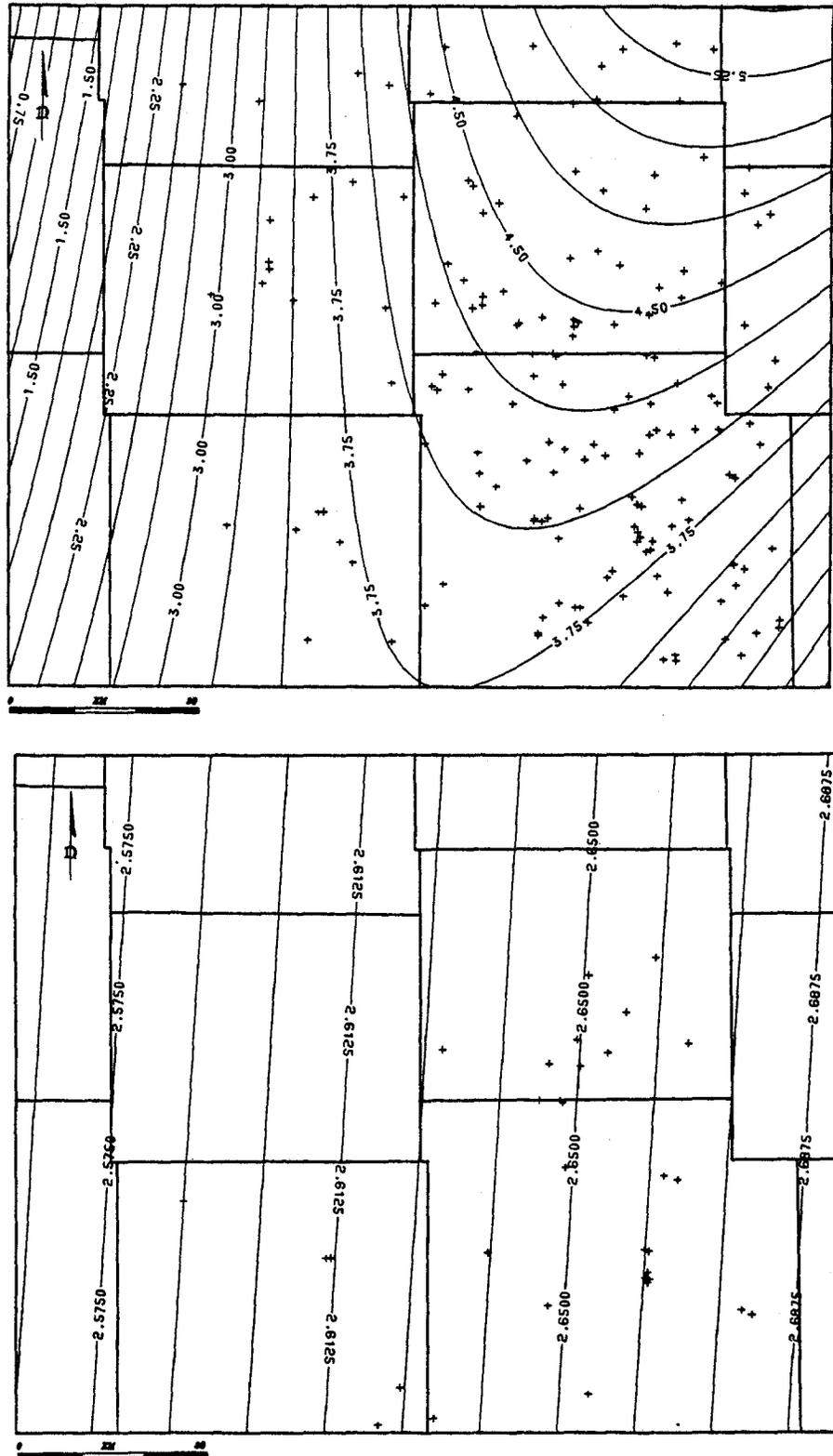


Figure 14. A. Second order trend surface of average neutron log responses of "Lower Limestone." Units in neutron porosity.

B. First order trend surface of average density log responses of "Lower Limestone." Units in grams per cubic centimeter.

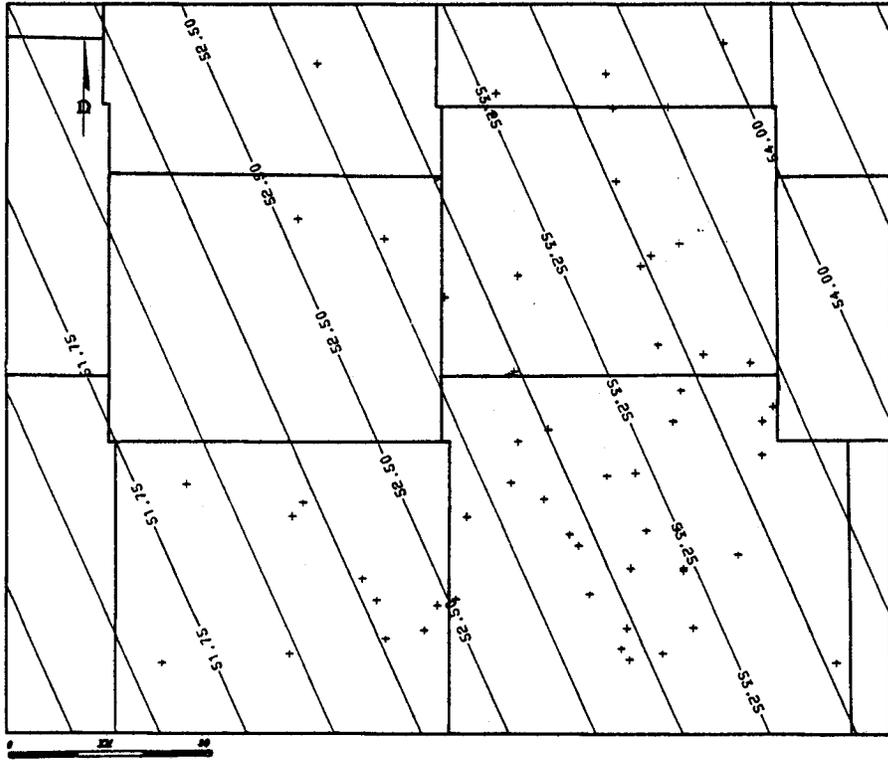


Figure 15. First-order trend surface of average sonic log responses of "Lower Limestone." Units in microseconds per foot.

Another problem normally to be considered before the start of any log analysis is the correction of depth miscalibration between logs measured in one well. Logs are said to be "on depth" when corresponding peaks or valleys of different logs register at the same depth. Poor depth registration was often observed but no attempt was made to correct for it, as working with average log responses automatically eliminates this problem, as long as top and bottom elevation of the same stratigraphic interval are picked separately on each log.

Computation of Porosity and Mineral Fractions

The average log responses were normalized according to the approach described in the last section and grids representing average log responses of neutron porosity, bulk density, and transit time were calculated. They constitute the data source for the calculation of porosity and mineral fractions of the Viola Limestone.

The computational procedure resulting in the derivation of porosity and mineral fractions is based on Equation 14, but differs in its numerical representation, as the coefficient values for neutron porosity of dolomite and quartz as well as the transit time coefficient of quartz were changed. These coefficient values must be selected from tables in standard logging manuals as they depend to some degree on the average amount of porosity in the formation and, in the case of the neutron porosity coefficients, on the type of neutron tool employed. If different neutron tools were used in an area, their responses have to be connected to a common scale prior to normalization and gridding using procedures which are available in logging manuals. The matrix equation employed in the lithofacies analysis of the Viola assumes the form:

$$\underline{C} \underline{X} = R$$

Written out as:

$$\begin{bmatrix} 100.00 & 2.0 & -4.0 & 0.0 \\ 1.0 & 2.87 & 2.65 & 2.71 \\ 189.0 & 43.5 & 55.1 & 47.5 \\ 1. & 1. & 1. & 1. \end{bmatrix} \begin{bmatrix} \phi \\ D \\ Q \\ C \end{bmatrix} = \begin{bmatrix} \phi N \\ \rho_b \\ \Delta t \\ 1.0 \end{bmatrix} \quad [21]$$

The equation is solved by matrix inversion

$$\underline{X} = \underline{C}^{-1} \underline{R}$$

and written as:

$$\begin{bmatrix} \phi \\ D \\ Q \\ C \end{bmatrix} = \begin{bmatrix} .006 & 0.0 & .003 & -.139 \\ .292 & 7.690 & .072 & -24.280 \\ -.089 & 3.846 & .109 & -15.617 \\ .0538 & -11.538 & -.185 & 41.037 \end{bmatrix} \begin{bmatrix} \phi N \\ \rho_b \\ \Delta t \\ 1.0 \end{bmatrix} \quad [22]$$

The computation is accomplished by retrieving a neutron porosity, bulk density, and transit time response from grid nodes that are determined by identical row and column indices and performing a matrix multiplication with a row vector of the inverse of the coefficient matrix. The resulting value corresponds to a volume fraction and is transferred to another grid where its location is defined by the indices of the log responses.

A short computer program (App. 5) performs this operation by reading rows sequentially from each input matrix. It then accepts a row vector of the inverse of the coefficient matrix and calculates a row of volume fractions. The program is executed four times to calculate four grids containing fractional porosity, and the volume fractions of dolomite, quartz, and calcite. All four grids should be viewed as a contiguous set, since corresponding grid elements pertain to the same geographical location.

Viola Rock Types

In order to relate computed mineral fractions to rock types commonly encountered in the Viola formation, a compilation of lithologies used in describing the Viola is given in this section. In the existing literature, the Viola Limestone of south-central Kansas is described as a carbonate sequence whose bulk composition includes limestone, cherty limestone, cherty dolostone, and residual chert over the area of study (Adkison, 1972). Intercalations of shale with dolostone beds are reported by Ver Wiebe (1948) and secondary porosity, in the form of vugs and fractures is described by Biederman (1966). Lithologies cited in 30 sample logs (Table 1) are a semi-quantitative correlation of these assessments.

Table 1

FREQUENCY OF CITATIONS OF COMMON ROCK TYPES ARRANGED IN
APPROXIMATE STRATIGRAPHIC ORDER

Residual chert, vuggy	12
Dolomite, cherty, vuggy	10
Dolomite, cross-laminated, cherty	4
Dolomite, cherty, calcitic	6
Shale, dolomitic	3
Limestone, cross-laminated, cherty, dolomitic	23
Limestone, cross laminated	29

In general, not more than three rock types are differentiated in an individual sample log. Accessory components such as glauconite, phosphate nodules, and pyrite are rarely mentioned and, if ignored, the bulk

composition of the Viola can be described by a combination of six components, namely primary and secondary porosity, calcite, dolomite, chert and shale.

This set of lithology descriptors is not only adequate to describe the Viola in south-central Kansas, but can be applied to the Viola or its equivalents in Oklahoma (Wengerd, 1948; Mairs, 1966), Arkansas (Freeman, 1966), and Iowa (Agnew and others, 1956). This overall uniformity of the Viola over the whole Midcontinent makes it possible to compare some major lithologies observed in outcrop sections located in the vicinity of the city of Dubuque, Iowa with those described from the subsurface of south-central Kansas. Plates 9a, b and 10a, b (courtesy of J. H. Doveton, Kansas Geological Survey) provide an example of the major lithologies of the Viola limestone with the exception of pure limestone and residual chert.

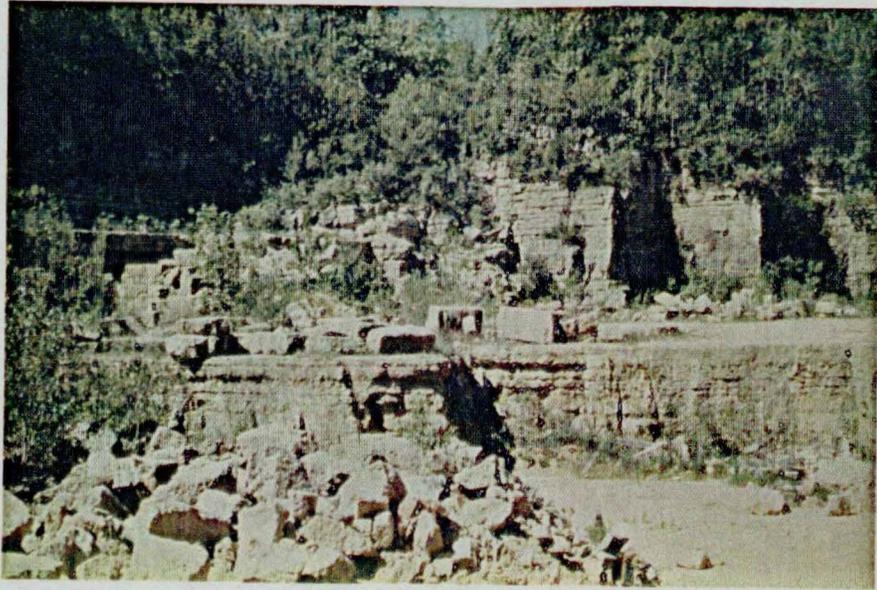
Lithofacies Classification

To achieve continuity with lithological descriptions of the Viola arrived at by conventional methods, an attempt was made to express the computed fractions of calcite, dolomite and quartz in terms comparable to those employed by subsurface geologists for the Viola of south-central Kansas (Table 1). The classification of the mineral fractions into lithofacies was achieved by plotting the mineral percentages into a ternary diagram (Fig. 16). The ternary diagram is constructed in an unconventional way as allowance had to be made for the representation of negative mineral fractions which constituted over 50 percent of the computed total. The mineral fractions were normalized with respect to porosity prior to plotting, so that their sum would represent 100 percent. Out of the 2091 points (41 by 51 matrix) calculated, only 192 are shown in

Plate 9a. Noncherty unit - Dolomite, yellowish-buff, thin to medium bedded, dolomitic shale interbeds.

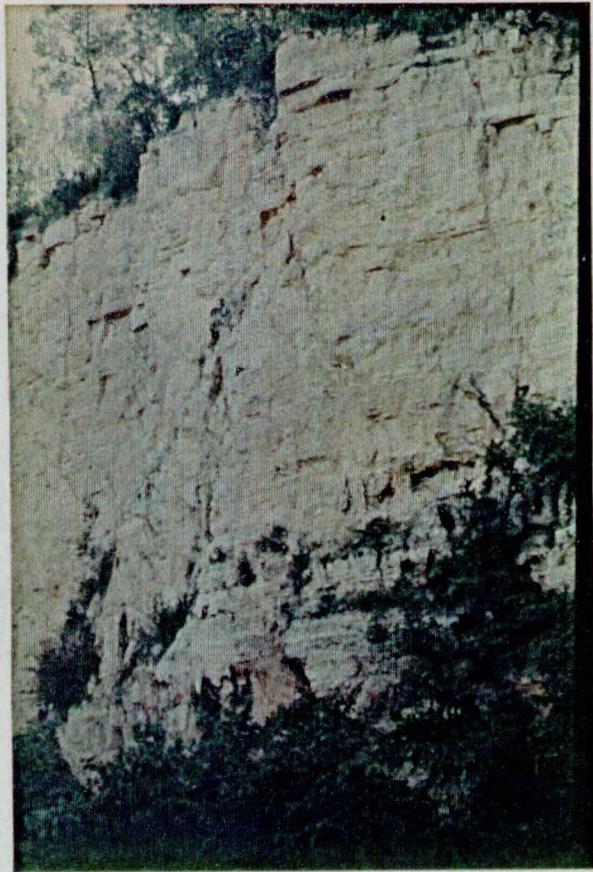
Plate 9b. Upper cherty unit - Dolomite, buff, thick to thin bedded, cherty, vuggy.

Lower cherty unit - Dolomite, light grey, thick to thin bedded, cherty, calcitic, vuggy.



76
 MAQUOKETA
 SHALE

Noncherty unit
 G R O U P



Upper
 cherty unit
 G A L E N A (70m)
 Lower
 ST PETER
 SANDSTONE

Plate 10a. Chert unit - Nodular chert layers between dolostone beds.

Plate 10b. Cherty unit - Detail of highly siliceous horizon in dolostone. Chert occurs in nodules and finely disseminated form replacing dolomite. Secondary porosity present as vugs and small fractures.

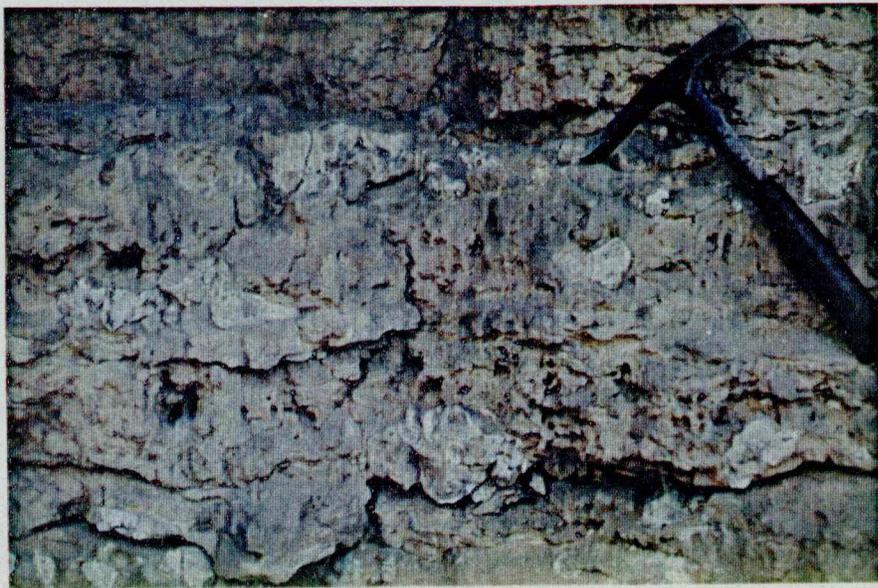
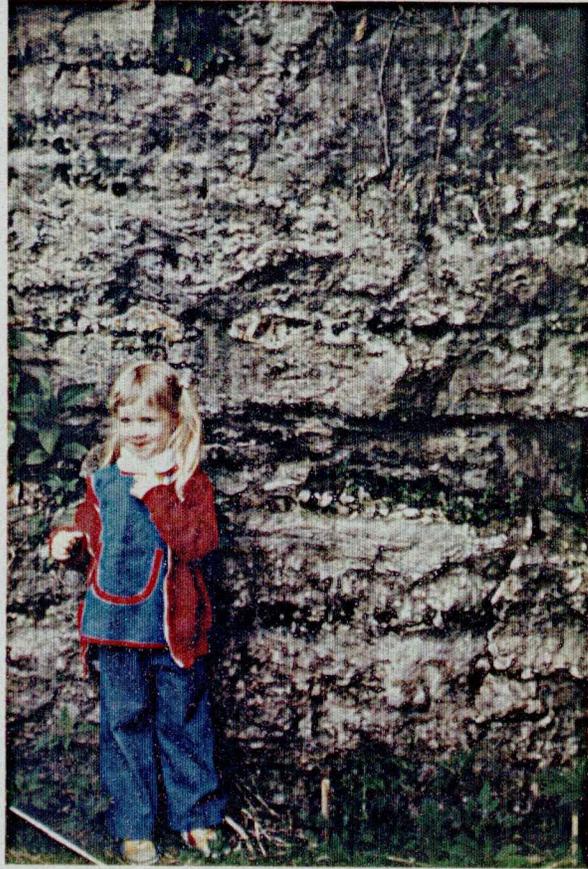


Figure 16. The criterion for selection was that a grid cell surrounding a grid node had to contain at least one porosity log, providing some control in the calculation of mineral fractions from log response averages.

The ternary diagram in Figure 16 is divided into six areas, each representing a lithofacies characterized by a dominant or typical constituent. The center triangle corresponds to a ternary diagram proper and is symmetrically divided into three lithofacies that are determined by the endmembers calcite, dolomite, and quartz. Points that plot within the triangle as well as in a 10 percent margin surrounding it are classified as limestone, dolostone or chert facies. Points that fall within the 10 percent margin can be expressed by a mixture of two endmembers as the following considerations will demonstrate. The center triangle of the ternary diagram can be regarded to be approximately equivalent to the base triangle of the tetrahedron pictured in Figure 12, which contains valid solutions of the log response equations in terms of calcite, dolomite, quartz and porosity. The lengths of the sides of the tetrahedron's base triangle represent 100 percent of a component, as does the side of a bounding triangle represent 100 percent porosity. By projecting a point outside the tetrahedron onto the base triangle, only points that are situated extremely close to a bounding triangle will plot within the 10 percent margin. Out of this reason it was felt justified to classify these points as lithofacies defined by the triangle endmembers.

The remainder of the diagram is divided into three lithofacies defining a carbonate with residual chert, residual chert with carbonate, and a shaly carbonate facies. The introduction of two lithologies not solved for by the log response equations is based on evidence provided by the interpretation of the M-N plot of the Belcher A1 well. Negative

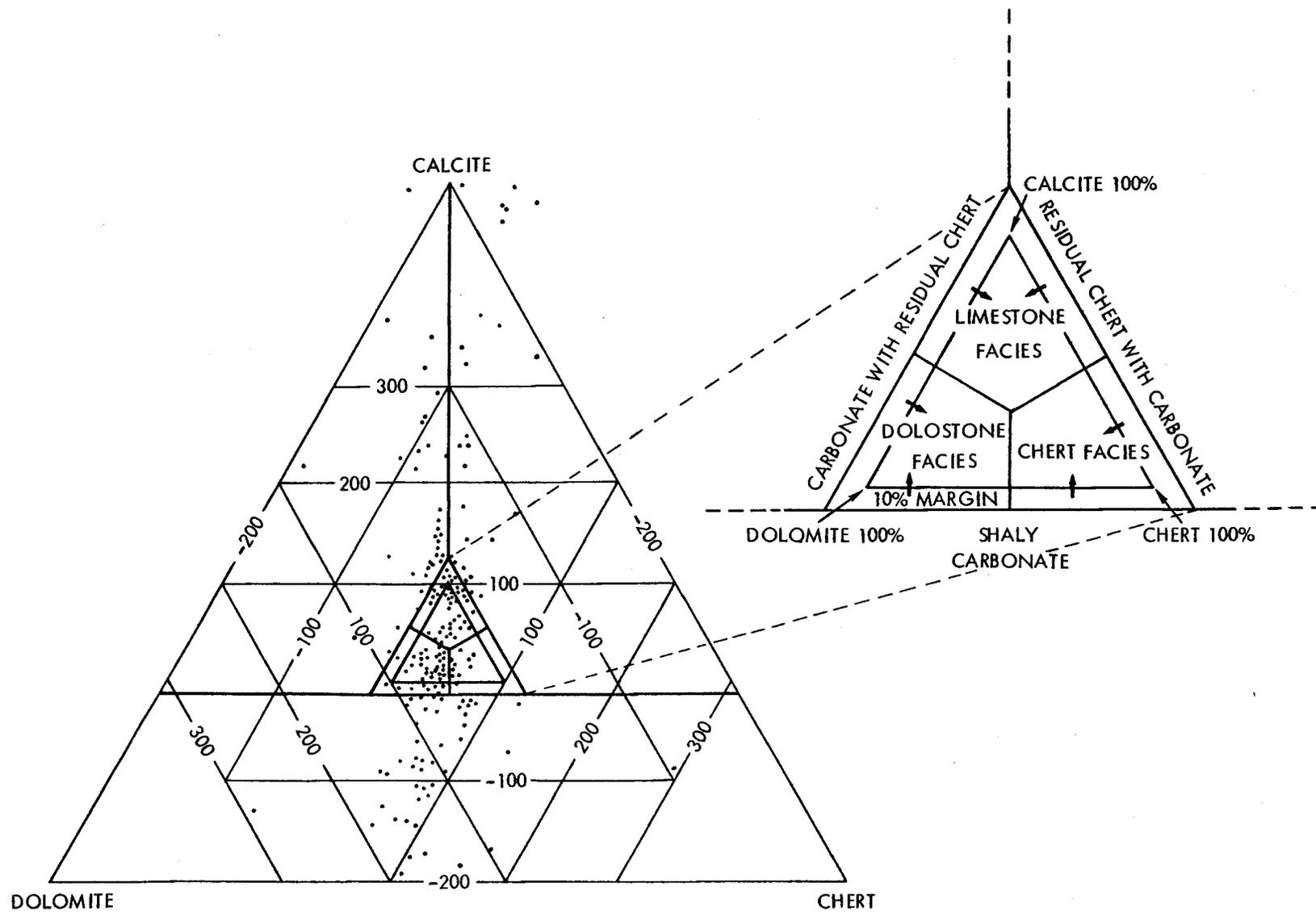


Figure 16. Ternary diagram for lithofacies classification of computed mineral fractions.

fractions of calcite are attributed to the presence of shale by direct analogy with Figure 13. The identification of residual chert, however, is based on a hypothesized association with significant secondary porosity. This assumption is strongly supported by observations from cuttings. Adkison (1972) describes the Viola as consisting almost entirely of residual chert over structural high areas and residual chert is commonly described in sample logs as characterized by vuggy porosity. Additionally, Doveton (1966) describes cores of Mississippian residual chert from south-central Kansas with a high amount of secondary porosity. The association of notable amounts of secondary porosity with residual chert is accepted here. Solutions of the log response equations with a positive calcite fraction, but a negative dolomite and/or chert fraction are therefore caused by secondary porosity and classified as residual chert. The distinction of two facies is made on grounds of differing residual chert content and reflects the notion that points plotting in the field labeled residual chert with carbonate are derived from the right half of the ternary diagram which represents rocks with a higher proportion of chert than the left half.

The names of the defined lithofacies give an indication of the Viola bulk composition but can be interpreted in more detail (Table 2) if related to Viola lithologies described in the foregoing section.

A computer program classified the calculated mineral fractions according to the limiting percentage values shown in the ternary diagram of Figure 16. Code values represented by integers ranging from one to six were assigned to each lithofacies and stored in a 41 by 51 grid which is contiguous to the set of grids containing the mineral fractions. This grid constitutes the basis for the Viola lithofacies map.

Table 2

LITHOLOGY INTERPRETATION OF COMPUTED BULK MINERAL COMPOSITION

Limestone facies	- Limestone, dolomitic, cherty (can be pure limestone)
Dolostone facies	- Dolostone, calcitic, cherty (small amount of secondary porosity)
Chert facies	- Chert, banded, dolomitic, calcitic (minor amount of secondary porosity)
Shaly carbonate facies	- Dolostone, cherty, calcitic, shale intercalations (shale generally not exceeding 20 percent)
Residual chert and carbonate facies	- Chert fragments in carbonate matrix, high secondary porosity
Carbonate and residual chert facies	- Chert fragments in carbonate matrix, high amount of secondary porosity (grading downwards into cherty, calcitic dolomite)

VII. STRUCTURAL AND LITHOFACIES ANALYSIS

The classification of the Viola's compositional components into a system of six lithofacies marked the end of the data collection and derivation process. A set of structural and lithofacies maps is used to display the data and an interpretation of the Viola structure, and lithofacies distribution is outlined in the following discussion.

Preparation of Structural Maps

Four structural maps were constructed to describe the geometry of the Viola formation of south-central Kansas. They include a structure map contoured on top of the formation (Plate 2), an isopach map (Plate 3), and a trend surface with its residual map (Figs. 17, 18). The structure map is contoured using an interval of 20 meters with the outlines of oilfields producing in the Viola (compare with Plate 1) superimposed on it. The isopach map is contoured with an interval of five meters and displays three levels of shading, dividing the formation thickness into three classes. The light shading indicates a thickness of less or equal to 25 meters, the medium tone a thickness of 25 to 40 meters and thicknesses above 50 meters are shaded in dark tone. Oil pools producing from the Viola are superimposed as bold elliptical outlines. A second order trend surface was chosen as being the best approximation of the regional structure. It explains over 97 percent of the structural variation and contains a significant increase of variation compared to a first order trend. A third order trend adds only 1.5 percent of explained variation which is not a significant increase according to an F-test (McCallagh, 1973). The structural residuals of the second order trend surface were mapped and the positive residuals in Figure 18 are shown shaded.

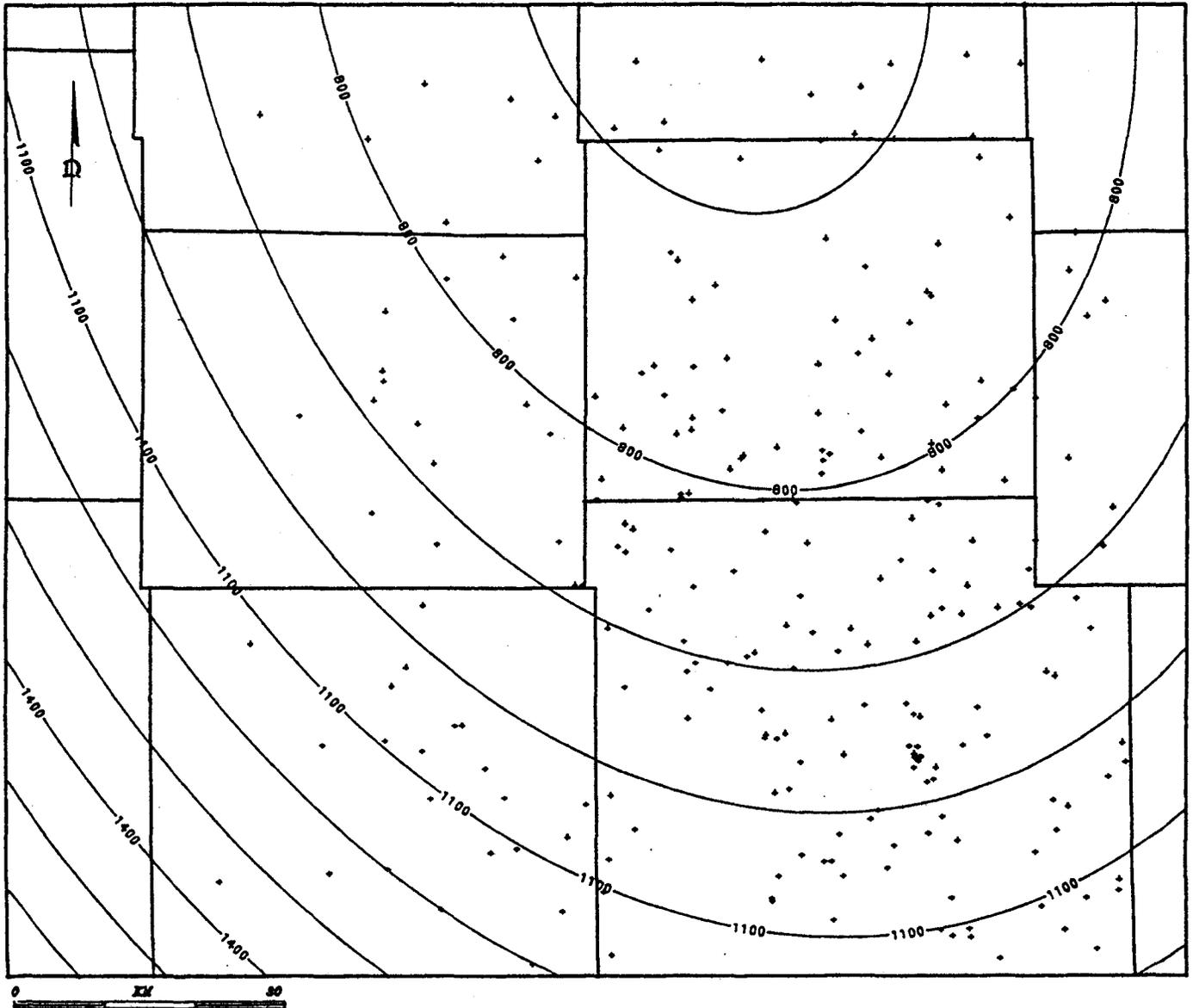


FIGURE 6 : QUADRATIC TREND SURFACE OF THE STRUCTURAL ELEVATION OF THE TOP OF THE VIOLA LIMESTONE MEASURED IN METERS SUB-SEA LEVEL.

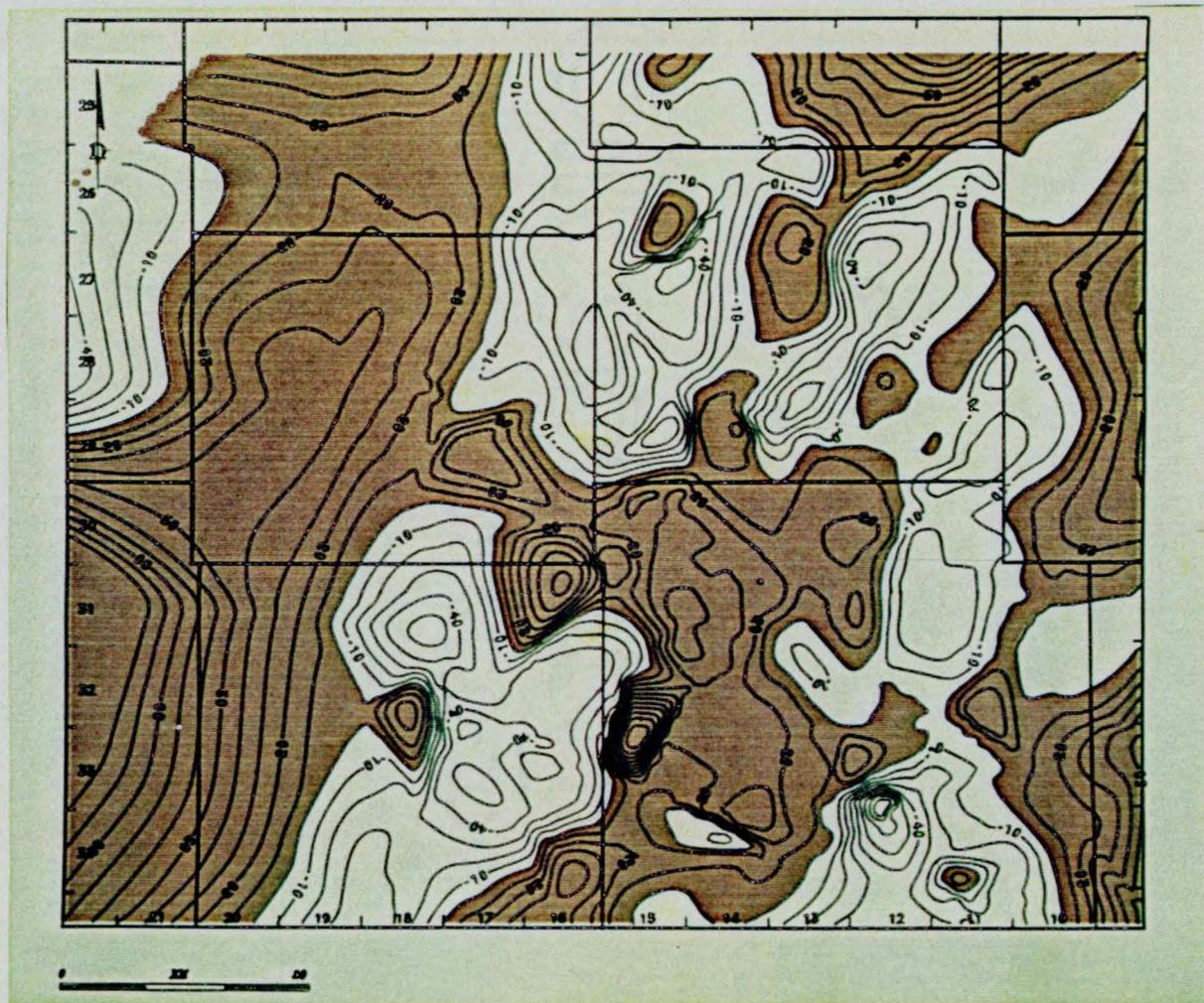


Figure 18. Structure residual map of second order trend surface. Contour interval 10 meter. Positive residuals shaded.

All maps were constructed by the interactive TERRAPLOT software package (McCullagh, in preparation) on an ECLIPSE minicomputer and the final maps were drawn on a XYNETICS flatbed plotter. The maps are based on a square grid of 41 by 51 nodes and contoured with the highest amount of smoothing possible on the ECLIPSE computer.

Preparation of Lithofacies Maps

Three isofacies maps were contoured which portray the variation of percent limestone (Fig. 20), percent dolostone (Fig. 21), and percent chert (Fig. 22) as continuous variables. A lithofacies map (Plate 5) displays the computed six lithofacies in form of a raster map.

The three isofacies maps are constructed by eliminating primary and secondary porosity as well as shale content as components of Viola bulk composition. This was accomplished by normalizing the computed fractions of primary porosity, calcite, dolomite, and chert with regard to porosity. The remaining mineral components constitute now 100 percent of the bulk composition and a second normalization was undertaken by setting computed negative mineral fractions to zero and expressing the remaining positive fraction(s) in terms of mineral composition. This procedure illustrated in Figure 19 projects all points outside the ternary diagram onto the diagrams vertices or sides and all computed mineral fractions can be mapped in a continuous percentage contour map. All three isofacies maps are displayed with a contour interval of 25 percent and areas containing over 50 percent of a component are shaded. These maps are to be interpreted with care, because of the normalization process, but do provide a good estimation of the dominant mineralogical component, especially in areas where a component constitutes less than 100 percent of total composition.

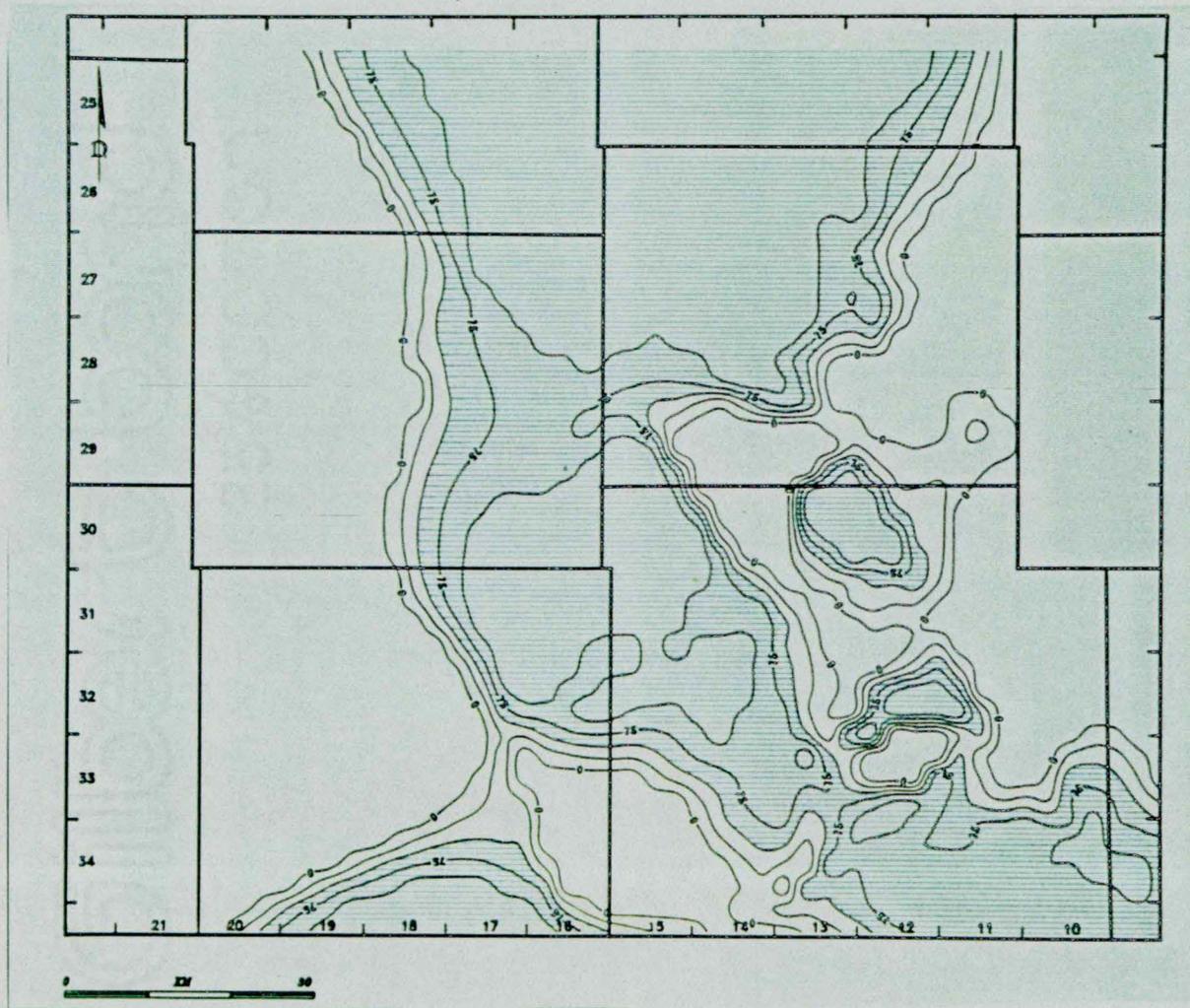


Figure 20. Limestone isofacies map. Contour interval 25 percent. Shaded areas contain more than 50 percent calcite.

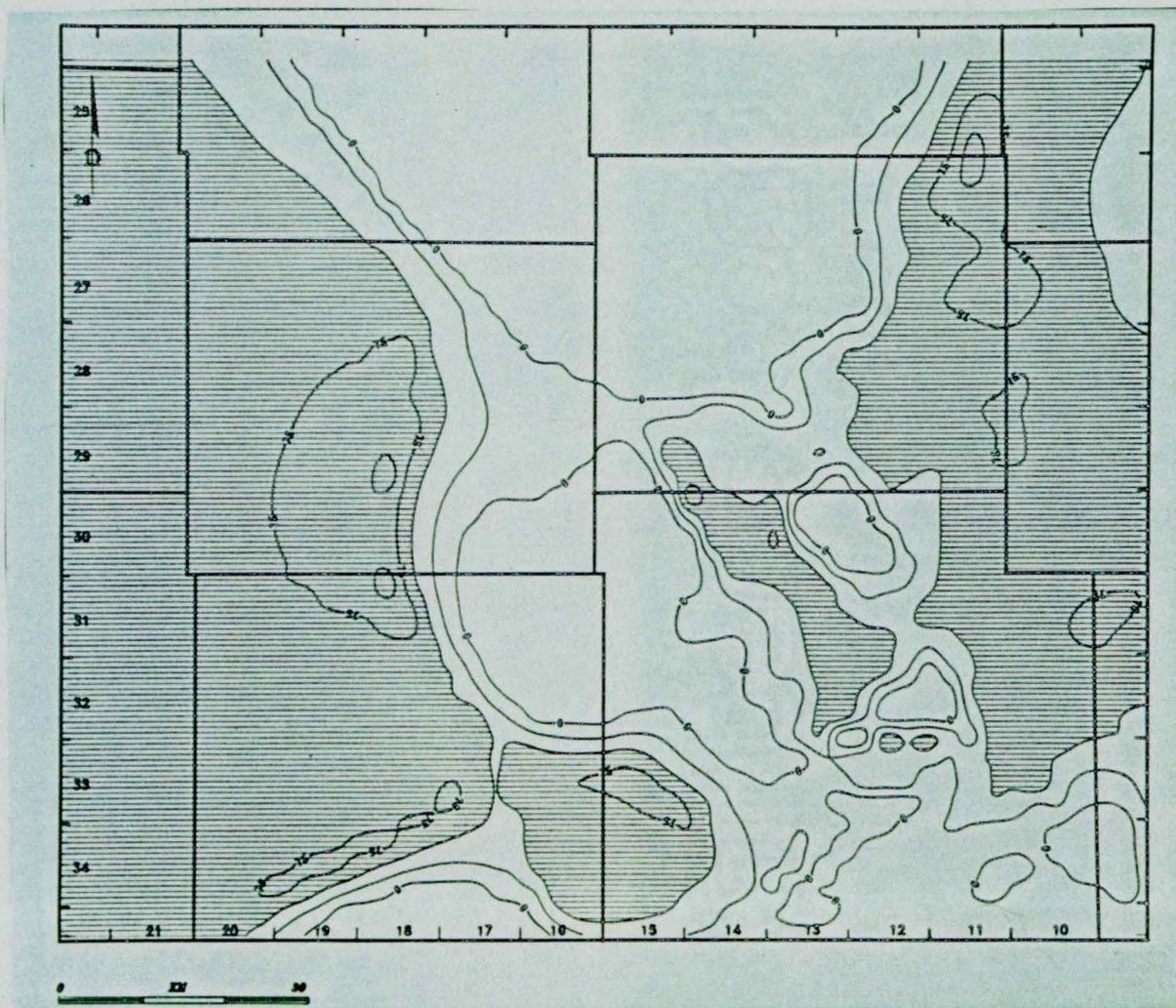


Figure 21. Dolostone isofacies map. Contour interval 25 percent. Shaded areas contain more than 50 percent dolomite.

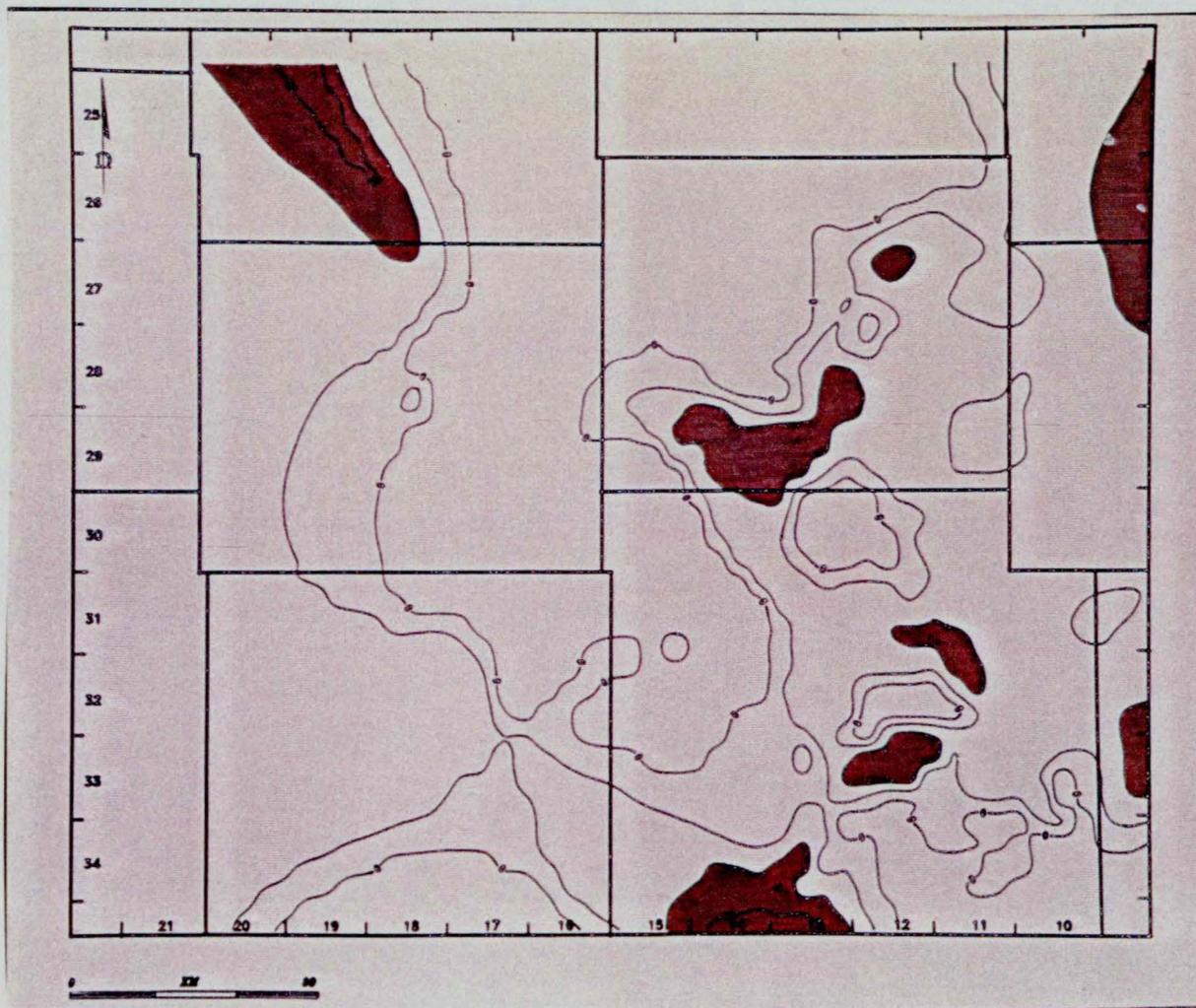


Figure 22. Chert isofacies map. Contour interval 25 percent. Shaded areas contain more than 50 percent quartz.

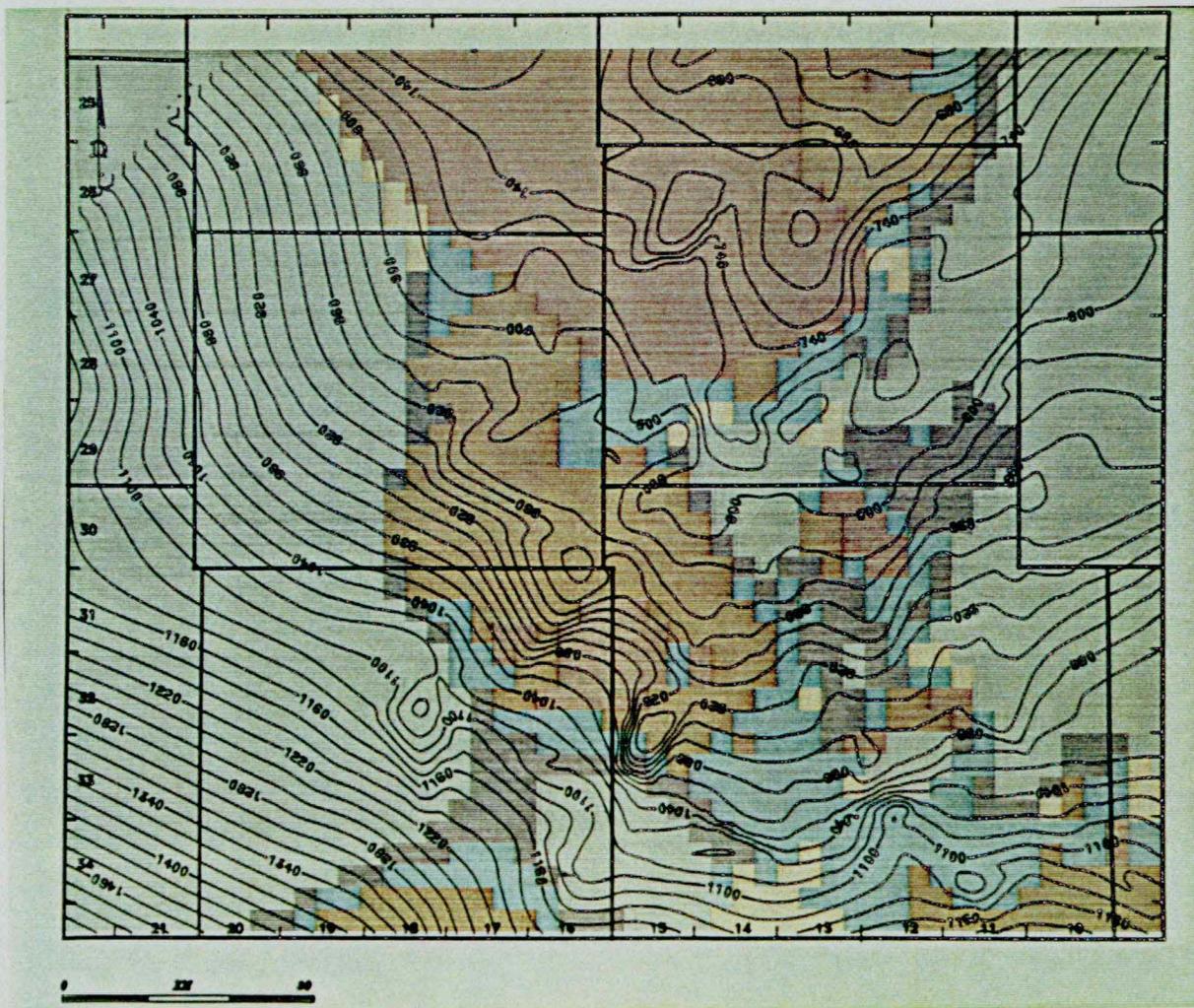


Figure 23. Lithofacies map with superimposed structure. Plate 8 (in pocket) gives the explanation of color coding.

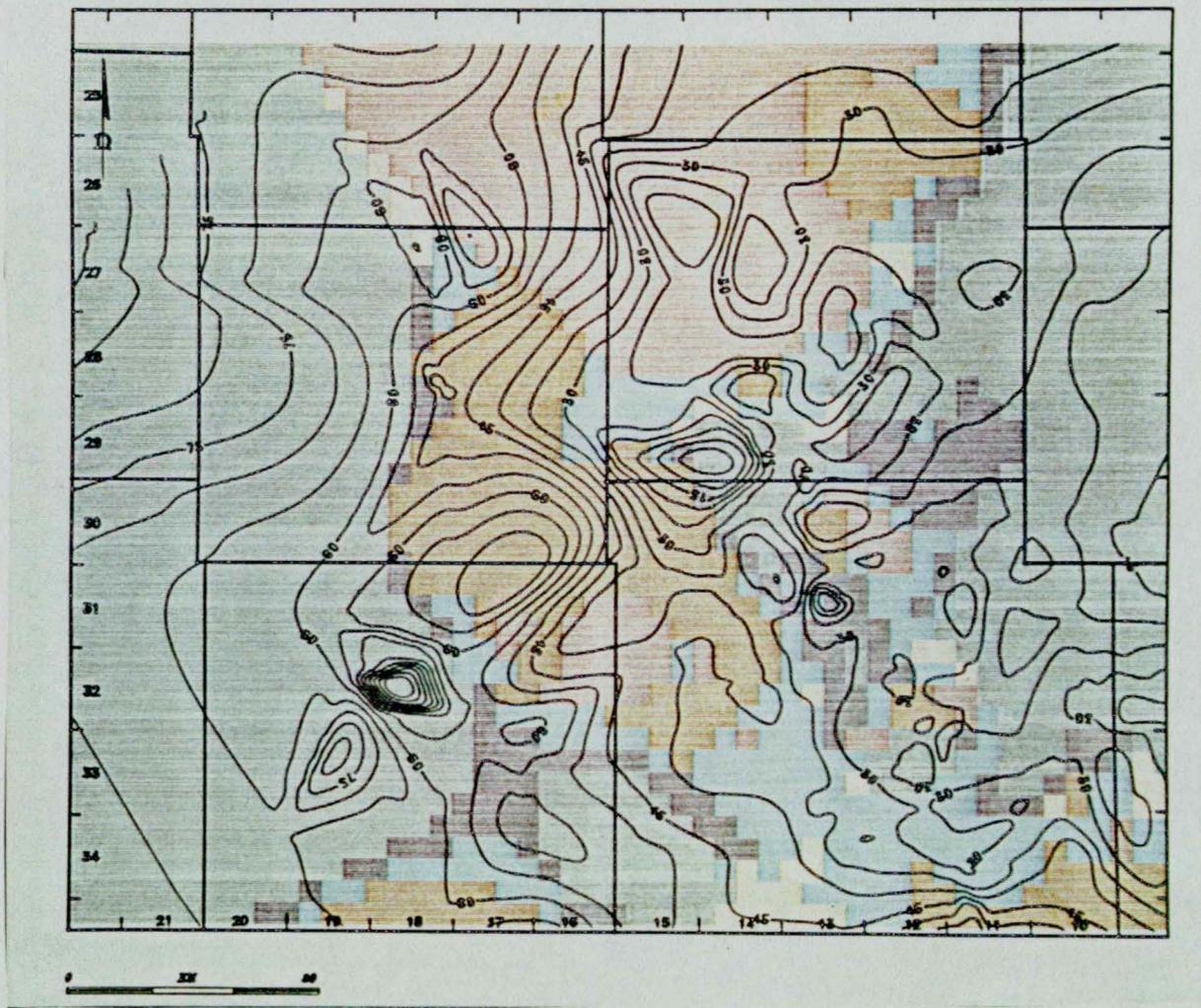


Figure 24. Lithofacies map with superimposed formation thickness. Plate 8 (in pocket) gives explanation of color code.

The three isofacies maps are contoured by TERRAPLOT in the same fashion as the structure maps.

A lithofacies map (Plate 5) completes the display of Viola lithologies. This map is based on a 41 by 51 grid described in the last chapter. The grid is coded in six numbers each representing a lithofacies based on the interpretation of the ternary diagram in Figure 16. As the lithofacies codes represent non-continuous data a raster mapping technique was chosen to display each grid cell as a pixel with the lithofacies identified by different symbols or colors.

In order to facilitate the recognition and interpretation of structural trends and lithofacies patterns, the structure map (Plate 2) and the isopach map (Plate 3) were superimposed on the lithofacies raster map (Figs. 23, 24).

Major Structural Trends and Lithofacies Distribution

The combination of structure and master lithofacies map in Figure 23 defines three areas differing in their structural and lithofacies patterns. They can be related to regional structural elements, i.e., the Pratt Anticline, the Hugoton Embayment, and the Sedgwick Basin (Fig. 1).

The Pratt Anticline is defined as the triangular area in the north pointing south with a regional dip of about three meters per kilometer (16 ft/mi). It is structurally outlined in the west and south by the 800 meter contour (all contours express elevations below sea level) and in the northeast by the 740 meter contour. The lithology of the Viola over this structural high consists almost entirely of residual chert surrounded by a rim of limestone. The strike of the eastern margin as determined by the line of transition of residual chert into limestone corresponds approximately to N20°E, which is one of the major structural

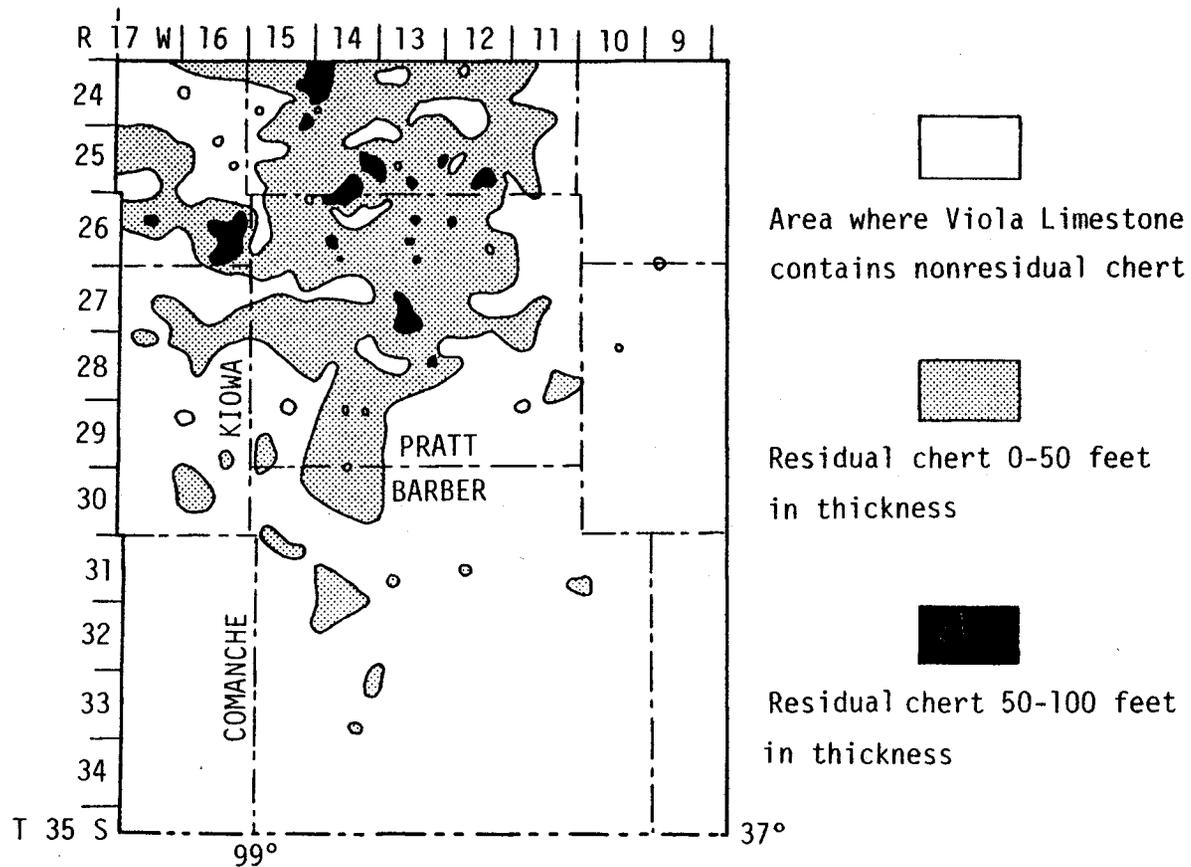


Figure 25. Chert isofacies map prepared from sample logs (from Adkison, 1972).

trends in Kansas and related to the structural attitude of the Nemaha Anticline (Merriam, 1963). The western margin of the Pratt Anticline has a direction of strike of about N45°W, corresponding to the other major trend in Kansas exemplified by the attitude of the Central Kansas Uplift (Merriam, 1963). The area to the south of the Pratt Anticline shows increasing regional dip interrupted by plateau-like structural noses. The lithology changes from north to south from residual chert underlain by carbonates to limestones and dolostones.

The remaining two areas flank the Pratt Anticline in the east and west and constitute parts of the Sedgwick Basin and Hugoton Embayment. The lithology of these areas is classified as shaly carbonate, but it should be kept in mind (Figs. 6, 14a, b, 15) that the distribution of control points with regard to structure and lithofacies maps in particular is very poor in the western quarter of the study area.

The Pratt Anticline and its southern extension is also very well defined on the three isofacies maps. Areas enclosed by the 100 percent limestone contour (Fig. 20) are covered largely by residual chert and surrounded by a predominantly calcitic carbonate. To the east and west of the Pratt Anticline, dolomitic carbonates prevail.

A comparison of Adkison's (1972) chert isofacies map reproduced here in part as Figure 25 shows a broad similarity in the distribution of residual chert with the lithofacies map (Fig. 23) prepared from the analysis of petrophysical well logs. Plate 7 shows three cross-sections based on sample logs that agree well with the residual chert distribution of Figure 23. On the other hand, Adkison's map is based on a greater number of sample logs and the variation of residual chert thickness and residual chert distribution is correct within the limitations of the sample logs which are based on well cuttings. A map based on sample logs

may contain variation not present in the subsurface due to the fact that well cuttings represent generally a mixture of lithologies from different formations. The residual distribution of chert agrees well with areas of low regional relief and relatively high structural elevation, as shown in Figure 23. The process of averaging the porosity log responses and the lack of density logs in the northern part of the area caused smoothing of local lithology variation.

Minor Structural Trends

Secondary structural features superimposed on the Pratt Anticline and the basinal areas are identified best by comparing the structure residual map (Fig. 18) with the chert isofacies map (Fig. 22), and the raster lithofacies maps (Figs. 23, 24). The pattern of positive and negative residuals exhibit a striking orthogonality in areas of good well average. A dominant trend strikes approximately southwest and northeast. This trend is best exemplified by an almost unbroken succession of positive residuals ranging from T.35R.17 to T.26R.10 incorporating the Lake City Anticline (Merriam, 1963) in T.31R.13 and the Cunningham Anticline (Merriam, 1963), which extends from the southwest corner of T.28R.11 to T.26R.6. A parallel trend of positive residuals extends from T.32R.11 to T.29R.9 and is approximately on strike with the Willowdale Anticline (Merriam, 1963) to the east of the mapped area.

Two positive structures described by Merriam (1963) on evidence of oil pool contour maps on the top of the Lansing Group (Upper Pennsylvanian) as the Moore and Coats dome are located in T.26R.15 and T.29R.14 respectively. Four structures exhibiting similar shapes on the residual map are mapped in T.33R.18; T.33R.15; T.31R.16; and T.27R.13. Rich (1935a) describing the pattern of a structural residual map which

he derived by a graphical method (Rich, 1935b) from a structure contour map was

at once struck by the pronounced rectangular pattern of the structure and . . . that the area seems to be divided into blocks bounded by nearly straight sides, or fracture lines. (Rich, 1935).

In a discussion on seismic anomalies on the Pratt Anticline Brewer (1956) suspects faulting and differential erosion of Lower Paleozoic rocks. His definition of the Pratt Anticline is virtually identical with a ridge (Fig. 18) of high positive residuals bisecting Pratt County in a north-south direction. This ridge includes the Coats Dome (T.29R.14) which appears as a north-south trending rectangular block and terminates in T.26R.13 in a similar but larger feature. Both blocks are connected by a northeast striking structurally less pronounced bridge and the whole feature is interpreted by Brewer (1959) as an uplifted block bounded by faults in the east and north. Two of the other three features, with a similar appearance can be related to domal structures mapped on top of the Precambrian by Cole (1976). They are located in T.33R.15 and T.33R.18. The feature in Barber County strongly suggests an uplifted block bounded by faults. The last of the mentioned structures is located in T.31R.16 but may be caused by the grid interpolation technique rather than by structural variation, as the northwest corner of Comanche County has no control points.

The cited references and the features mentioned suggest that fault-bounded blocks with an areal extension of one or two townships are an important structural element of the study area.

Less important with regard to regional structure but of economic significance, are faults that are mappable generally only after production drilling is completed following the discovery of a pool. These faults

have a very limited extension and an area bounded by such faults seldom covers more than two or three sections (Brewer, 1956; Merriam, 1963).

All three classes of structural elements identified by Merriam (1963) are present in the study area, although only the first two could be identified on the structural maps. A structure of regional extent is represented by the Pratt Anticline and surrounding basinal areas. Minor structures such as faulted blocks and anticlines are superimposed on these major elements. Local closures and minor faults could not be defined at a finer scale than presented by the distance between control points. The four uplifted blocks which have good control point coverage are tentatively named Iuka Horst (T.27R.13), Coats Horst (T.29R.14), Deerhead Horst (T.33R.15), and Coldwater Horst (T.33R.18) after nearby municipalities.

Structural Evolution

Lee (1954) discussed principles for the interpretation of isopach maps and states:

A map depicting the thickness of a sequence of rocks between surfaces that were once flat or relatively flat records the structural movements that occurred between the development of the limiting surfaces. Such an isopachous map is essentially a structure map of the first surface at the time of the second.
(Lee, 1954)

These principles can be applied to the interpretation of the Viola isopach map (Plate 3) and the description of the structural evolution is aided by the lithofacies and isofacies maps.

The Viola limestone of south-central Kansas was deposited in an epicontinental sea (Ross, 1976) that extended over a stable shelf region (Ireland, 1966). The bathymetry of this Ordovician sea was related to the regional structural elements illustrated in Figure 5b.

A study by Taylor (1947) of the Viola of the Salina Basin (Fig. 1) demonstrated that the Viola shows a gradual increase in thickness towards the center of the basin. This is exemplified by lithologic members of the formation that are unaffected by post-Ordovician erosion. Similar conclusions were expressed by Lee, Leatherock, and Bottinelly (1948), who stated additionally that the Viola was deposited on a beveled surface of Simpson sediments. It is assumed here that the original thickness of the Viola in south-central Kansas followed a pattern of increasing thickness in a southwesterly direction from the Central Kansas Arch (Fig. 5b) into the southwest Kansas Basin. The deposition of the Viola Limestone in the study area was controlled by regional structural elements but without noticable local tectonic control. Variation of formation geometry as portrayed by the structure contour map (Plate 2) and the isopach map (Plate 3) can, therefore, be tentatively related to structural and erosional events that occurred after the deposition of the Viola formation.

Studies by Adkison (1972), Merriam (1963), and Lee (1956) conclude that the structural configuration of Kansas has remained virtually stable since the beginning of Middle Pennsylvanian time. Tectonical events that noticably affected the Viola Limestone must have taken place in the span between Upper Ordovician and Middle Pennsylvanian time. The identification and timing of these events is attempted by comparing the sequence of stratigraphic units as identified on well logs with the postulated succession of units once deposited in south-central Kansas (Table 3). Evidence provided by Lee (1956) allows the assumption that the Viola of south-central Kansas was once overlain by the Upper Ordovician Maquoketa Shale and that Silurian and Devonian

Table 3

UNDIFFERENTIATED STRATIGRAPHIC UNITS AND ROCK TYPES DEPOSITED
IN SOUTH-CENTRAL KANSAS FROM MIDDLE ORDOVICIAN TO MIDDLE
PENNSYLVANIAN TIME

Pennsylvanian	shales, sandstones basal conglomerate
Mississippian	carbonates Boice Shale
Devonian	Chattanooga Shale
Devonian/Silurian	*Hunton Group
Ordovician	*Maquoketa Shale Viola Limestone

(*Units not encountered in well logs.)

carbonates of the Hunton Group constituted the stratigraphic unit encountered above it. The removal of both units and evidence provided by the structure and lithofacies maps allows the following reconstruction of structural events.

The first tectonic event caused uplift of the Chautauqua Arch and the Pratt Anticline before the Late Devonian Chattanooga Shale and the early Mississippian Boice Shale were deposited. Rocks of the Hunton Group and the underlying Maquoketa Shale were completely stripped from the mapped area and the Viola was reduced considerably in thickness as Viola profiles in locations outside the study area suggest (Adkison, 1972). The rapid decrease in thickness along a north trending line in the center of the area (Plate 3) can be attributed to differential uplift of the Pratt Anticline compared to the area in the west where the Viola was more protected from erosion. This interpretation, however,

is only tentative as the Pratt Anticline probably exerted some influence on the original thickness of the formation. Additionally, the previously described paleogeographic setting during Viola deposition favored a thickening of the formation towards the southwest. The regional trend of formation thickness (Plate 3) probably represents depositional variation in thickness enhanced by differential erosion during Devonian times. Except for the latest stage of that erosional episode all products of weathering were transported from south-central Kansas towards the Quachita basin of Oklahoma and Texas repeating the same general pattern as during the early Ordovician when the Arbuckle Group was eroded following regional uplift (Ireland, 1955). The latest stage of erosion was apparently dominated by chemical weathering which caused *verkarstung* of highlands leaving a regolith of chemically resistant rocks. The residual chert over the Pratt Anticline (Plate 5) is interpreted as such a deposit.

As an interesting aside, an isopach map of the Chattanooga Shale was constructed which shows a very gradual decrease of formation thickness from the southeast corner of Barber County where it measures about five meters towards a line that follows the general eastern outline of the Pratt Anticline between T.35R.16 and T.27R.9. Beyond that line the Chattanooga is not present. It could very well be that this formation was deposited in low lying areas while karst weathering proceeded on topographic highs.

A rapidly deepening sea covered the Chattanooga and the remainder of the area with a thick deposit (up to 80 meters) of shale in early Mississippian time. This unit is named the Boice Shale and is overlain by Mississippian carbonates whose original thickness became drastically

reduced by erosion over wide parts of the area following uplift caused by the second tectonic event recognized in the study area.

This structural event began its major cycle of activity in the Late Mississippian and culminated in Early Pennsylvanian time (Lee, 1956; Merriam, 1963). Its effect on the Viola Limestone is categorically different from the former tectonic event. While the former event caused differential erosion of the Viola thereby largely determining the formation's bulk lithofacies, the second event finalized the structural configuration of the formation as displayed in the structure map (Plate 2) and the structure residual map (Fig. 18). The final shape of the Pratt Anticline was established and the fault-bounded blocks described previously were activated. It is on the surface of these fault-bounded blocks that early Pennsylvanian erosion reached the Viola Limestone and caused additional thinning of the formation. This is evident on the isopach map (Plate 3) over areas occupied by the Tuka Horst, Coats Horst, and Coldwater Horst. The area occupied by the Moore Dome (T.27R.15) seems to have been subjected to the same process. Brewer (1956) reported Pennsylvanian rocks in direct contact with rocks of the Arbuckle Group over a small area on the Coats Horst. This indicates that these uplifted blocks represented considerable topographic relief as a few hundred feet of rocks including Mississippian carbonates, Boice Shale, Viola Limestone, and Simpson Group were removed but are identified on well logs in the immediate vicinity.

In contrast, the Deerhead Horst which shows the strongest positive anomaly on the structural residual map does not indicate erosion of the Viola formation in Early Pennsylvanian time (Plate 3, T.33R.15).

It is concluded that uplift of this horst did not commence until the beginning of Pennsylvanian deposition. Dellwig (1956) reported an earthquake from Barber County of January 6, 1956. The intensity of this earthquake was estimated between five and six according to the Modified Mercalli Scale, which classifies it among the larger earthquakes ever recorded in Kansas. Mapping the Deerhead Horst into the isoseismal map provided by Dellwig (1956), the earthquake's epicenter corresponds with the location of the Horst, indicating that this feature still is tectonically active.

The structural grain of Kansas was finalized in Early Pennsylvanian time and exhibits trends striking generally northeast or southwest, which are depicted well by the chert isofacies map (Fig. 22). These trends are thought to correspond to readjustments of tectonic trends in the Precambrian basement (Rich, 1933). The interpretation of some minor structures as fault-bounded blocks implies that the basement is also broken into blocks of similar size at least in the vicinity of tectonic lineaments bounding regional structural elements where differential movement was at its strongest.

Sedimentation

A reconstruction of the depositional history of a stratigraphic unit is based on the identification of rock types which can be interpreted with regard to their environment of deposition. The geographic pattern of environments and their migration through time defines the depositional history of a unit and enables the construction of paleogeographic maps which provide ". . . the framework in which the analysis of earth history must be set" (Krumbein and Sloss, 1951).

Prior to the reconstruction of the Viola's depositional history, the observed rock types have to be interpreted with regard to the accumulations of sediment from which they originated. Unfortunately, dolomitization has largely obliterated the original sediment particles and sedimentary structures, but petrologic data published by Biederman (1965) from Viola rocks of the El Dorado field in Kansas and by Freeman (1965) from the Viola of Arkansas allow some conclusions as to the composition of the original carbonate sediment. The petrologic data can be related to Viola lithologies of the study area and an interpretation of Viola sedimentation in south-central Kansas can be given.

Freeman (1965) published two photomicrographs (his Figs. 20 and 21) both of which are limestones with no recognizable proportion of dolomite. His Figure 20 shows trilobite, bryozoan, crinoid, and brachiopod fragments (his interpretation) imbedded in calcite cement. A porosity of about 20 percent appears to be the result of complete and partial dissolution of skeletal parts. The rock can be classified as a packstone according to Dunham's (1962) scheme because the original sediment probably consisted of a framework of skeletal fragments with interstitial micrite which recrystallized into sparite. Figure 21 of Freeman (1965) represents the Fernvale Limestone which is considered the uppermost member of the Viola by Wengerd (1948) but a distinct formation by Amsden (1979). Petrologically it consists of crinoid debris (Freeman's interpretation) with calcite cement overgrowth. The cement grows in optical continuity with the crinoid fragments and is interpreted as rim cement (Bathurst, 1952) which implies growth by filling pore space. The possible interpretation of the overgrowth as syntaxial rims (Bathurst, 1952) which grow as a replacement of micrite is rejected on evidence provided

by Moore (1957) and Evamy and Shearman (1965, 1969) who observed that crinoid fragments associated with lime mud show little overgrowth. About 50 percent of the area of the photomicrograph is occupied by crinoid fragments, indicating an initial porosity of 50 percent, now completely obliterated by rim cement. The rock is classified as a grainstone with the original sediment consisting largely of crinoid fragments devoid of intergranular micrite.

Biederman (1965) published a series of photomicrographs from the Viola Limestone of the El Dorado field in Butler County, Kansas. His Figures 19, 20, and 30 portray an equigranular dolostone with vuggy porosity that appears to have formed by leaching of fossil fragments with the vugs resembling crinoid and trilobite remnants. The axial canal of an observed crinoid fragment is preserved as a circular clot of dolomite crystals surrounded by pore space. The sediment probably consisted of skeletal parts surrounded by lime mud, which entered the axial canals of columnal crinoid fragments. The mud recrystallized as sparite and was dolomitized, although it is possible that the dolomite crystals grew by replacing micrite. Sparite and micrite are generally dolomitized first (Lucia, 1962) and the calcite fossil fragments were dissolved before they could be replaced by dolomite. This rock can be classified as a wackestone, as the skeletal parts apparently did not form a grain-supported framework. Three other figures (his Figs. 15, 23, and 22) show idiotopic and hypidiotopic dolomite fabrics with no recognizable fossil fragments. Most dolomite crystals exhibit a dark center interpreted by Biederman (1965) as clay minerals or organic matter. The sediment probably was a lime mud containing a small fraction of both. The dolomite crystals possibly grew in the mud with clay particles forming an idiotopic fabric when micrite was removed prior

to the completion of dolomitization. The limestone equivalent of this rock would be classified as a mudstone.

The conclusions drawn from the published photomicrographs of dolomitized Viola rocks with regard to the character of the sediment are supported by studies of Lucia (1962), Lucia and Murray (1967, and Murray and Lucia (1967). Lucia (1962) describes a variety of Devonian rocks from Texas exhibiting various degrees of dolomitization. The degree of dolomitization of limestones is directly related to the amount of micrite associated with the crinoid fragments in the sediment. Crinoidal limestones cemented by rim cement have a measured porosity of 1.6 percent and a permeability of .01 millidarcies, and are not dolomitized. Crinoidal limestones are dolomitized when micrite was associated with the skeletal parts. Dolomitization of micrite and occasionally crinoid fragments as well as leaching of calcitic fragments from partially dolomitized rocks results in porosities that range from five to about 30 percent. The amount of porosity developed is greatest when the micrite fraction of the sediment was between five and 20 percent, indicating that dolomitized packstones make excellent reservoir rocks.

This process of selective dolomitization is documented in Mississippian rocks of the Turner Valley formation of Alberta (Murray and Lucia, 1967). Carbonate rocks ranging from grainstone to wackestone exhibit different degrees of dolomitization. The grainstones consist largely of cross-bedded crinoid debris cemented by rim cement and are not dolomitized. Packstones contain about 15 percent dolomite and wackestones are dolomitized thoroughly. Field relations of these rocks show that grainstones are spatially separated from wackestones by packstones. Erosion surfaces and vertically succeeding sets of cross beds dipping 180 degrees apart indicate that the grainstones were

deposited by tidal currents which reworked a sediment consisting of crinoid fragments and lime mud. Murray and Lucia (1967) suggest that the density of the crinoid population, that provided the skeletal fragments, was greatest close to the tidal channels, where constant water motion provided a constant supply of nutrients. Away from the channels food supply was limited and could support only a small population of crinoids. It is between tidal channels that most of the lime mud was deposited providing a mixture of micrite with scattered crinoid fragments which consolidated as a wackestone. Packstones originated in areas between channels and areas where water was least agitated. Dolomitizing waters could not penetrate the grainstone made impermeable by rim cement which, therefore, remained a limestone. The packstone and wackestone were dolomitized either partially or completely depending on the amount of micrite present.

Dolomitization by rock selectivity explains the lithologies of the Viola Limestone as interpreted from published photomicrographs (Biederman, 1965; Freeman, 1965) and descriptions of well cuttings (Table 1). The "Lower Limestone" unit of the Viola in south-central Kansas is described by Adkison (1972) as a cross-bedded, medium to coarse crystalline, crinoidal limestone. The porosity of this unit as derived from geophysical logs is close to two percent which is in good agreement with the porosity of 1.6 percent measured by Lucia (1962) on crinoidal grainstones cemented by rim cement. The cross-bedding indicates that the unit was deposited by currents.

Almost all remaining lithologies listed in Table 1 can be interpreted with the descriptions given previously of dolomitized Viola rocks from Butler County, Kansas. Dolostone originated as lime mud and can be described as a mudstone. Vuggy dolomite originated as a wackestone or

packstone from a lime mud with differing proportions of skeletal parts. Of the remaining lithologies the dolomitic shale probably originated in areas with a slow rate of carbonate production and residual chert is a regolith deposit as already discussed and formed by tectonically induced erosion. The description of a dolomite with cross-bedding is considered incorrect and represents most probably a cross-bedded, dolomitic limestone. Such a lithology can form, when depositional environments shift and lime mud is deposited on top of current deposited crinoid debris. Micrite can settle into the porespace of the underlying sediment and restrict the formation of rim cement preserving initial pore space which allows penetration of dolomitizing waters.

The identification of the sediments that were deposited in south-central Kansas during Viola time allow a tentative reconstruction of the formations depositional history. The overall paleogeographic setting (Fig. 4), the lithofacies map (Plate 5), and a profile of the Viola Formation (Plate 6) provide information on the spatial relations of environments.

The onset of Viola deposition is marked by a grainstone which represents the "Lower Limestone" unit. The cross-bedding indicates that the sediment was probably moved by long-shore currents equivalent to those that deposited the St. Peter Sandstone. The shore-parallel bars left behind a sheet of crinoidal debris when they shifted landward following the shoreline of a transgressing sea. Quartz grains described from the lower part of this basal limestone (Adkison, 1972) indicate some erosion of St. Peter Sandstone probably near the shoreline. Deepening of the water led to the deposition of sediments forming packstone, wackestone, or mudstone, the type of which largely dependent on water agitation. The lower 20 feet of the profile shown in Plate 6a

represents the "Lower Limestone" whose upper zones show an increased degree of dolomitization caused by the process described previously. The rest of the section shows alternations of generally slightly dolomitized limestone and cherty, dolomite occasionally interrupted by a shale stringer. The limestones are interpreted in analogy to the "Lower Limestone" unit and the dolomites represent mudstone or wackestone. Between 5585 feet and 5622 feet, the section may be made up of packstone as indicated by the high proportion of porosity.

The sediments that contained differing proportions of lime mud formed as non-current deposits. These deposits were scoured by wind-driven currents that removed the lime mud and formed bars of cross-bedded skeletal debris. The origin of the grainstones in tidal channels seems unlikely, as the influence of lunar tides is considered minimal in epeiric seas (Friedman and Sander, 1978). The depth of water was probably in the order of 20 to 30 meters (Friedman and Sanders, 1978).

A broad regional pattern of depositional environments can be deduced from the lithofacies map (Plate 5), although the map must be interpreted with the isopach map (Plate 3) to estimate the effect of differential erosion.

The Pratt Anticline influenced sedimentation by constituting a positive undulation of the seafloor. This shoal area experienced more current and wave action than the areas to the east and west and predominantly grainstones and packstones were deposited which are represented on the map as limestone and dolostone facies. The difference in depth of water between the shoal and the surrounding areas is probably in the order of five to 10 meters and a higher proportion of wackestone and mudstone was deposited in deeper waters. These rocks are shown on the map as shaly carbonate facies. Migrating grainstone bars imposed local

variations on these areas resulting in the complex carbonate lithology of the Viola limestone.

Dolomitization

Dolostones are divided into two groups, those that formed penecontemporously by replacement of unconsolidated carbonate sediment are termed "primary dolomites," while "secondary dolomites" formed by dolomitization of pre-existing limestones. Dolomitization is controlled by permeability, composition and particle size of the host rock or sediment, as well as by parameters such as temperature, pressure, ionic concentration and composition of the pore waters (Davies, 1979).

Dolomitization may be caused by hypersaline brines with a high Mg:Ca ratio, or it may occur in zones where sea water and freshwater mix (Badiozamani, 1973). Hypersaline brines form in lagoonal environments and a close spatial relationship of such environments with the carbonate sediments or rocks to be dolomitized is required. On the other hand, dolomitization in the mixed water zone requires a paleogeographic setting where exposed areas caused by tectonic uplift or eustatic fluctuations in sea level provide for fresh-water recharge. A number of detailed models for the origin of dolomite were put forward over the last 20 years or so and are reviewed briefly to provide for possible explanations of the process that caused dolomitization of the Viola Limestone.

Penecontemporary dolomite was documented by Illing, Wells, and Taylor (1965) from sabkhas of the Persian Gulf and by Shinn, Ginsburg, and Lloyd (1965) from supratidal flats of the Bahamas. The dolomitization of aragonitic sediments is accomplished by hypersaline brines with a Mg:Ca ratio of greater than 30:1. Evaporation of interstitial sea-water by capillary action results in a hypersaline brine from which

gypsum precipitates. This removal of calcium is the cause for the high Mg:Ca ratio. The system is recharged when abnormally high or storm tides flood across the supratidal environment.

The Bonaire model (Deffeyes, Lucia, and Weyl, 1965) explains the dolomitization of Recent and Plio-Pleistocene limestones on Bonaire Island, Netherlands Antilles. Their observations in a Recent environment support the concept of evaporite reflux or seepage refluction which was developed previously to explain dolomitization of ancient reefal limestones (Adams and Rhodes, 1960). This model requires a body of sea water which is isolated from the fully marine environment by a barrier generally thought of as reefs. Evaporation will form a brine with a high Mg:Ca ratio after precipitation of gypsum. This dense brine sinks downward and seaward and presumably causes dolomitization of carbonate sediments or limestones by moving through the porespace. The lagoonal environment is recharged by seepage of sea water through a permeable barrier.

The Dorag model (Badiozamani, 1973) is based on the concept of dolomitization by groundwater which was revived by Hanshaw, Back, and Deike (1971). Badiozamani (1973) mixed different proportions of Yuccatan groundwater with sea water and concluded from his computations that a mixture of freshwater with a proportion of about five to 30 percent sea water is less saturated with respect to calcite than the original groundwater but supersaturated with respect to dolomite. It is believed that such waters will cause the replacement of calcite by dolomite over long periods of time forming well developed dolomite crystals in contrast to the poorly ordered crystals from Recent intertidal flats. Badiozamani (1973) applied his Dorag model to Ordovician carbonates of Wisconsin

which are dolomitized over areas that experienced exposure several times during the Ordovician while laterally equivalent rocks were not subjected to subaerial exposure and remained limestones.

Recently Wanless (1979) showed that dolomite can form as a response of limestone to stress. The pressure solution-dolomitization process is thought to be responsible for rocks that consist of alternating laminae of limestone and dolostone, probably reflecting compositional differences in the sediment which resulted in a different response to stress. Wanless (1979) also attributes ribbon limestones which consist of limestone lenses surrounded by a continuous network of dolostone layers to pressure solution-dolomitization.

Connate water expelled by compaction of shales was assumed by Jodry (1964) as the agent responsible for dolomitization of Silurian reefs in Michigan. This model is believed important when shales are deposited in close paleogeographic relation to permeable limestones.

Other mechanisms of dolomite formation include hydrothermal and metamorphic processes.

The last two processes can certainly be disregarded as the cause for dolomitization of the Viola formation. Metamorphism is virtually unknown in sedimentary strata of the Midcontinent and hydrothermal fluids generally are active in tectonic fracture zones where they could cause dolomitization, but this process is of no regional importance. The sabkha model also is inadequate to explain the dolostones of the Viola. The Viola was laid down in a fully marine environment as indicated by its fauna (Decker, 1933), and evaporite deposits that are associated with supratidal deposits in tropical and subtropical zones are absent in the Viola. The pressure solution-dolomitization model can be used to explain dolomite enrichment along stylolites as observed by Freeman (1965) in

pre-Viola limestones. The petrologic features described by Wanless (1979) as indicative for dolomitization caused by stress response have not been described from the Viola and it is, therefore, unlikely that this process is responsible for the majority of Viola dolostones. Shale deposits do not occur laterally with Viola rocks of south-central Kansas and the stratigraphically lower Simpson Shale is separated from the Viola by the Platteville formation which is only partially dolomitized. Dolomitization by expelled connate water is, therefore, an unlikely dolomitization model for the Viola.

At the close of the Ordovician the epeiric sea covering the study area became increasingly hypersaline (Ross, 1976) as depicted in Figure 4. The Maquoketa Shale of Iowa is described by Agnew and others (1956) as deposited in a hypersaline environment. It is not clear, though, if the Maquoketa was deposited by a regressing Viola sea, or by a transgressing sea which invaded terrain where Viola rocks were subjected to subaerial erosion. The latter is suggested by information provided by Lee, Leatherock, and Bottinelly (1948) and Adkison (1972) who describe the Maquoketa as being deposited on a surface showing erosional relief. Either way, the lack of evaporites in the Maquoketa does not suggest an environment hypersaline enough to provide brines for the dolomitization of the Viola according to the Bonnaire model.

Eustatic fluctuations of the epeiric sea caused by the Late Ordovician glaciation (Sheehan, 1973) exposed wide areas of the Midcontinent to subaerial erosion and the influx of freshwater. Mixing of freshwater with the sea water contained in the porespace of Viola rocks led to dolomitization of the formation as set forth by the Dorag model. Dolomitization was fabric selective and resulted in the lateral and vertical

gradational pattern from pure limestones to pure dolostones as described from the Viola of the study area.

Origin of Chert

Two main generations of chert with regard to time of formation are recognized in Paleozoic rocks of the Midcontinent. Moore (1957) describes chert nodules from Mississippian carbonates of the Ozark region which preserve delicate calcitic fossil fragments. These fragments are lacking in the adjacent otherwise fossiliferous limestone. Banks (1970) reports chert nodules from the Mississippian Leadville formation of Colorado which are surrounded by layers of dolomite. The layers wrap around the chert nodules indicating silicification prior to compaction and final lithification of the carbonate sediment. This chert is termed an "early chert" as it formed either during sedimentation of the carbonate sediment or simultaneously during early compaction and diagenesis as some replacement of quartz by dolomite and vice versa (Banks, 1970) indicates. Early chert is generally concordant with sedimentary bedding (Meyers, 1978) and the main sources of silica are considered to be siliceous sponge spicules as well as detrital sediments. Meyer (1978) demonstrated in a detailed field study, that formation of early chert is facies dependent. He showed that 82 percent of the chert formed in mud supported carbonates.

The other mode of origin of chert is dependent on the post-depositional and diagenetic history of the rocks and related to circulation of silica-rich fluids along tectonically induced fracture zones. These fluids may be hydrothermal (Fowler, 1933) or related to groundwater movement from silica-rich sediments into carbonates (Fowler, 1933; Banks, 1970).

Chert occurs in the Viola formation of south-central Kansas in association with dolomitized limestones. Plate 6a clearly shows that limestones that are interpreted as crinoidal grainstones contain none or little chert. Petrographic evidence from Biederman (1965; his Figs. 11 through 18) shows that cementation by silica seems to have occurred after dolomitization, although euhedral dolomite crystals thought growing in lime-mud or spar are surrounded by chert which could indicate a change in diagenetic conditions and that silica started to replace micrite before dolomitization was complete.

Although dolomitization seems to have preceded the formation of chert, a thoroughly chertified packstone with well recognizable fossil fragments may indicate that in some instances chert may have formed prior to dolomite. Lacking other and more detailed petrologic information, it is suggested that dolomite and chert formed closely together with respect to time. Both minerals could form only in Viola rocks that had initial porosity preserved, as the grainstones are virtually free of either, because of completion of the growth of rim cement prior to conditions favorable to dolomitization and formation of chert.

Meyers and James (1978) and Knauth (1979) proposed similar models for the origin of chert. Both models have the chert form in a mixing zone of fresh water with sea water related to an unconformity (Meyers and James, 1978) which postulates subaerial erosion and provides a recharge area for fresh water. Knauth (1979) suggests that a mixture of fresh water with about 30 to 80 percent sea water favors the replacement of calcite by silica. If Knauth's (1979) conclusions are correct, then relative high proportions of sea water in the mixing zone would favor replacement of calcite by silica, while a relative low (see Dorag model) fraction of sea water would favor the replacement of calcite by dolomite.

Either process was fabric selective and dependent on the permeability of the host rock. Chertification presumably is strongest where a favorable chemical composition of the mixing zone waters was met with silica concentrations in the host rock. This could explain the arrangement of chert nodules concordant with bedding.

Silicification along fracture zones by hydrothermal solutions or by circulation of groundwater is suggested as an explanation for the silica-rich zones that parallel the structural grain of the study area as clearly identified by the chert isofacies map (Fig. 22).

VIII. ECONOMIC CONSIDERATIONS

Structural highs associated with porosities of greater than seven percent are favorable conditions for hydrocarbon accumulations in the Viola Limestone of south-central Kansas. The porosity map (Plate 4; porosities greater than eight percent are shaded) compared with the suite of structure maps (Plates 2 and 3; Fig. 22) indicates preferred trends in the location of oil pools. A strong NE-trend is exemplified by a string of oil fields located on the crest of the Cunningham Anticline, and a weaker NW-trend, is observed in Barber County.

Almost all oil pools produce not only from the Viola Limestone but include Arbuckle, Simpson and Mississippian pay zones. Unfortunately, individual wells which produce from the Viola could not be identified from the available information, but some tentative conclusions with respect to Viola lithofacies and reservoir characteristics can be given.

The majority of oil pools is located on or in close proximity to the Pratt Anticline. Structural highs in form of horsts and anticlines combine with residual cherts deposits. Secondary porosity and fractures allow for large accumulations of hydrocarbons which can be produced easily due to large fracture-caused permeabilities. In areas where the Viola is thin and residual chert is absent reservoirs are rare (Ranges 10 and 9). Well cemented grainstones at the base of the Viola and relative lack of dolomitized packstones due to removal by erosion may be the reason.

Future drilling appears to be most promising in the western third of the area. The lack of control points in this area is due to the fact that wells generally are terminated in Mississippian carbonates which are one of the most prolific hydrocarbon producers in Kansas. Based on

the conclusions with regard to the environment of Viola deposition, the chance of encountering good reservoir rocks as dolomitized packstones and wackestones is considered good, and drilling should commence close to the western flank of the Pratt Anticline, as structural highs in the form of horsts or anticlines are likely to be associated with major tectonic lineaments.

IX. FUTURE RESEARCH

The method developed for lithofacies analysis can be extended to include petrophysical logs other than the gamma ray and porosity logs used in this study. The spontaneous potential log, for example, can be used to estimate the resistivity of the formation's brine and the resistivity log measures the resistivity of the pore fluids which may include brine and hydrocarbons. When these responses are gridded in an analogous way as described for the porosity log responses the water and hydrocarbon saturation of the unit under study can be calculated by simple grid-to-grid operations. These calculations require the porosity values calculated prior in the lithofacies analysis. Lithofacies and structural analyses could, therefore, be combined with hydrocarbon estimations in an efficient method. The requirements are digitized well logs and, preferably interactive, automated mapping and well logging software packages.

Structural and lithofacies analysis can be enhanced by applying spatial filtering methods to the computed grids. Multivariate statistical analyses of structural and lithologic variables may isolate certain combinations of variables as an indicator of conditions favorable to hydrocarbon accumulations.

An extension of the lithofacies analysis of the Viola, as presented in this study, should attempt a tentative division of the formation based on unprocessed log responses. Iterative lithology computations may allow the definition of members with similar overall rock characteristics. If these units can be related to conditions of sediment deposition, their lateral and vertical variation with regard to unit geometry will allow

the reconstruction of the formations depositional and possibly erosional history in more detail.

When digitized well logs are available over the entire stratigraphic column of an area, automated spatial well log analysis of divisions of the entire column will be possible and the reconstruction of the geologic history will be based on data generally not utilized to the extent possible. A better understanding of the geologic history will result in identifying the locations and origins of economic valuable deposits.

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APPENDIX 1

Well Identification and Well Names

WELL ID-NO.	LOCATION AND NAME
1	SW NW 10 26 11 BAUMAN 1
3	SW SW NW 36 26 11 MARDIS 1
5	NW NE NW 3 26 12 STEWART 1
6	NE NW 2 26 13 WOOD
10	1 26 15 ELLIS 1
11	NE NE NW 10 26 16 SCHULTZ A1
19	NW NW 34 26 17 ROENBAUGH 1
20	SE NW NW SE 25 27 12 FINCHAM 1
21	NW SE NW 25 27 12 BARNES 1
27	NE SW SW SE 7 27 14 JONES 1
28	SW NW 7 27 14 COMMERCIAL JON
29	NW NW SE 29 27 14 IVAN ADAMS 1
35	SE SE SE 13 27 16 ROSE 1
36	SE SE NE 7 27 16 MATHEWS 1
37	NW SE 32 27 16 WOODARD 1
38	SW SW 15 27 17 CURTIS 1
39	NE NE NE 35 27 18 STEWART 1
40	NW SE SE 24 27 18 WOODS 1
43	SW SW SW 25 28 11 DYCHE 1
44	SE NE 28 28 11 DUDREY A1
45	SE SE SW 31 28 11 ARMSTEAD 1
46	NW NE SW SE 21 28 12 HAYES 1
47	SW SW NE 8 28 12 BECKER 1
48	SW NW 2 28 12 THOMAS 1
49	SW NE 18 28 12 HELSEL 1
51	NW NW 1 28 13 HILLARD 2
54	NW NW NE 20 28 14 MICHAEL 1
55	NW NE SE 15 28 14 WOOLFOLK 1
56	SW SW SE 25 28 15 JOHNSON 1
57	SW SW SW 29 28 15 THOMPSON 1
58	SW NW 23 28 15 MILLER 1
59	SE SE SE 14 28 15 SEYFERT 1
60	SE SE NW 33 28 16 KUHN 1
65	SW SW NW 4 28 17 THOMPSON 1
66	NW NW NW 35 28 18 ADRENS 1
67	NE NW NE 23 28 18 HARDY 1
68	SE 23 28 18 HARDY 1B
72	NE NW 35 29 11 THOMPSON J1
73	SW NW 30 29 11 JOHN H1
74	SW SE 4 29 11 FORD 1-4
75	NW SW NE SE 7 29 12 REECE 1
76	NE NE SW 13 29 12 THOMPSON 1
77	SW SW NW 21 29 12 J. R. DAUNER 1
79	SE NE 3 29 13 MASON 1

81		SW SW	14	29	13	MASON	1
82		NW SW	17	29	13	SHRIVER	1
83		NW NE	23	29	13	FRONTA GALLIAR	
84	SW	SW NW	26	29	13	COMBS	3
85	NE	NW SW	23	29	13	KINZIE	1
86	NE	NE NW	3	29	14	GRACE EADS	1
87	NE	NE SW	5	29	14	JENKINS	1
88		NE SW	7	29	14	STELZER	1
89		NW SW	32	29	14	HUBANK	1
90		NW SE	31	29	14	HOWELL	1
91		SW SE	31	29	14	HOWELL	2
92	NE	SW NE	23	29	14	MOSS	2
93		NE NE	23	29	14	MOSS	1
94		SE NW	8	29	14	HUTCHINS	1
95	NE	NE SW	29	29	15	KERR	A1
96		SW SW	32	29	15	WILTSHIRE	3
97	SW	SW NW	11	29	16	HOWELL	A1
98	SW	NW SW	5	29	17	MORFORD	1
99		SW NW	21	29	17	HAMMOND	1
102	NW	NW NW	1	29	19	COLLINGWOOD	1
105		NW NW	21	30	11	LAVERENTZ	1
106	NE	NE NE	36	30	11	MEASE	1
107		SE NW	25	30	11	SLEEPER	1
108	NE	NE NW	36	30	12	THOM	1
109	NE	NE SE	32	30	12	OLSON	1
110	NW	SE NW	27	30	12	CARGILL	A1
111	NW	NW SW	11	30	12	SADIE KUMBERG	
112		SW NW	1	30	12	KNOP	1
113		NE SE	1	30	12	J. F. COSS	1
114	SW NW	NW NW	22	30	13	GRIGSBY	1
115		NW	18	30	13	KNACKSTEDT	1
116		NW NW	6	30	13	SHRIVER	1
117		NW NW	4	30	13	LAMBERT	A1
118		SE NW	4	30	13	LAMBERT	A2
119		SE SW	32	30	14	MILLS	1
120		SW SW	26	30	14	LAMBERT	1
121		NW SW	31	30	15	WALKER	B1
122		SE NE	24	30	15	HOAGLAND	1
123	SE	SE NE	21	30	15	WALKER	1
124	NE	NE NW	21	30	15	U.S. GYPSUM	1
125	SE	SE SW	10	30	15	HULLIE	1
126	NE	NE SE	9	30	15	MOFFETT	1
127		NW SE	36	30	16	WALKER	1
130		NW NE	22	31	10	STONE	1

131	NE NW NE	9 31	10 MORRISE 1
133	NE NE NE	18 31	11 CHAIN RANCH 1
135	NW SE	12 31	11 WARWICK 1
136	SE NE	11 31	11 LOUTHAM 1
137	NE SW	10 31	11 BERGNER 1
138	NE NW	5 31	11 CHAIN 1
139	NW NW NE	30 31	12 CLARKE 1
140	SE SE	22 31	12 UPDEGRAFF 1
141	SE NE	14 31	12 J.R. MOTT
142	NW SE	12 31	12 MOTT 1
144	NW NW SE	32 31	13 BROOKS 1
145	SW SW NE	26 31	13 ELLIOTT 1
146	SW NE	21 31	13 SMITH 1
147	NE NE	21 31	13 SMITH 1
148	NW SW	17 31	13 DEWITT 1
149	SE SE SW	13 31	13 A. SMITH 1
150	NW SW	4 31	13 KETNER 1
152	NW NW	34 31	14 W.C. MILLS 1
153	SE SE NE	26 31	14 RUSSEL LAKE 1
154	SE NE SW	26 31	14 MILLS FEED LAN
155	NE NW SW	19 31	14 SHAFT 1
156	NW NW SW	17 31	15 KAMINSKA 1
157	SE NE	10 31	15 C.K. REED 1
159	SW SE	6 31	17 YOST 1
160	NE NW	36 31	18 DELANEY 1
161	SE NE	19 31	19 ELLIS 1C
162	NW NE	36 32	10 HASS 1
163	NE SE	36 32	10 HARBAUGH 1
164	NW NW NE	6 32	10 LEO DICK 1
165	SW NW	5 32	10 GARRETT 1
166	NE NE NE	31 32	11 MCCLURE 1
167	SW SW NE	28 32	11 LUKENS 1
168	SE SE NE	17 32	11 SWARTZ 1
169	NW NE NW	34 32	12 DUNCAN 1
170	NE SW SE	34 32	12 ELIZABETH MEAD
171	NW SE	34 32	12 ANNA DUNCAN 1
172	SW SE	34 32	12 RANDELS 1
173	NE NE	34 32	12 RANDELS 2
174	NW SW SW	35 32	12 HAZEL SMITH 1
175	NW NW NW	23 32	12 BLOOM 2
176	SW NE NW	18 32	12 ELSEA 1
177	SW SE	15 32	12 LONKER 1
178	NW NW	15 32	12 GILLESPIE 1
179	NE SE	35 32	13 LONKER 1

232	NE NE SE	21 34	10	GARNER 1
233	SE SW NW	13 34	10	SKAGGS 1
234	SE NE SW	32 34	10	HELEN PORTERFI
235	NW NW SW	32 34	11	GOLDMAN 1
236	NE NE NE	25 34	11	STOLEBARGER 1
238	SW NE	1 34	11	SWARTZ 1
239	NW SW	36 34	12	WETZ 1
240	SE SE NE	24 34	12	HUMPHREY 1
241	SW NE	8 34	12	MCCRACKEN 1
242	SE SE	27 34	13	STERLING D1
243	SW NE	14 34	13	DIEL A1
244	SW SE	11 34	13	DONOVAN 1D
245	SW	7 34	13	CLARKE 1
246	SE SW	3 34	13	BLUNK 2
247	SE NE	5 34	13	FALEN-HOLMES 1
248	SE SE	3 34	13	DONOVAN 1
249	NE	24 34	14	GRAVES B1
250	NE NE SW	18 34	15	WELLS 1
251	SE NE	6 34	15	PLATT 1
252	SW SE	22 34	16	HUCK 1
253	SE SE	3 34	18	BRINKMAN 1
254	NE SW	20 34	17	EHRLICH 1
255	NE NE	12 34	19	OLLER 1
256	NE SW	11 34	20	L'UELLA MAI 1
257	NW NW NE	10 35	10	GEDEMAN 1
258	NW NW SW	10 35	11	WARSHBURNE B1
259	NW NW	5 35	11	BLOND-GOLDMAN
261	NW NE NE NE	1 35	12	YATES A1
262		16 35	14	WOLGAMOTT 1
263	SE SE	6 35	15	BALLET RANCH 1
265	SE SE NW	8 35	16	MCMORAN 1
270	NE NE	18 33	17	LEWIS 1
273	NE SW	31 31	14	MILLS 1
274	NE NE NE	31 31	14	MILLS ESTATE 1
276	NE NE NE	5 33	13	BAIER 1
280	NW SE	31 33	16	MURIEL GREGG 1
287	NE NE NE	27 29	14	KERR 1
288	NE NE	9 29	15	A. J. BRYANT 1
291	SE SE SW	6 25	10	BROWNLEE 1
293	NW SE NE	4 25	11	MCCOMB 1B
294	SW SW SW	34 25	11	THACHER
295	SW SE	3 25	12	EDWARD FRITZEM
297	SW SW NE	17 25	12	MCCUNE
299	SW NW SW	32 25	12	COPENHAVER 1

301	SE SE NE	6	25	13	SEEVERS 1B
302	SE SW SW	14	25	13	G RUSSEL 1
305	NE SW	30	25	14	CHILDS 1
306	SW SW NE	2	25	15	BARSTON 1C
307	SW SW SW	27	25	15	FRACK 1
308	NW NW	25	25	16	JOHNSON 1
309	SW SW	16	25	16	PALMITER 1
313	NW SE SW	9	25	17	SIBLEY 1
315	NE NE SW	35	25	18	BUTLER 1
317	SW SW SW	22	25	19	JACK MALETER 1
323	SE NE NE	11	26	14	WEBSTER 1
330	NE NW	36	27	10	SCHWATZ 1
331	NE NE NE	21	27	10	MCNAMEE 1
332	NE NE SW	3	27	10	TONN 1
333	NE NW SW	17	27	12	HOONE 1
337	NW NW	7	27	11	MAAS 1
339	SW NW SE	2	27	13	SHEGOG 1
343	NW SW	22	27	14	REED 1
343	NW SW	22	27	14	REED 1
345	NW NW SE	31	28	10	FENN 1
347	NW NW	2	28	10	COOLEY EST 1
348	NE NE NE	22	28	13	HERTHLEIN 1
349	SE NW SE	21	29	10	SIMON 1
354	NW NW NE	12	30	10	SWINGLE 1
355	NE NW	19	30	10	?
356	NE SE	23	30	10	SCAHAUFLER
358	SW NW SE	14	30	16	ROBBINS GALLUP
362	SW	16	30	17	CANTON 1
363	NE SE	3	30	18	PARKING
369	SE SW	18	32	14	STUMPH A1
373	SW SW SE NE	24	34	14	GRAVES 1B
375	NE NE	3	33	12	ELIZABETH MEAD

APPENDIX 2

Data File for Viola Limestone

ID	X-COOR	Y-COOR	STR	TH	NEUTR	SONIC	DENSITY	RES-NEUTR	RES-DENS	RES-SONIC
1	10.3077	8.9884	737.	29.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
3	10.5561	8.4723	743.	28.	9.71	-1.00	-1.00	2.31	-1.00	-1.00
5	9.5788	9.1489	668.	30.	-1.00	62.74	-1.00	-1.00	-1.00	0.34
6	8.9549	9.1340	703.	31.	16.45	74.98	-1.00	0.85	-1.00	-13.18
10	7.5854	9.0693	704.	-1.	-1.00	59.09	-1.00	-1.00	-1.00	0.91
11	6.5687	8.9860	725.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
19	5.7884	8.4596	754.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
20	9.8869	7.8077	761.	28.	-1.00	-1.00	2.60	-1.00	0.01	-1.00
21	9.8509	7.8430	761.	27.	11.02	-1.00	-1.00	-1.41	-1.00	-1.00
27	7.7371	8.1240	758.	17.	12.73	-1.00	-1.00	0.09	-1.00	-1.00
28	7.6775	8.1908	724.	-1.	-1.00	-1.00	-1.00	0.38	-1.00	-1.00
29	7.8633	7.7856	760.	25.	8.77	-1.00	-1.00	0.97	-1.00	-1.00
35	6.8898	7.9811	771.	42.	9.88	-1.00	-1.00	0.79	-1.00	-1.00
36	6.2669	8.1663	780.	56.	9.67	-1.00	-1.00	1.05	-1.00	-1.00
37	6.3580	7.6308	792.	44.	-1.00	60.45	-1.00	-1.00	-1.00	0.22
38	5.7936	7.9788	770.	69.	-1.00	-1.00	-1.00	1.88	-1.00	-1.00
39	5.2727	7.6951	795.	60.	9.86	-1.00	-1.00	0.22	-1.00	-1.00
40	5.3808	7.8565	812.	57.	-1.00	60.24	-1.00	-1.00	-1.00	1.11
43	10.5805	7.0059	819.	27.	12.62	-1.00	-1.00	-1.00	-1.00	-1.00
44	10.3071	7.0743	775.	28.	7.92	-1.00	-1.00	-0.35	-1.00	-1.00
45	10.0067	6.8716	781.	29.	5.32	-1.00	-1.00	1.44	-1.00	-1.00
46	9.5249	7.1415	750.	33.	5.75	-1.00	2.68	1.71	-0.03	-1.00
47	9.3821	7.4393	770.	26.	8.00	59.76	-1.00	-1.00	-1.00	1.93
48	9.7046	7.5783	765.	22.	-1.00	61.67	-1.00	-1.00	-1.00	-0.37
49	9.2652	7.3183	776.	21.	13.11	60.85	-1.00	-1.08	-1.00	3.45
51	9.0711	7.6029	728.	18.	-1.00	-1.00	2.53	-1.00	-0.03	-1.00
54	7.8715	7.2104	774.	20.	-1.00	64.67	-1.00	-1.00	-1.00	-2.81
55	8.1523	7.2781	748.	-1.	28.72	-1.00	-1.00	-1.00	-1.00	-1.00
56	7.6231	6.9674	782.	24.	5.67	-1.00	-1.00	2.28	-1.00	-1.00
57	7.0446	6.9583	815.	25.	-1.00	60.50	-1.00	-1.00	-1.00	1.77
58	7.4355	7.1644	770.	-1.	7.11	-1.00	-1.00	0.46	-1.00	-1.00
59	7.5391	7.2217	778.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
60	6.4667	6.8875	809.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
66	5.1713	6.9236	849.	53.	7.09	-1.00	-1.00	-0.38	-1.00	-1.00
67	5.2467	7.1814	830.	52.	14.79	-1.00	-1.00	-1.61	-1.00	-1.00
68	5.2553	7.0934	829.	46.	9.39	-1.00	-1.00	1.06	-1.00	-1.00
72	10.5082	6.2153	853.	24.	-1.00	57.37	-1.00	-1.00	-1.00	0.19
73	9.9763	6.3049	804.	24.	-1.00	56.66	-1.00	-1.00	-1.00	1.56
74	10.2810	6.7553	797.	26.	11.81	-1.00	2.59	-3.25	0.05	-1.00
75	9.2949	6.6443	774.	36.	-1.00	-1.00	2.66	-1.00	-0.02	-1.00
76	9.8860	6.5349	795.	26.	6.99	-1.00	-1.00	-0.64	-1.00	-1.00
77	9.4601	6.4182	786.	32.	4.10	56.04	-1.00	2.61	-1.00	1.89
79	8.9240	6.8023	801.	23.	-1.00	-1.00	-1.00	-1.00	0.11	-1.00
81	8.9603	6.4838	784.	33.	7.09	-1.00	2.59	-1.00	0.02	-1.00
82	8.5792	6.5096	802.	33.	4.43	-1.00	2.63	2.01	-0.05	-1.00

83	9.0239	6.4526	787.	36.	5.41	-1.00	-1.00	1.95	-1.00	-1.00
84	8.9548	6.2839	779.	35.	7.01	-1.00	-1.00	0.85	-1.00	-13.18
85	8.9691	6.3958	778.	37.	7.70	-1.00	-1.00	0.71	-1.00	-1.00
86	8.1115	6.8302	746.	36.	11.87	-1.00	-1.00	-0.84	-1.00	-1.00
87	7.8619	6.7629	762.	-1.	7.03	-1.00	-1.00	1.41	-1.00	-1.00
88	7.7308	6.6252	808.	-1.	8.18	-1.00	-1.00	1.27	-1.00	-1.00
89	7.8321	6.1149	789.	-1.	-1.00	60.15	-1.00	-1.00	-1.00	5.87
90	7.7696	6.1141	788.	-1.	-1.00	80.92	-1.00	-1.00	-1.00	-1.00
91	7.7700	6.0820	784.	-1.	16.28	65.73	-1.00	-3.34	-1.00	-3.01
92	8.2735	6.4170	762.	27.	10.68	-1.00	-1.00	-2.24	-1.00	-1.00
93	8.2966	6.4412	758.	26.	10.64	-1.00	-1.00	0.36	-1.00	-1.00
94	7.8557	6.6588	766.	-1.	11.16	-1.00	-1.00	-1.86	-1.00	-1.00
95	7.1010	6.2390	837.	17.	14.21	-1.00	-1.00	-1.00	-1.00	-1.00
96	7.0624	6.0704	827.	28.	2.17	-1.00	-1.00	-1.00	-1.00	-1.00
97	6.6710	6.6334	826.	28.	11.61	-1.00	-1.00	-0.74	-1.00	-1.00
98	5.5489	6.7189	858.	45.	10.21	-1.00	-1.00	0.19	-1.00	-1.00
99	5.6855	6.3757	832.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
102	4.5464	6.7886	892.	-1.	13.86	-1.00	-1.00	-1.29	-1.00	-1.00
105	10.2351	5.7016	859.	27.	7.37	-1.00	-1.00	-0.61	-1.00	-1.00
106	10.7162	5.4609	891.	25.	6.21	-1.00	-1.00	0.95	-1.00	-1.00
108	9.9017	5.4501	875.	26.	5.92	-1.00	-1.00	0.89	-1.00	-1.00
109	9.4592	5.3806	829.	29.	5.66	-1.00	-1.00	0.19	-1.00	-1.00
110	9.6312	5.5422	825.	25.	7.66	55.03	-1.00	-0.21	-1.00	3.28
111	9.7209	5.8947	815.	24.	-1.00	56.02	-1.00	-1.00	-1.00	1.81
112	9.8534	6.0477	822.	23.	4.44	-1.00	-1.00	2.20	-1.00	-1.00
113	9.9490	6.0171	835.	23.	5.72	-1.00	-1.00	0.80	-1.00	-1.00
114	8.8324	5.6873	806.	16.	14.14	-1.00	-1.00	-0.80	-1.00	-1.00
115	8.4779	5.7893	809.	31.	7.81	-1.00	-1.00	1.83	-1.00	-1.00
116	8.4584	6.0606	794.	32.	5.23	-1.00	2.60	2.07	0.02	-1.00
117	8.7121	6.0645	795.	29.	7.26	-1.00	2.56	1.26	0.04	-1.00
118	8.7443	6.0329	794.	31.	9.82	-1.00	2.54	-0.48	0.02	-1.00
119	7.8745	5.3164	821.	32.	-1.00	60.05	-1.00	-1.00	-1.00	-8.13
120	8.2163	5.4496	811.	42.	8.19	59.10	-1.00	0.16	-1.00	0.36
121	6.9409	5.3319	865.	-1.	12.81	-1.00	-1.00	-1.00	-1.00	-1.00
122	7.6823	5.6331	799.	25.	8.66	-1.00	-1.00	-0.37	-1.00	-1.00
123	7.3020	5.6181	819.	-1.	9.74	-1.00	-1.00	1.12	-1.00	-1.00
124	7.2366	5.6652	815.	-1.	13.04	-1.00	-1.00	0.91	-1.00	-1.00
125	7.3645	5.8114	803.	-1.	10.39	-1.00	-1.00	-0.41	-1.00	-1.00
126	7.2992	5.8580	795.	-1.	13.00	-1.00	-1.00	-1.00	-1.00	-1.00
127	6.8783	5.3308	846.	-1.	12.22	-1.00	-1.00	-1.00	-1.00	-1.00
130	11.2409	4.9555	935.	19.	11.38	-1.00	-1.00	-1.26	-1.00	-1.00
131	11.1179	5.2139	902.	22.	7.00	-1.00	-1.00	-0.37	-1.00	-1.00
133	10.1448	5.0731	903.	31.	5.11	-1.00	2.66	1.57	0.00	-1.00
135	10.7347	5.1360	904.	25.	6.70	-1.00	-1.00	0.65	-1.00	-1.00
136	10.6393	5.1665	899.	25.	-1.00	55.84	-1.00	-1.00	-1.00	3.21

137	10.4510	5.1322	909.	24.	5.13	-1.00	-1.00	1.81	-1.00	-1.00
138	10.1954	5.3182	887.	25.	-1.00	56.74	-1.00	-1.00	-1.00	-1.00
139	9.3482	4.8118	860.	26.	5.85	-1.00	-1.00	0.70	-1.00	-1.00
140	9.7636	4.8401	908.	25.	5.85	-1.00	-1.00	0.92	-1.00	-1.00
141	9.8854	5.0619	900.	26.	9.22	-1.00	-1.00	-0.76	-1.00	-1.00
142	9.9785	5.1265	897.	25.	7.26	-1.00	2.67	0.56	-0.05	-1.00
144	8.7225	4.6113	900.	30.	5.94	-1.00	-1.00	0.49	-1.00	-1.00
145	9.0973	4.7608	875.	27.	8.55	-1.00	-1.00	-0.57	-1.00	-1.00
146	8.8511	4.8900	910.	18.	8.03	-1.00	-1.00	-1.39	-1.00	-1.00
147	8.8821	4.9220	867.	13.	-1.00	68.37	-1.00	-1.00	-1.00	-9.24
148	8.6609	4.9813	845.	35.	7.45	-1.00	-1.00	-1.42	-1.00	-1.00
149	9.2042	4.9515	853.	26.	7.27	60.36	-1.00	0.02	-1.60	-2.00
150	8.7822	5.2358	834.	32.	-1.00	-1.00	2.65	-1.00	-0.02	-1.00
152	8.1643	4.6571	863.	40.	-1.00	55.42	-1.00	-1.00	-1.00	-0.37
153	8.3961	4.7477	862.	35.	12.56	-1.00	-1.00	-2.78	-1.00	-1.00
154	8.3279	4.7153	858.	37.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
155	7.7926	4.8489	840.	44.	15.66	64.59	-1.00	-1.39	-1.00	-5.64
156	7.1528	4.9626	886.	35.	8.30	-1.00	-1.00	-2.19	-1.00	-1.00
157	7.5003	5.1158	839.	37.	-1.00	58.89	-1.00	-1.00	-1.00	-1.00
159	5.5902	5.1573	993.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
160	5.4423	4.6176	1068.	62.	-1.00	51.69	-1.00	-1.00	-1.00	1.40
161	4.1217	4.8219	1092.	59.	-1.00	-1.00	-1.00	-1.00	-0.10	-2.64
162	11.5155	3.9525	1012.	-1.	17.42	62.30	-1.00	-1.00	-1.00	-1.00
163	11.5485	3.8899	988.	33.	12.94	56.30	-1.00	-1.00	-1.00	-1.00
164	10.8625	4.5767	941.	18.	7.30	-1.00	-1.00	0.11	-1.00	-1.00
165	10.9342	4.5391	953.	22.	7.74	-1.00	-1.00	-0.31	-1.00	-1.00
166	10.1640	3.9372	966.	25.	6.08	-1.00	-1.00	-0.19	-1.00	-1.00
167	10.3675	4.0181	946.	22.	6.88	56.54	-1.00	0.48	-1.00	2.74
168	10.2844	4.2696	953.	24.	8.56	-1.00	-1.00	-4.68	-1.00	-1.00
169	9.7084	3.9329	953.	28.	7.01	-1.00	-1.00	-0.59	-1.00	-1.00
170	9.7569	3.8388	959.	30.	-1.00	-1.00	2.60	-1.00	0.03	-1.00
171	9.7490	3.8627	960.	24.	3.52	58.30	2.68	2.58	-0.07	-11.48
172	9.7495	3.8311	957.	26.	-1.00	56.14	-1.00	-1.00	-1.00	0.83
173	9.7792	3.9259	954.	28.	-1.00	-1.00	2.62	-1.00	0.00	-1.00
174	9.8041	3.8391	962.	30.	-1.00	-1.00	2.62	-1.00	0.00	-1.00
175	9.7984	4.1863	938.	25.	4.43	-1.00	2.59	1.65	0.00	-1.00
176	9.3258	4.2922	921.	28.	-1.00	56.26	-1.00	-2.29	-1.00	0.63
177	9.7429	4.2094	934.	30.	4.56	-1.00	2.65	1.15	-0.03	-1.00
178	9.6784	4.3033	932.	30.	4.96	51.23	-1.00	1.38	-1.00	5.72
179	9.1524	3.8557	956.	27.	-1.00	58.97	-1.00	-1.00	-1.00	-0.53
180	8.6535	4.0418	923.	36.	6.05	-1.00	-1.00	-2.92	-1.00	-1.00
181	8.5838	4.0006	924.	37.	6.82	-1.00	-1.00	-1.10	-1.00	-1.00
182	9.0451	4.1608	939.	31.	5.98	-1.00	-1.00	0.48	-1.00	-1.00
183	8.5579	4.1186	911.	37.	-1.00	57.02	-1.00	-1.00	-1.00	-0.42
184	8.4815	4.0065	922.	40.	6.29	-1.00	-1.00	-0.79	-1.00	-1.00

185	8.4888	4.0305	921.	41.	7.22	-1.00	-1.00	-1.19	-1.00	-1.00
186	7.8278	4.1787	910.	38.	9.97	-1.00	2.60	-1.47	-0.02	-1.00
187	8.4536	4.2513	909.	38.	-1.00	58.79	-1.00	-1.00	-1.00	-1.78
188	8.0153	4.4301	876.	42.	5.72	-1.00	-1.00	1.25	-1.00	-1.00
193	5.5784	3.8922	1113.	54.	4.65	-1.00	-1.00	1.54	-1.00	-1.00
195	5.9187	4.1179	1052.	53.	4.69	-1.00	-1.00	2.57	2.40	0.05
196	5.8564	4.1169	1053.	54.	3.48	-1.00	-1.00	2.62	1.49	0.02
197	5.2646	3.9834	1058.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
199	5.3253	4.0787	1130.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
200	5.3195	4.4530	1083.	51.	-1.00	56.38	-1.00	-1.00	-1.00	1.21
201	-4.7337	3.9457	1133.	62.	7.23	-1.00	-1.00	-0.83	-1.00	-1.00
202	11.5428	3.7877	1011.	13.	12.62	-1.00	-1.00	-1.00	-1.00	-1.00
203	10.9514	3.2039	1043.	31.	8.05	-1.00	-1.00	-3.77	-1.00	-1.00
204	11.0511	3.4039	1030.	32.	10.89	-1.00	-1.00	2.68	-0.68	-0.04
205	10.9226	3.4640	1024.	30.	5.09	-1.00	-1.00	2.65	1.34	0.01
206	11.3948	3.6658	1012.	26.	6.40	-1.00	-1.00	0.32	-1.00	-1.00
207	10.1147	3.1158	1052.	32.	4.06	-1.00	-1.00	1.69	-1.00	-1.00
208	9.4358	3.3799	988.	29.	5.48	-1.00	-1.00	-0.62	-1.00	-1.00
209	9.8550	3.6190	979.	31.	6.43	-1.00	-1.00	0.64	-1.00	-1.00
210	9.9094	3.6429	979.	26.	6.01	-1.00	-1.00	0.20	-1.00	-1.00
211	9.7432	3.7443	968.	28.	7.70	-1.00	-1.00	-0.23	-1.00	-1.06
212	9.9313	3.7457	977.	25.	6.64	-1.00	-1.00	0.86	-1.00	-1.00
213	9.8626	3.1775	1057.	29.	-1.00	55.53	-1.00	-1.00	-1.00	0.34
214	9.5742	3.0735	1117.	30.	4.65	-1.00	-1.00	1.45	-1.00	-1.00
215	9.3745	3.3009	1000.	30.	7.53	-1.00	-1.00	-3.99	-1.00	-1.00
216	9.9855	3.3202	1040.	28.	4.11	-1.00	-1.00	1.28	-1.00	-1.00
217	9.1094	3.1692	1012.	33.	-1.00	58.10	-1.00	-1.00	-1.00	-1.23
218	8.5605	3.5261	961.	37.	-1.00	-1.00	2.65	-1.00	-0.04	-1.00
219	8.6855	3.5608	960.	37.	-1.00	55.62	-1.00	-1.00	-1.00	0.83
220	7.3716	3.2201	1026.	42.	9.00	-1.00	-1.00	-0.03	-1.00	-1.00
221	7.1710	3.5081	950.	44.	-1.00	56.73	-1.00	-1.00	-1.00	0.21
222	7.2922	4.4516	947.	41.	-1.00	58.51	-1.00	-1.00	-1.00	0.33
223	6.8083	3.1468	1096.	50.	-1.00	55.13	-1.00	-1.00	-1.00	1.83
224	6.9604	3.4329	1046.	45.	-1.00	54.95	-1.00	-1.00	-1.00	1.77
225	6.1125	3.7409	1092.	60.	6.93	-1.00	-1.00	-0.28	-1.00	2.50
226	6.1509	3.0147	1164.	47.	-1.00	52.37	-1.00	-1.00	-1.00	-1.00
228	6.2734	3.4900	1092.	54.	6.25	-1.00	-1.00	0.38	-1.00	-0.97
231	11.4804	2.6901	1104.	28.	6.26	-1.00	-1.00	0.94	-1.00	-1.00
232	11.2017	2.6262	1114.	43.	11.36	-1.00	-1.00	-1.29	-1.00	-1.00
233	11.4862	2.7769	1102.	29.	5.68	-1.00	-1.00	0.44	-1.00	-1.02
234	11.0152	2.3523	1152.	43.	14.55	-1.00	-1.00	0.07	-1.00	-1.00
235	10.2067	2.3590	1104.	36.	8.46	-1.00	-1.00	0.24	-1.00	-1.00
236	10.8194	2.5521	1136.	38.	7.28	-1.00	-1.00	-1.79	-1.00	-1.00
238	10.7719	3.0183	1065.	30.	5.99	-1.00	-1.00	1.40	-1.00	-1.00
239	9.9626	2.2503	1128.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00

240	10.0600	2.6263	1106.	28.	6.40	-1.00	-1.00	-1.00	-1.00	-1.00
241	9.5151	2.8843	1105.	30.	-1.00	56.03	-1.00	-1.00	-1.00	0.94
242	9.0517	2.4345	1096.	38.	-1.00	-1.00	2.56	-1.00	0.02	-1.00
244	9.1392	2.8156	1051.	31.	-1.00	55.38	-1.00	-1.00	-1.00	1.52
245	8.5888	2.8156	1025.	40.	5.52	-1.00	-1.00	0.41	-1.00	-1.00
246	8.9798	2.9374	1028.	35.	4.05	-1.00	-1.00	2.10	-1.00	-1.00
247	8.7899	2.9951	1019.	35.	5.82	-1.00	-1.00	0.26	-1.00	-1.00
248	9.0426	2.9388	1041.	34.	7.11	57.30	-1.00	-0.05	-1.00	1.03
249	8.5292	2.6247	1062.	40.	8.38	-1.00	-1.00	-3.55	-1.00	-1.00
250	7.1026	2.6834	1082.	51.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
251	7.1543	2.9618	1057.	49.	5.67	-1.00	-1.00	0.70	-1.00	-1.00
252	6.7548	2.5139	1095.	50.	7.14	-1.00	2.71	-0.42	0.03	-1.00
253	5.2820	2.8771	1224.	61.	-1.00	53.63	-1.00	-1.00	-1.00	-1.49
254	5.7246	2.5341	1219.	56.	3.92	-1.00	-1.00	1.13	-1.00	-1.00
255	4.7837	2.8421	1272.	62.	3.90	54.03	-1.00	-1.00	-1.00	-1.00
256	3.8437	2.7697	1328.	44.	-1.00	-1.00	-1.00	-1.00	-1.00	1.89
257	11.2909	2.1870	1162.	43.	12.08	-1.00	-1.00	-1.00	-1.00	-1.00
258	10.4638	2.1078	1160.	46.	10.42	-1.00	-1.00	-1.00	-1.00	-1.00
259	10.2158	2.2882	1129.	45.	8.33	78.17	-1.00	0.75	-1.00	-1.00
261	10.0613	2.2992	1128.	42.	9.17	-1.00	-1.00	1.12	-1.00	-1.00
262	8.1329	1.9561	1172.	44.	7.88	-1.00	-1.00	0.31	-1.00	-1.00
263	7.1646	2.1395	1154.	51.	-1.00	-1.00	2.57	-1.00	0.08	-1.00
265	6.4909	2.0619	1166.	63.	-1.00	-1.00	2.63	-1.00	-0.00	-1.00
270	5.6470	3.4818	1154.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
273	7.8205	4.5891	860.	39.	7.55	-1.00	-1.00	-6.94	-1.00	-1.00
274	7.8898	4.6609	861.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
276	8.7839	3.7921	942.	35.	8.14	-1.00	-1.00	-1.51	-1.00	-1.00
280	6.3744	3.0489	1139.	50.	-1.00	53.84	-1.00	-1.00	-1.00	2.33
287	8.1809	6.3200	769.	12.	14.47	-1.00	-1.00	-1.00	-1.00	-1.00
288	7.2811	6.6822	794.	29.	7.49	-1.00	2.56	1.49	-0.00	-1.00
291	10.6614	9.8067	697.	35.	8.39	-1.00	-1.00	1.48	-1.00	-1.00
293	10.2051	9.8801	637.	37.	10.13	58.62	-1.00	1.48	-1.00	3.01
294	10.2501	9.1710	718.	33.	17.74	-1.00	-1.00	-2.42	-1.00	-1.00
295	9.5543	9.8029	636.	35.	7.97	-1.00	-1.00	2.13	-1.00	-1.00
297	9.2974	9.6036	652.	-1.	16.51	-1.00	-1.00	1.04	-1.00	-1.00
299	9.2416	9.1932	672.	27.	22.24	-1.00	-1.00	-3.51	-1.00	-1.00
301	8.4555	9.8447	671.	-1.	15.60	-1.00	-1.00	-1.00	-1.00	-1.00
302	8.8717	9.5352	657.	33.	-1.00	60.06	-1.00	-1.00	-1.00	4.01
305	7.6270	9.3068	701.	-1.	-1.00	58.13	-1.00	-1.00	-1.00	2.04
306	7.3915	9.8328	673.	-1.	7.58	-1.00	-1.00	2.78	-1.00	-1.00
307	7.2082	9.2631	720.	-1.	11.90	-1.00	-1.00	-0.17	-1.00	-1.00
308	6.7102	9.3601	725.	-1.	10.05	-1.00	-1.00	0.41	-1.00	-1.00
309	6.3324	9.5138	728.	53.	8.84	-1.00	-1.00	0.58	-1.00	-1.00
313	5.6037	9.6435	721.	73.	-1.00	64.23	-1.00	-1.00	-1.00	1.89
315	5.1222	9.1591	772.	64.	7.66	-1.00	-1.00	-1.73	-1.00	-1.00

317	4.1958	9.3711	832.	48.	8.18	-1.00	-1.00	-0.93	-1.00	-1.00
323	8.2702	8.9886	701.	32.	9.52	-1.00	-1.00	-1.27	-1.00	-1.00
330	11.3729	7.7622	795.	21.	6.83	-1.00	-1.00	-1.28	-1.00	-1.00
331	11.0561	8.0190	779.	26.	10.06	-1.00	-1.00	1.27	-1.00	-1.00
332	11.1146	8.3391	781.	24.	10.81	-1.00	-1.00	-3.59	-1.00	-1.00
333	9.3257	8.0611	759.	-1.	7.70	-1.00	-1.00	-2.29	-1.00	0.63
337	9.9476	8.2512	761.	26.	10.22	-1.00	-1.00	-1.81	-1.00	-1.00
339	8.9902	8.2962	691.	26.	-1.00	-1.00	-1.00	0.22	-1.00	-4.80
343	8.0574	7.9077	736.	35.	14.34	-1.00	-1.00	-2.14	-1.00	-1.00
345	10.7707	6.9287	826.	24.	11.01	-1.00	-1.00	0.60	-1.00	-1.00
347	11.2150	7.6315	798.	20.	7.90	-1.00	-1.00	0.13	-1.00	-1.00
348	8.9260	7.2258	763.	19.	12.90	-1.00	-1.00	-1.84	-1.00	-1.00
349	11.0520	6.4075	861.	21.	9.51	-1.00	-1.00	-0.87	-1.00	-1.00
354	11.4276	5.9840	865.	18.	6.28	-1.00	-1.00	0.59	-1.00	-1.00
355	10.7678	5.7085	865.	23.	-1.00	57.12	-1.00	-1.00	-1.00	2.38
356	11.3448	5.6553	877.	16.	6.97	-1.00	-1.00	0.90	-1.00	-1.00
358	6.7428	5.7053	840.	54.	8.21	-1.00	-1.00	0.48	-1.00	-1.00
362	5.7083	5.6862	926.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
363	5.1583	5.9526	930.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
369	7.8278	4.1787	910.	38.	9.76	-1.00	2.59	-1.47	-0.02	-1.00
373	8.5334	2.5974	1062.	-1.	5.93	-1.00	-1.00	-1.32	-1.00	-1.00
375	9.7811	3.7999	963.	28.	5.85	-1.00	2.62	0.68	-0.00	-1.00

APPENDIX 3

Dat File for "Lower Limestone"

ID	X-COOR	Y-COOR	STR	TH	NEUTR	SONIC	DENSITY	RES-NEUTR	RES-DENS	RES-SONIC
1	10.3077	8.9884	761.	4.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
2	9.9966	9.1132	712.	3.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
3	10.5561	8.4723	767.	4.	2.72	-1.00	-1.00	2.31	-1.00	-1.00
5	9.5788	9.1489	696.	1.	-1.00	53.48	-1.00	-1.00	-1.00	0.34
6	8.9549	9.1340	732.	2.	5.50	66.85	-1.00	0.85	-1.00	-13.18
10	7.5854	9.0693	752.	-1.	-1.00	52.39	-1.00	-1.00	-1.00	0.91
11	6.5687	8.9860	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
19	5.7884	8.4596	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
20	9.8869	7.8077	785.	3.	-1.00	-1.00	2.64	-1.00	0.01	-1.00
21	9.8509	7.8430	786.	2.	6.26	-1.00	-1.00	-1.41	-1.00	-1.00
27	7.7371	8.1240	773.	3.	4.42	-1.00	-1.00	0.09	-1.00	-1.00
28	7.6775	8.1908	769.	-1.	4.12	-1.00	-1.00	0.38	-1.00	-1.00
29	7.8633	7.7856	778.	6.	3.53	-1.00	-1.00	0.97	-1.00	-1.00
35	6.8898	7.9811	804.	9.	3.40	-1.00	-1.00	0.79	-1.00	-1.00
36	6.2669	8.1663	833.	3.	2.87	-1.00	-1.00	1.05	-1.00	-1.00
37	6.3580	7.6308	832.	5.	-1.00	52.60	-1.00	-1.00	-1.00	0.22
38	5.7936	7.9788	834.	4.	1.79	-1.00	-1.00	1.88	-1.00	-1.00
39	5.2727	7.6951	852.	3.	3.16	-1.00	-1.00	0.22	-1.00	-1.00
40	5.3808	7.8565	866.	3.	-1.00	51.49	-1.00	-1.00	-1.00	1.11
43	10.5805	7.0059	842.	3.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
44	10.3071	7.0743	800.	4.	4.99	-1.00	-1.00	-0.35	-1.00	-1.00
45	10.0067	6.8716	805.	4.	3.15	-1.00	-1.00	1.44	-1.00	-1.00
46	9.5249	7.1415	779.	4.	2.94	-1.00	2.69	1.71	-0.03	-1.00
47	9.3821	7.4393	796.	1.	-1.00	51.63	-1.00	-1.00	-1.00	1.93
48	9.7046	7.5783	786.	2.	-1.00	54.04	-1.00	-1.00	-1.00	-0.37
49	9.2652	7.3183	793.	3.	5.77	50.07	-1.00	-1.08	-1.00	3.45
51	9.0711	7.6029	743.	3.	-1.00	-1.00	2.68	-1.00	-0.03	-1.00
54	7.8715	7.2104	792.	1.	-1.00	55.97	-1.00	-1.00	-1.00	-2.81
55	8.1523	7.2781	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
56	7.6231	6.9674	802.	4.	2.05	-1.00	-1.00	2.28	-1.00	-1.00
57	7.0446	6.9583	837.	3.	-1.00	51.14	-1.00	-1.00	-1.00	1.77
58	7.4355	7.1644	800.	-1.	3.84	-1.00	-1.00	0.46	-1.00	-1.00
59	7.5391	7.2217	795.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
60	6.4667	6.8875	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
65	5.6655	7.5213	-1.	2.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
66	5.1713	6.9236	898.	4.	3.73	-1.00	-1.00	-0.38	-1.00	-1.00
67	5.2467	7.1814	879.	3.	5.00	-1.00	-1.00	-1.61	-1.00	-1.00
68	5.2553	7.0934	872.	3.	2.32	-1.00	-1.00	1.06	-1.00	-1.00
72	10.5082	6.2153	874.	4.	-1.00	53.51	-1.00	-1.00	-1.00	0.19
73	9.9763	6.3049	825.	3.	-1.00	52.02	-1.00	-1.00	-1.00	1.56
74	10.2810	6.7553	820.	3.	7.81	-1.00	2.60	-3.25	0.05	-1.00
75	9.2949	6.6443	804.	6.	-1.00	-1.00	2.67	-1.00	-0.02	-1.00
76	9.8860	6.5349	818.	3.	5.16	-1.00	-1.00	-0.64	-1.00	-1.00
77	9.4601	6.4182	815.	3.	1.87	51.57	-1.00	2.61	-1.00	1.89
79	8.9240	6.8023	818.	6.	-1.00	-1.00	2.53	-1.00	0.11	-1.00

81	8.9603	6.4838	794.	22.	5.49	-1.00	2.62	-1.00	0.02	-1.00
82	8.5792	6.5096	831.	4.	2.44	-1.00	2.70	2.01	-0.05	-1.00
83	9.0239	6.4526	818.	5.	2.53	-1.00	-1.00	1.95	-1.00	-1.00
84	8.9548	6.2839	810.	4.	3.59	-1.00	-1.00	0.85	-1.00	-13.18
85	8.9691	6.3958	811.	4.	3.76	-1.00	-1.00	0.71	-1.00	-1.00
86	8.1115	6.8302	778.	5.	5.28	-1.00	-1.00	-0.84	-1.00	-1.00
87	7.8619	6.7629	794.	-1.	2.96	-1.00	-1.00	1.41	-1.00	-1.00
88	7.7308	6.6252	839.	-1.	3.06	-1.00	-1.00	1.27	-1.00	-1.00
89	7.8321	6.1149	801.	-1.	-1.00	47.14	-1.00	-1.00	-1.00	5.87
90	7.7696	6.1141	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
91	7.7700	6.0820	793.	-1.	7.61	56.01	-1.00	-3.34	-1.00	-3.01
92	8.2735	6.4170	785.	4.	6.65	-1.00	-1.00	-2.24	-1.00	-1.00
93	8.2966	6.4412	780.	-1.	4.04	-1.00	-1.00	0.36	-1.00	-1.00
94	7.8557	6.6588	798.	-1.	6.22	-1.00	-1.00	-1.86	-1.00	-1.00
95	7.1010	6.2390	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
96	7.0624	6.0704	850.	4.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
97	6.6710	6.6334	851.	3.	4.76	-1.00	-1.00	-0.74	-1.00	-1.00
98	5.5489	6.7189	898.	5.	3.36	-1.00	-1.00	0.19	-1.00	-1.00
99	5.6855	6.3757	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
102	4.5464	6.7886	949.	-1.	4.29	-1.00	-1.00	-1.29	-1.00	-1.00
105	10.2351	5.7016	882.	4.	4.89	-1.00	-1.00	-0.61	-1.00	-1.00
106	10.7162	5.4609	914.	3.	3.16	-1.00	-1.00	0.95	-1.00	-1.00
107	10.6443	5.5474	-1.	3.	2.58	52.05	-1.00	1.58	-1.00	1.61
108	9.9017	5.4501	897.	3.	2.35	-1.00	-1.00	0.89	-1.00	-1.00
109	9.4592	5.3806	855.	3.	4.06	-1.00	-1.00	0.19	-1.00	-1.00
110	9.6312	5.5422	847.	4.	4.50	50.12	-1.00	-0.21	-1.00	3.28
111	9.7209	5.8947	836.	3.	-1.00	51.65	-1.00	-1.00	-1.00	1.81
112	9.8534	6.0477	843.	3.	2.19	-1.00	-1.00	2.20	-1.00	-1.00
113	9.9490	6.0171	854.	3.	3.58	-1.00	-1.00	0.80	-1.00	-1.00
114	8.8324	5.6873	821.	1.	5.13	-1.00	-1.00	-0.80	-1.00	-1.00
115	8.4779	5.7893	835.	5.	2.48	-1.00	-1.00	1.83	-1.00	-1.00
116	8.4584	6.0606	821.	5.	2.29	-1.00	2.62	2.07	0.02	-1.00
117	8.7121	6.0645	820.	4.	3.12	-1.00	2.60	1.26	0.04	-1.00
118	8.7443	6.0329	821.	3.	4.87	-1.00	2.62	-0.48	0.02	-1.00
119	7.8745	5.3164	849.	4.	-1.00	61.07	-1.00	-1.00	-1.00	-8.13
120	8.2163	5.4496	849.	3.	4.07	52.67	-1.00	0.16	-1.00	0.36
121	6.9409	5.3319	918.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
122	7.6823	5.6331	820.	4.	4.57	-1.00	-1.00	-0.37	-1.00	-1.00
123	7.3020	5.6181	850.	-1.	2.99	-1.00	-1.00	1.12	-1.00	-1.00
124	7.2366	5.6652	853.	-1.	3.19	-1.00	-1.00	0.91	-1.00	-1.00
125	7.3645	5.8114	835.	-1.	4.56	-1.00	-1.00	-0.41	-1.00	-1.00
126	7.2992	5.8550	835.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
127	6.8783	5.3308	901.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
130	11.2409	4.9555	952.	2.	5.10	-1.00	-1.00	-1.26	-1.00	-1.00
131	11.1179	5.2139	922.	3.	4.33	-1.00	-1.00	-0.37	-1.00	-1.00

133	10.1448	5.0731	929.	5.	2.54	-1.00	2.66	1.57	0.00	-1.00
135	10.7347	5.1360	926.	3.	3.36	-1.00	-1.00	0.65	-1.00	-1.00
136	10.6393	5.1665	921.	3.	-1.00	50.41	-1.00	-1.00	-1.00	3.21
137	10.4510	5.1322	930.	3.	2.26	-1.00	-1.00	-1.81	-1.00	-1.00
138	10.1954	5.3182	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
139	9.3482	4.8118	882.	4.	3.43	-1.00	-1.00	0.70	-1.00	-1.00
140	9.7636	4.8401	929.	4.	3.18	-1.00	-1.00	0.92	-1.00	-1.00
141	9.8854	5.0619	922.	4.	4.91	-1.00	-1.00	-0.76	-1.00	-1.00
142	9.9785	5.1265	917.	5.	3.59	-1.00	2.71	0.56	-0.05	-1.00
144	8.7228	4.6113	926.	4.	3.63	-1.00	-1.00	0.49	-1.00	-1.00
145	9.0973	4.7608	898.	3.	4.71	-1.00	-1.00	-0.57	-1.00	-1.00
146	8.8511	4.8900	926.	2.	5.57	-1.00	-1.00	-1.39	-1.00	-1.00
147	8.8821	4.9220	879.	-1.	-1.00	62.39	-1.00	-1.00	-1.00	-9.24
148	8.6609	4.9813	874.	7.	5.62	-1.00	-1.00	-1.42	-1.00	-1.00
149	9.2042	4.9515	876.	4.	4.15	55.23	-1.00	0.02	-1.00	-2.00
150	8.7822	5.2358	863.	4.	-1.00	-1.00	2.67	-1.00	-0.02	-1.00
152	8.1643	4.6571	899.	4.	-1.00	53.39	-1.00	-1.00	-1.00	-0.37
153	8.3901	4.7477	892.	5.	6.92	-1.00	-1.00	-2.78	-1.00	-1.00
154	8.3279	4.7153	891.	5.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
155	7.7926	4.8489	876.	8.	5.50	58.50	-1.00	-1.39	-1.00	-5.64
156	7.1528	4.9626	917.	4.	6.22	-1.00	-1.00	-2.19	-1.00	-1.00
157	7.5003	5.1198	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
159	5.5902	5.1573	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
160	5.4423	4.6176	1127.	4.	-1.00	50.83	-1.00	-1.00	-1.00	1.40
161	4.1217	4.8219	1167.	-1.	-1.00	54.57	2.69	-1.00	-0.10	-2.64
162	11.5155	3.9525	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
163	11.5485	3.8899	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
164	10.8625	4.5767	957.	2.	3.70	-1.00	-1.00	0.11	-1.00	-1.00
165	10.9342	4.5391	972.	2.	4.11	-1.00	-1.00	-0.31	-1.00	-1.00
166	10.1640	3.9372	988.	2.	3.99	-1.00	-1.00	-0.19	-1.00	-1.00
167	10.3675	4.0181	966.	3.	3.29	50.67	-1.00	0.48	-1.00	2.74
168	10.2844	4.2696	974.	3.	8.56	-1.00	-1.00	-4.68	-1.00	-1.00
169	9.7084	3.9329	976.	4.	4.49	-1.00	-1.00	-0.59	-1.00	-1.00
170	9.7569	3.8388	985.	4.	-1.00	-1.00	2.62	-1.00	0.03	-1.00
171	9.7490	3.8627	981.	4.	1.28	64.73	2.74	2.58	-0.07	-11.48
172	9.7495	3.8311	979.	3.	-1.00	52.40	-1.00	-1.00	-1.00	0.83
173	9.7792	3.9259	978.	5.	-1.00	-1.00	2.65	-1.00	0.00	-1.00
174	9.8041	3.8391	987.	5.	-1.00	-1.00	2.65	-1.00	0.00	-1.00
175	9.7984	4.1863	959.	5.	2.28	-1.00	2.66	1.65	0.00	-1.00
176	9.3258	4.2922	945.	4.	-1.00	52.55	-1.00	-2.29	-1.00	0.63
177	9.7429	4.2094	960.	4.	2.80	-1.00	2.70	1.15	-0.03	-1.00
178	9.6784	4.3033	958.	4.	2.60	47.55	-1.00	1.38	-1.00	5.72
179	9.1524	3.8557	979.	3.	-1.00	53.62	-1.00	-1.00	-1.00	-0.53
180	8.6535	4.0418	954.	4.	6.94	-1.00	-1.00	-2.92	-1.00	-1.00
181	8.5838	4.0006	956.	5.	5.12	-1.00	-1.00	-1.10	-1.00	-1.00

182	9.0451	4.1608	965.	5.	3.54	-1.00	-1.00	0.48	-1.00	-1.00
183	8.5579	4.1186	943.	4.	-1.00	53.39	-1.00	-1.00	-1.00	-0.42
184	8.4815	4.0065	961.	1.	4.81	-1.00	-1.00	-0.79	-1.00	-1.00
185	8.4888	4.0305	958.	4.	5.21	-1.00	-1.00	-1.19	-1.00	-1.00
186	7.8278	4.1787	943.	5.	5.60	-1.00	-1.00	2.66	-1.47	-0.02
187	8.4536	4.2513	943.	4.	-1.00	54.74	-1.00	-1.00	-1.00	-1.78
188	8.0153	4.4301	913.	4.	2.81	-1.00	-1.00	1.25	-1.00	-1.00
193	5.5784	3.8922	1164.	3.	2.02	-1.00	-1.00	1.54	-1.00	-1.00
195	5.9187	4.1179	1102.	3.	1.26	-1.00	-1.00	2.55	2.40	0.05
196	5.8564	4.1169	1103.	4.	2.16	-1.00	-1.00	2.58	1.49	0.02
197	5.2646	3.9834	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
198	4.9805	4.1694	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
199	5.3253	4.0787	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
200	5.3195	4.4580	1123.	11.	-1.00	50.88	-1.00	-1.00	-1.00	-1.31
201	4.7337	3.9457	1191.	5.	4.07	-1.00	-1.00	-0.83	-1.00	-1.00
202	11.5428	3.7877	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
203	10.9514	3.2039	1071.	3.	7.13	-1.00	-1.00	-3.77	-1.00	-1.00
204	11.0511	3.4039	1060.	2.	4.07	-1.00	-1.00	2.72	-0.68	-1.00
205	10.9226	3.4640	1051.	3.	2.11	-1.00	-1.00	2.66	1.34	0.01
206	11.3948	3.6658	1035.	2.	3.02	-1.00	-1.00	0.32	-1.00	-1.00
207	10.1147	3.1158	1082.	2.	1.90	-1.00	-1.00	1.69	-1.00	-1.00
208	9.4358	3.3799	1012.	4.	4.43	-1.00	-1.00	-0.62	-1.00	-1.00
209	9.8550	3.6190	1007.	3.	3.14	-1.00	-1.00	0.64	-1.00	-1.00
210	9.9094	3.6429	1001.	3.	3.58	-1.00	-1.00	0.20	-1.00	-1.00
211	9.7432	3.7443	992.	3.	4.08	-1.00	-1.00	-0.23	-1.00	-1.00
212	9.9313	3.7457	998.	4.	2.94	-1.00	-1.00	0.86	-1.00	-1.00
213	9.8626	3.1775	1082.	4.	-1.00	52.84	-1.00	-1.00	-1.00	0.34
214	9.5742	3.0735	1142.	5.	2.25	-1.00	-1.00	1.45	-1.00	-1.00
215	9.3745	3.3009	1026.	4.	7.79	-1.00	-1.00	-3.99	-1.00	-1.00
216	9.9855	3.3202	1065.	3.	2.39	-1.00	-1.00	1.28	-1.00	-1.00
217	9.1094	3.1692	1039.	6.	-1.00	54.23	-1.00	-1.00	-1.00	-1.23
218	8.5605	3.5261	994.	4.	-1.00	-1.00	2.69	-1.00	-0.04	-1.00
219	8.6855	3.5608	992.	5.	-1.00	52.10	-1.00	-1.00	-1.00	0.83
220	7.3716	3.2201	1063.	6.	3.91	-1.00	-1.00	-0.03	-1.00	-1.00
221	7.1710	3.5081	989.	5.	-1.00	52.33	-1.00	-1.00	-1.00	0.21
222	7.2922	4.4516	983.	5.	-1.00	52.35	-1.00	-1.00	-1.00	0.33
223	6.8083	3.1468	1139.	7.	-1.00	50.57	-1.00	-1.00	-1.00	1.83
224	6.9604	3.4329	1087.	4.	-1.00	50.71	-1.00	-1.00	-1.00	1.77
225	6.1125	3.7409	1144.	9.	4.00	49.80	-1.00	-0.28	-1.00	2.50
226	6.1560	3.0147	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
228	6.2734	3.4900	1143.	3.	3.35	53.29	-1.00	0.38	-1.00	-0.97
231	11.4804	2.6901	1128.	3.	2.03	-1.00	-1.00	0.94	-1.00	-1.00
232	11.2017	2.6262	1154.	3.	4.37	-1.00	-1.00	-1.29	-1.00	-1.00
233	11.4862	2.7769	1128.	3.	2.56	54.58	-1.00	0.44	-1.00	-1.02
234	11.0152	2.3523	1192.	3.	2.99	-1.00	-1.00	0.07	-1.00	-1.00

235	10.2067	2.3590	1138.	3.	3.12	-1.00	-1.00	0.24	-1.00	-1.00
236	10.8194	2.5521	1170.	4.	5.00	-1.00	-1.00	-1.79	-1.00	-1.00
238	10.7719	3.0183	1093.	3.	1.97	-1.00	-1.00	1.40	-1.00	-1.00
239	9.9626	2.3503	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
240	10.0600	2.6263	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
241	9.5151	2.8843	1130.	5.	-1.00	52.12	-1.00	-1.00	-1.00	0.94
242	9.0517	2.4345	1129.	6.	-1.00	-1.00	2.63	-1.00	0.02	-1.00
243	9.1404	2.7524	-1.	5.	2.82	-1.00	-1.00	0.89	-1.00	-1.00
244	9.1392	2.8156	1077.	5.	-1.00	51.44	-1.00	-1.00	-1.00	1.52
245	8.5888	2.8156	1059.	6.	3.39	-1.00	-1.00	0.41	-1.00	-1.00
246	8.9798	2.9374	1059.	4.	1.68	-1.00	-1.00	2.10	-1.00	-1.00
247	8.7899	2.9951	1049.	4.	3.55	-1.00	-1.00	0.26	-1.00	-1.00
248	9.0426	2.9388	1069.	6.	3.83	51.92	-1.00	-0.05	-1.00	1.03
249	8.5292	2.6247	1097.	5.	7.33	-1.00	-1.00	-3.55	-1.00	-1.00
250	7.1026	2.6834	1128.	5.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
251	7.1543	2.9618	1100.	7.	3.13	-1.00	-1.00	0.70	-1.00	-1.00
252	6.7548	2.5139	1142.	3.	4.18	-1.00	2.59	-0.42	0.02	-1.00
253	5.2820	2.8771	-1.	-1.	-1.00	53.49	-1.00	-1.00	-1.00	-1.49
254	5.7246	2.5341	1271.	3.	2.46	-1.00	-1.00	1.13	-1.00	-1.00
255	4.7837	2.8421	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
256	3.8437	2.7697	1371.	1.	-1.00	49.72	-1.00	-1.00	-1.00	1.59
257	11.2909	2.1870	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
258	10.4638	2.1078	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
259	10.2158	2.2882	1170.	4.	2.58	-1.00	-1.00	0.75	-1.00	-1.00
261	10.0613	2.2992	1167.	2.	2.27	-1.00	-1.00	1.12	-1.00	-1.00
262	8.1329	1.9561	1211.	5.	3.40	-1.00	-1.00	0.31	-1.00	-1.00
263	7.1646	2.1395	1200.	6.	-1.00	-1.00	2.54	-1.00	0.08	-1.00
265	6.4909	2.0619	1224.	5.	-1.00	-1.00	2.62	-1.00	-0.00	-1.00
270	5.6470	3.4818	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
273	7.8205	4.5891	896.	3.	5.03	-1.00	-1.00	-0.94	-1.00	-1.00
274	7.8898	4.6609	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
276	8.7839	3.7921	972.	4.	5.49	-1.00	-1.00	-1.51	-1.00	-1.00
280	6.3744	3.0489	1179.	10.	-1.00	49.95	-1.00	-1.00	-1.00	2.33
287	8.1809	6.3200	778.	3.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
288	7.2811	6.6822	819.	4.	2.72	-1.00	2.63	1.49	-0.00	-1.00
291	10.6614	9.8067	729.	4.	3.94	-1.00	-1.00	1.48	-1.00	-1.00
293	10.2051	9.8801	669.	4.	3.92	51.04	-1.00	1.48	-1.00	3.01
294	10.2501	9.1710	747.	5.	7.64	-1.00	-1.00	-2.42	-1.00	-1.00
295	9.5543	9.8029	668.	3.	3.14	-1.00	-1.00	2.13	-1.00	-1.00
297	9.2974	9.6036	668.	-1.	4.14	-1.00	-1.00	1.04	-1.00	-1.00
299	9.2416	9.1932	695.	4.	8.60	-1.00	-1.00	-3.51	-1.00	-1.00
301	8.4555	9.8447	683.	-1.	6.01	-1.00	-1.00	-1.00	-1.00	-1.00
302	8.8717	9.5352	687.	3.	-1.00	49.67	-1.00	-1.00	-1.00	4.01
305	7.6270	9.3068	744.	-1.	-1.00	51.29	-1.00	-1.00	-1.00	2.04
306	7.3915	9.8328	705.	-1.	1.80	-1.00	-1.00	2.78	-1.00	-1.00

307	7.2082	9.2631	756.	-1.	4.61	-1.00	-1.00	-0.17	-1.00	-1.00
308	6.7102	9.3601	772.	-1.	3.80	-1.00	-1.00	0.41	-1.00	-1.00
309	6.3324	9.5138	778.	4.	3.43	-1.00	-1.00	0.58	-1.00	-1.00
313	5.6037	9.6435	789.	5.	-1.00	50.97	-1.00	-1.00	-1.00	1.89
315	5.1222	9.1691	832.	4.	4.99	-1.00	-1.00	-1.73	-1.00	-1.00
317	4.1958	9.3711	878.	2.	3.49	-1.00	-1.00	-0.93	-1.00	-1.00
323	8.2702	8.9886	728.	4.	6.08	-1.00	-1.00	-1.27	-1.00	-1.00
330	11.3729	7.7622	814.	2.	6.03	-1.00	-1.00	-1.28	-1.00	-1.00
331	11.0561	8.0190	801.	3.	3.59	-1.00	-1.00	1.27	-1.00	-1.00
332	11.1146	8.3391	801.	4.	8.56	-1.00	-1.00	-3.59	-1.00	-1.00
333	9.3257	8.0611	772.	-1.	7.14	-1.00	-1.00	-2.29	-1.00	0.63
337	9.9476	8.2512	785.	3.	6.77	-1.00	-1.00	-1.81	-1.00	-1.00
339	8.9902	8.2962	716.	1.	4.63	58.37	-1.00	0.22	-1.00	-4.80
343	8.0574	7.9077	767.	4.	6.73	-1.00	-1.00	-2.14	-1.00	-1.00
345	10.7707	6.9287	847.	3.	3.95	-1.00	-1.00	0.60	-1.00	-1.00
347	11.2150	7.6315	814.	4.	4.58	-1.00	-1.00	0.13	-1.00	-1.00
348	8.9260	7.2258	789.	3.	6.47	-1.00	-1.00	-1.84	-1.00	-1.00
349	11.0520	6.4075	879.	3.	5.23	-1.00	-1.00	-0.87	-1.00	-1.00
354	11.4276	5.9840	881.	2.	3.53	-1.00	-1.00	0.59	-1.00	-1.00
355	10.7678	5.7085	886.	2.	-1.00	51.33	-1.00	-1.00	-1.00	2.38
356	11.3448	5.6553	891.	2.	3.13	-1.00	-1.00	0.90	-1.00	-1.00
358	6.7428	5.7053	887.	7.	3.49	-1.00	-1.00	0.48	-1.00	-1.00
362	5.7083	5.6862	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
363	5.1583	5.9526	-1.	-1.	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
369	7.8278	4.1787	943.	5.	5.50	-1.00	2.66	-1.47	-0.02	-1.00
373	8.5334	2.5974	1098.	-1.	5.10	-1.00	-1.00	-1.32	-1.00	-1.00
375	9.7811	3.7999	988.	3.	3.16	-1.00	2.66	0.68	-0.00	-1.00

APPENDIX 4

Computer Program GRIDOP Used in Computing Mineral
Fractions from Gridded Average Porosity Log Responses

PROGRAM GRIDOP READS THREE MATRICES ONE ROW AT A TIME FROM EACH. THE MATRICES CONTAIN THE CORRECTED, AND GRIDDED AVERAGE LOG RESPONSES IN THE ORDER NEUTRON, DENSITY, AND SONIC. A MATRIX CONTAINING FOR EXAMPLE COMPUTED POROSITY VALUES WILL REQUIRE THE FIRST ROW OF THE INVERSE MATRIX (EQ. 22, P.72).

M = NUMBER OF ROWS

N = NUMBER OF COLUMNS

A(1) = FIRST ELEMENT OF FIRST ROW OF EQ.22

A(2) = SECOND "

A(3) = THIRD "

CON = FOURTH "

```

C          TB:GRIDOP:F
C          INPUT: 1=NEUTRON,2=DENSITY,3=SONIC
C          DIMENSION D(1000,4),IS(10),A(3)
C          START AND NEWFILE OPEN AND CLOSE FILES
C          CALL START
C          DO 100 I=1,3
C          WRITE(6,200)I
100 CALL NEWFIL(IS,I,1)
C          WRITE(6,201)
C          ACCEPT M,N,A(1),A(2),A(3),CON
C          TYPE 'ELEMENTS OF INVERTED MATRIX'
C          TYPE ' '
C          TYPE A(1),A(2),A(3),CON
C          WRITE(6,202)
C          CALL NEWFIL(IS,4,1)
C          DO 101 I=1,M
C          DO 102 J=1,3
102 READ BINARY(J)(D(K,J),K=1,N)
C          DO 103 J=1,N
C          S=0
C          DO 104 K=1,3
104 S=S+D(J,K)*A(K)
103 D(J,4)=S+CON
101 WRITE BINARY(4)(D(J,4),J=1,N)
C          STOP
200 FORMAT(' FILENAME FOR MAP:',13)
201 FORMAT(' ROWS, COLS, 3 COEFF, CONSTANT:')
202 FORMAT(' OUTPUT FILENAME:')
C          END

```

BIOGRAPHICAL DATA

Name: Erhard Bornemann

Date and Place of Birth: October 26, 1947
Weiden/Oberpfalz, Federal Republic of Germany

Elementary School: Volksschule Vienenburg
Vienenburg/Harz, Federal Republic of Germany
Graduated: 1959

High School: Ratsgymnasium Goslar
Goslar/Harz, Federal Republic of Germany
Graduated: 1968

College: University College of Wales
Swansea, United Kingdom

Technische Universität Hannover
Hannover, Federal Republic of Germany
Diplom - Geologe: 1974

Graduate Work: The University of Kansas
Lawrence, Kansas
Research Assistantship

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