储集层非均质性分析的计算机方法：以西弗吉尼亚州下密西西比系油田为例

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本文使用几种计算法和统计法研究美国西弗吉尼亚洲中部格兰尼克里克油田大 Injun 砂岩储集层的结构及其与采油量的关系。计算机程序根据已出版的资料编写，以适合（1）计算渗透率对孔隙度的回归；（2）标绘三维孔隙度；（3）确定和标绘根据地球物理测井记录推断的相；（4）估算原始储量、累积产量和采油率。因为回归分析显示出测井记录和岩心孔隙度及岩心渗透率间微弱但重要的相关，所以，孔隙度可用于地层渗透率中以构成储集层的模式。也使用定量地层对比和多维定算法来估算在缺乏可用数据的情况下构造的影响。于井间使用克里格法内插绘制的剖面，突出了孔隙度较高的地带。使用地球物理测井资料和岩心描述，用聚类分析确定导电相。原始储量的估算结果与累计产量数据相结合，得出采油率的估算值。这些采油量变量图通常呈现在岩相图上观察到的相同的南北走向。

COMPUTER METHODS FOR ANALYSIS OF RESERVOIR HETEROGENEITY: EXAMPLE FROM A LOWER MISSISSIPPIAN OIL FIELD IN WEST VIRGINIA

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ABSTRACT

Several computational and statistical methods were used in the study of reservoir architecture and its relationship to oil production from the Mississippian Big Injun sandstone in Granny Creek field, central West Virginia (USA). Computer programs were written or adapted from published sources to: 1) calculate the regression of permeability on porosity; 2) map porosity in three dimensions; 3) define and map facies inferred from geophysical logs; and 4) estimate original oil in place, cumulative production, and recovery efficiency. Because regression analysis showed a weak but significant relationship between log and core porosity, and core permeability, porosity could be used in place of permeability to construct models of the reservoir. Quantitative stratigraphic correlation and multidimensional scaling were used to eliminate the effects of structure in the absence of a usable datum. Kriging was used for interpolation between wells, and the results were drawn as cross sections to highlight zones of relatively high porosity. Geophysical log data and core descriptions were used to define electrofacies by cluster analysis. Estimates of original oil in place were combined with cumulative production data to yield estimates of recovery efficiency. Maps of these oil production variables generally showed the same north—south trend observed on lithofacies maps.

INTRODUCTION

The idea of reservoir heterogeneity has become an important paradigm in the study of reservoir architecture. The conventional view of an oil or gas reservoir was one of relative uniformity in lithology and mineralogy. Variations in these characteristics were assumed to be on a very small scale. Consequently, the petroleum engineer could assume homogeneity in physical parameters such as porosity and permeability. This assumption was made partly as a matter of necessity or convenience, because the quantity of data required for a comprehensive study of reservoir architecture is extensive. Additionally, the petroleum engineer was limited in the complexity of flow simulators that could be run by available computer power.

However, times have changed. Geologists have come to realize that large quantities of potentially-recoverable mobile oil remain in many fields, in part because of the complexity of sedimentary rocks. This complexity probably affects recovery efficiency and cannot be ignored or simplified away. Now, when the geologist presents the petroleum engineer with a complex model of a reservoir, computer power is available to conduct complex simulations. Understanding reservoir heterogeneity can be used to plan field development and secondary recovery. Additionally, companies may elect to carry out a program of infill drilling in older fields on the verge of abandonment.

The sedimentologist can have a major impact on the volume of hydrocarbons produced from a reservoir. The environment of deposition influences the degree of reservoir heterogeneity (Galloway and Hobday, 1983). For example, fluvially-dominated deltas tend to consist of many intersecting units of varying lithologies ranging from shales to sandstones, resulting in poor continuity of the best reservoir facies from well to well. Wave dominated deltas exhibit the homogenizing effects of reworking of the deltaic sediments. The recovery of mobile oil is highest in the more homogeneous reservoirs. Tyler *et al.* (1984) found that recovery efficiency in Texas reservoirs ranges between 8 and 80%, the lowest percentages coming from reservoirs representing deposition in turbidites and submarine fans, with weak drive; the highest from wave-dominated deltas and barrier bars, with strong drive. Once depositional environment has been established, the sedimentologist must try to define lithologic units that make up the reservoir, determine the variation in porosity and permeability, and quantify the spatial patterns in these parameters at all scales.

This paper illustrates computer methods used in the study of reservoir architecture and its relationship to production in an oil field in central West Virginia (USA). Work included calculating the regression of permeability on porosity, mapping porosity in three dimensions, defining and mapping facies from geophysical logs, and estimating original oil in place, cumulative production, and recovery efficiency. Supported by the U. S. Department of Energy (Contract #DE-AC22-90BC14657), this work culminated in a published report on the petroleum geology and reservoir heterogeneity of the field (Hohn *et al.*, 1993).

BACKGROUND: GRANNY CREEK FIELD

The Granny Creek field is located in central West Virginia on the border of Roane and Clay counties (Figure 1). The field encompasses approximately 15.5 km^2 with approximately 700 wells. The field was discovered in 1924 and is still producing. Primary production is from the Big Injun and Squaw sandstones, both within the Early Mississippian Price Formation (Figure 2) at an average elevation of −256 meters below sea level for the Big Injun and −265 meters for the Squaw (Hohn *et al.*, 1993). The Big Injun was first documented in Mount Morris, Pennsylvania where substantial oil production was discovered in 1886 from a thick sandstone immediately below the Big Lime (Greenbrier Limestone) (Carll, 1890). The Big Injun produces oil and gas throughout northern and central West Virginia (Overbey *et al.*, 1963).

Fig. 1 Location of Granny Creek field

Penns	Lower	Pottsville Group
Mississippian	Upper	Mauch Chunk Group
	Middle	Greenbrier Ls.
	Lower	Maccrady Formation Price Formation
Devonian	Upper	Hampshire Formation Chemung Formation Brellier Formation

Fig. 2 Chart of Mississippian stratigraphic nomenclature in central West Virginia

The Big Injun in Granny Creek field unconformably underlies the Greenbrier Limestone and can be separated into an upper, coarse-grained unit and a lower, fine-grained unit (Figure 3)(Swales, 1988)The composition of the coarse-grained Big Injun varies from con-

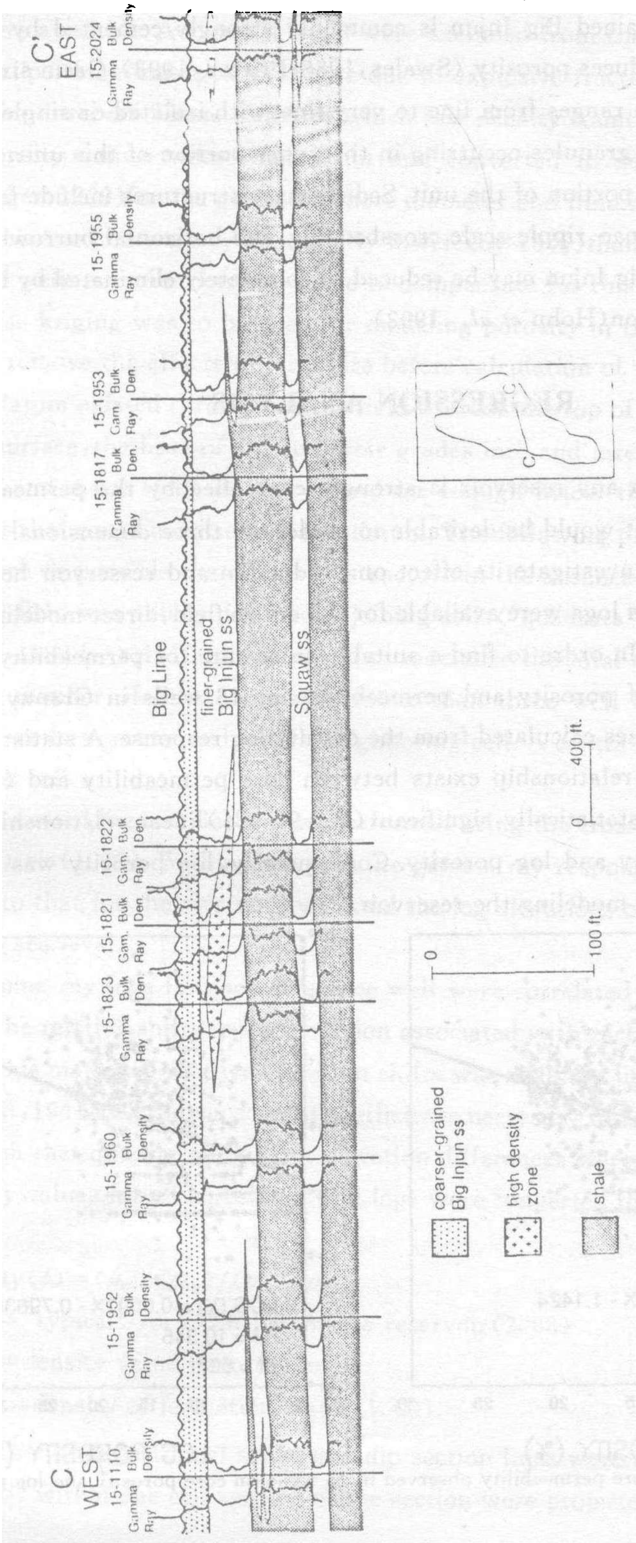

Fig. 3　Stratigraphic cross section of the Big Injun in Granny Creek field, showing the two units within the Big Injun, and truncation of the reservoir by an erosional surface

glomerate to fine sandstone, with thin shale interbeds. Sedimentary structures include horizontal laminae, planar or trough cross-bedding, clay drapes on low-angle crossbeds, and minor ripple-scale crossbeds in medium-grained sandstone (Hohn *et al.*, 1993). The lower portion of the coarse-grained Big Injun is commonly strongly cemented by quartz overgrowth which greatly reduces porosity (Swales, 1988; Britton, 1993). Grain size in the lower, fine-grained Big Injun ranges from fine to very fine, with isolated or single grain layers of coarse, quartz sand to granules occurring in the upper portion of this unit. Shale is present locally in the lower portion of the unit. Sedimentary structures include faint, horizontal to subhorizontal laminae, ripple-scale crossbedding, and horizontal burrows. Porosity in the lower, fine-grained Big Injun may be reduced or completely eliminated by intensive calcite or siderite cementation (Hohn *et al.*, 1993).

REGRESSION ANALYSIS

Oil production from any reservoir is strongly controlled by the permeability of the reservoir. Consequently, it would be desirable to model the three-dimensional permeability directly when trying to investigate its effect on production and resservoir heterogeneity. Because only 20 induction logs were available for the entire field, direct modeling of permeability was not possible. In ordre to find a suitable substitute for permeability, the results of whole-core analysis of porosity and permeability for 16 wells in Granny Creek were compared to porosity values calculated from the density log response. A statistically significant ($P > 99.9\%$) linear relationship exists between core permeability and core porosity (Figure 4). Similarly, a statistically significant ($P > 99.9\%$) linear relationship is present between core permeability and log porosity. Consequently, log porosity was chosen as a proxy for permeability in modeling the reservoir.

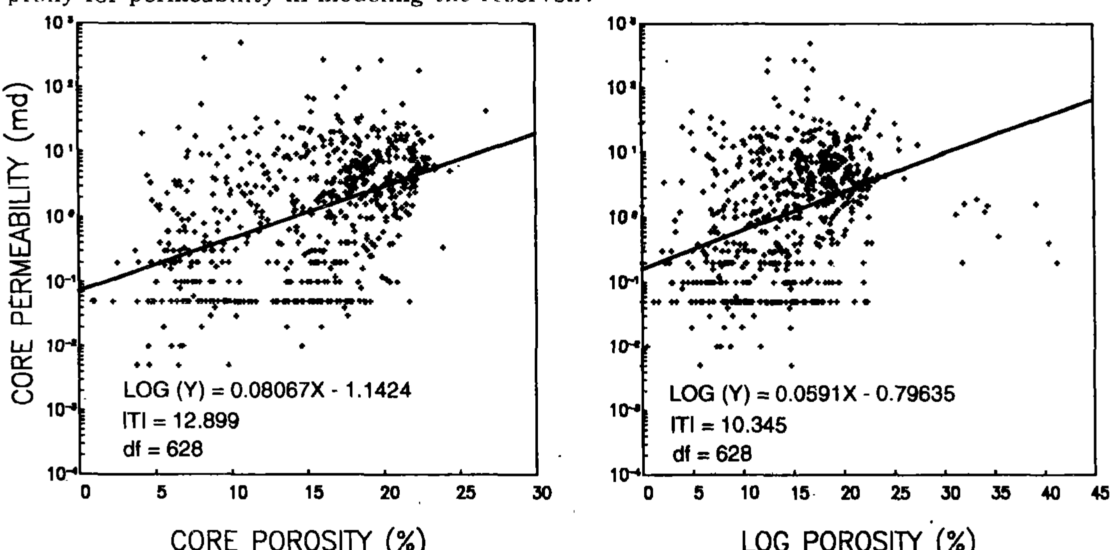

Fig. 4 Regression of core permeability observed in 16 wells on core porosity and log porosity

SPATIAL ANALYSIS OF POROSITY

Gamma ray and density logs from Granny Creek field were scanned and digitized into ASCII files. The log database was restricted to wells for which both gamma ray and density logs were available. Additional wells were excluded from the database because of unacceptable caliper logs(enlarged well bore due to explosive fracturing with nitroglycerin)in the big Injun interval. Those wells for which raw density counts had been recorded instead of API density values were singled out and converted to density (Alger *et al.*, 1971; Schlumberger, 1989)for the given well bore diameter and fluid in hole. Density values computed by this method were systematically lower (by 15%)than API density values logged in adjacent wells; a correction was made to compensate for this effect.

Because kriging was to be used for modeling porosity in three dimensions, it was important to remove the effects of structure before calculation of variograms. Unfortunately, no single datum existed throughout the field because the top of the reservoir represents an erosional surface, the base of the reservoir grades into and intertongues with the underlying shales, and many wells do not extend far enough below the Big Injun to penetrate a deeper unit that could have served as a datum. The following procedure was used to eliminate as much as possible the effects of structure in the absence of a datum:

1)The field was subdivided into adjoining cells("quadrats")of uniform size. A cell dimension of 1180 ft. $\times$1310 ft. was found to maximize the total number of cells while minimizing the number of cells containing fewer than three well locations. Cells with fewer than three wells were merged with a neighboring cell. A central or reference well was chosen for each cell.

2)Automated log correlation was performed using the cross-correlation algorithm proposed by Davis(1973). Within each cell, the gamma ray response for individual wells was correlated to that for the reference well and the log elevations of the correlated wells were adjusted to sea level.

3)Gamma-ray logs for each reference well were correlated against all other reference wells and the relative shifts in log elevation associated with each correlation were placed in a matrix. This matrix of relative elevation shifts was analyzed using multidimensional scaling(Kruskal, 1964)to produce a set of coefficients necessary to adjust the elevations of each quadrat such that quadrat-to-quadrat elevation differences were minimized.

Density values for all correlated well logs were converted to porosity using the formula:

$$\text{Porosity}(\phi)=(\rho_{ma}-\rho_{log})/(\rho_{ma}-\rho_{H_2O})$$

Where: ρ_{ma} = "typical" rock density for the reservoir(2.68)

ρ_{log} = density value from the log

ρ_{H_2O} = density of formation water(1.00).

A number of depositional strike and dip section lines were chosen for study. For each section, wells within one cell spacing of the section were projected into the plane of section nd distance-weighted gridding techniques used for interpolation. The section along depositional dip in Figure 5 shows the presence of zones of low porosity, 150 ft. to 650 ft. in ross-sectional width, separating zones of high porosity. Vertical exaggeration caused these ow porosity zones to appear spherical to oval in cross section, but in reality, low porosity ones are ovoid or "pancake-like" in three dimensions because their thickness is restricted o the thickness of the Big Injun interval. Cross sections such as this led to the conclusion hat reservoir in Granny Creek field may be compartmentalized by low porosity, low perneability zones (Hohn *et al.*, 1993).

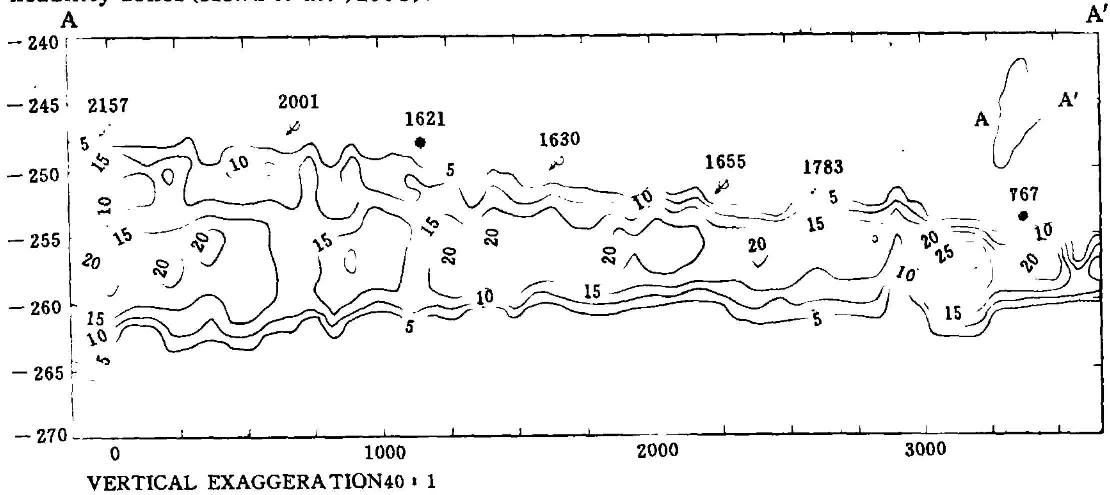

Fig. 5 Porosity cross section A- A'. Vertical exaggeration is 40 : 1. County permit numbers of well along section are shown above well symbols. Other wells adjacent to the cross section have been projected onto the plane of section. Vertical and horizontal scales are in meters. Contour interval is 5% porosity

FACIES ANALYSIS

Two different approaches were taken to identify and model facies in the Big Injun reservoir. Both utilized geophysical logs for ten, "type" wells from Granny Creek (Smosna and Bruner, 1991; Bruner and Smosna, 1992) selected because of continuous coring through the Big Injun interval. In the first, more conventional approach, lithofacies interpreted from core description (Smosna and Bruner, 1991; Bruner and Smosna, 1992) were associated with a set of gamma ray and density values taken from logs. Discriminant analysis was performed on geophysical log values associated with each lithofacies to determine if the classification based on core description could be replicated using log values alone. Various combinations of gamma ray and density values were tested as the "classifying variable" to find the combination that would most successfully classify each interval on the geophysical logs into the "correct" lithofacies. A linear combination of gamma ray and density values (weighted equally) was found to reproduce the lithofacies classification for the type well suite with a $\geq 70\%$ success rate. This was true regardless of whether the cores (and logs) were classified using a two-fold subdivision into coarse and fine lithofacies or a four-fold subdivision into channel, fluvial mouth bar, marine mouth bar, and distal bar lithofacies.

The second approach was more indirect. It used cluster analysis on the geophysical logs for the type wells in an attempt to find a "natural" classification scheme independent of the core descriptions. A four-fold subdivision into "electrofacies" (so termed because of their geophysical and statistical basis) was developed and used to classify each of the logs for the type wells. Discriminant analysis was performed for this classification scheme and it was found to be reproducible with a≥90% success rate.

To test the utility of both classification schemes at the field scale, linear discriminant function coefficients (Norusis, 1992) were calculated for each facies based on the set of gamma ray and density values associated with each. These coefficients were then used to calculate discriminant function scores at each depth interval on all correlated gamma ray and density logs from the Granny Creek field. Function scores were used to assign a particular facies at each depth interval, in effect converting the geophysical log into a facies log.

Using this new suite of correlated facies logs, a series of facies cross sections were produced along the same lines of section used in modeling porosity. Each facies on the logs was color-coded and displayed at its appropriate depth and position along the line of section. Once again, logs from wells immediately adjacent to the line of section were projected into the section and displayed.

Figure 6 is an example from Granny Creek using four electrofacies to classify the Big Injun interval. Electrofacies 1 is restricted to the upper, coarse-grained portion of the Big Injun and corresponds to the channel lithofacies of the core-based classification scheme. The remaining three electrofacies are generally restricted to the lower, fine-grained Big Injun and correspond approximately to the three mouth bar lithofacies of the core-based classification scheme. Dip-direction cross sections for the Biq Injun reservoir in Granny Creek,

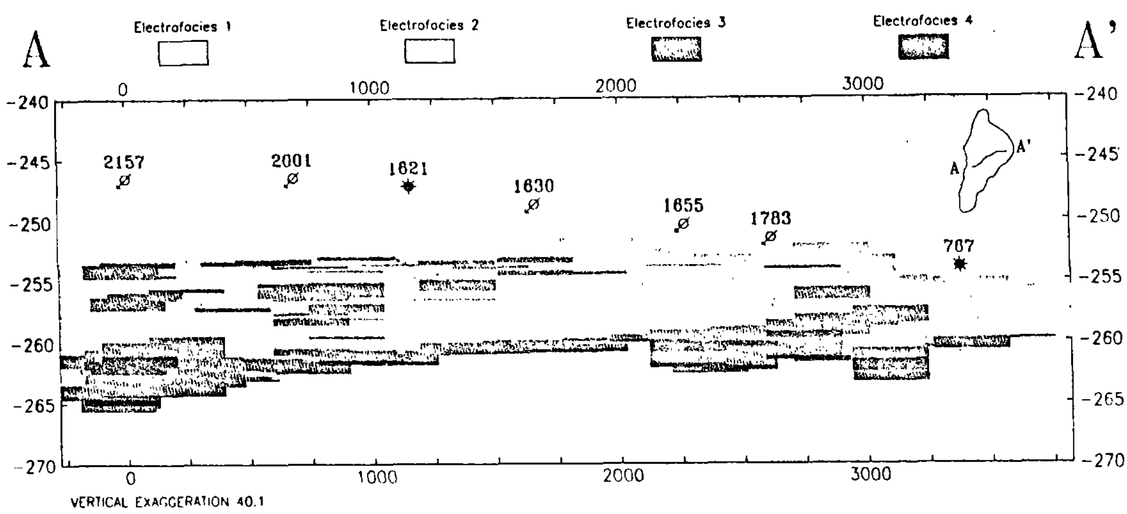

Fig. 6　Facies cross section A—A'. Four electrofacies were determined using cluster and discriminant analysis of geophysical log data. Numbers above well symbols are county permit numbers. Vertical exaggeration is 40 : 1. Vertical and horizontal scales are in meters

regardless of classification scheme, suggest the presence of a series of inclined, laterally adjacent lithologic bodies arranged from east to west. Results were also displayed in the form of maps of percent lithofacies present (Figure 7).

VOLUMETRICS

Original oil in place, cumulative production, and recovery efficiency were computed for each well in order to see whether production can be related to lithofacies interpreted from geophysical logs. Cumulative production data exist mainly for wells completed before geophysical well logging was performed routinely in West Virginia, whereas logs necessary for estimating porosity are available for water injection wells drilled later. Cumulative production was interpolated to a grid, and an estimate of cumulative production computed from the grid at each location in the total set of wells. Similarly, estimates of original oil in place were computed for the total set of well. Linear kriging was used (Hohn, 1988) to provide some smoothing in the interpolation process.

For every well in the field, original oil in place was calculated using the formula:

$$OOIP = 7758 \times (A \times H \times \phi \times (1 - S_w)) / B_o$$

Where: $OOIP$ = original oil in place

A = effective area drained by well (acres)

H = reservoir thickness (kriged estimate) (feet)

ϕ = porosity (kriged estimate)

S_w = water saturation (kriged estimate)

B_o = formation volume factor at reservoir pressure and temperature (1.113)

7758 = number of barrels per acre-foot

Because the drainage radius was not known, a value was chosen experimentally to yield an average recovery efficiency similar to one calculated by Whieldon and Eckard (1963) for Granny Creek field as a whole (38.4%). Recovery efficiency was calculated for each well as the ratio of cumulative production to original oil in place. Different values for drainage radius were observed to affect the range of values for original oil in place and recovery efficiency, but not the overall geographic trends in the distribution of those two parameters.

Estimated original oil in place (Figure 8) and cumulative oil production (Figure 9) both show a north—south high in the central part of the field. The lowest estimates occur in the southern margin of the field, where reservoir sandstones are interbedded with shales and water saturation is relatively high.

Highest recovery efficiencies (Figure 10) occur in the northern part of the field. Facies analysis shows a concentration of Electrofacies 2—Marine Mouth Bar that corresponds geographically with the trend of high recovery efficiencies.

CONCLUDING REMARKS

This paper outlines some of the statistical and graphical methods used in an integrated

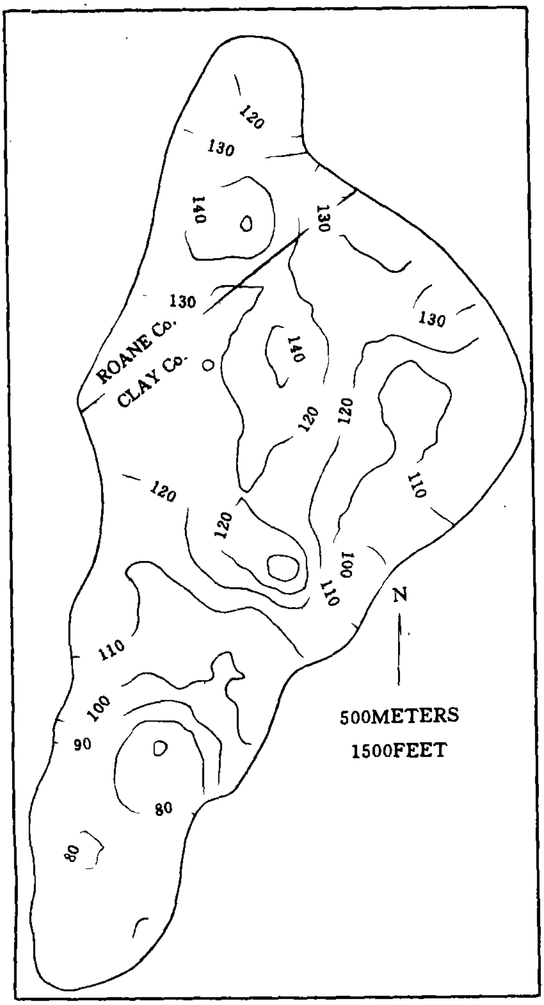

Fig. 7　Contour map showing the percent of the proximal lithofacies making up the Big Injun interval in Granny Creek field. Contour interval is 10%

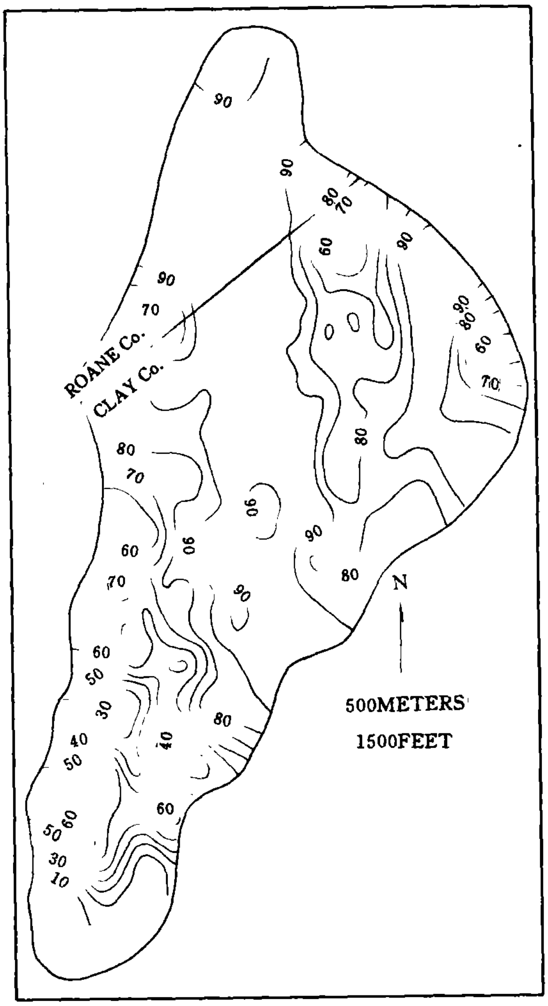

Fig. 8　Contour map of estimated original oil in place, Granny Creek field. Map unit is 10^3 barrels (1 barrel = 0.159 m^3)

study of an Early Mississippian oil reservoir in the Appalachian basin of the United States. The purpose of the work was to show the connection between lithology, proosity, and permeability on the one hand, and oil production on the other. Most of the computational and statistical work made use of published or commercial software.

Regression analysis showed a weak but significant relationship between log and core porosity, and core permeability. Because of a lack of data, porosity rather than permeability was used in constructiong models of the reservoir. These three-dimensional models required an innovative approach to eliminating the effects of structure in the absence of a usable datum. The approach used both a method for quantitative stratigraphic correlation and multidimensional scaling. Kriging was used for interpolation between wells, and the results

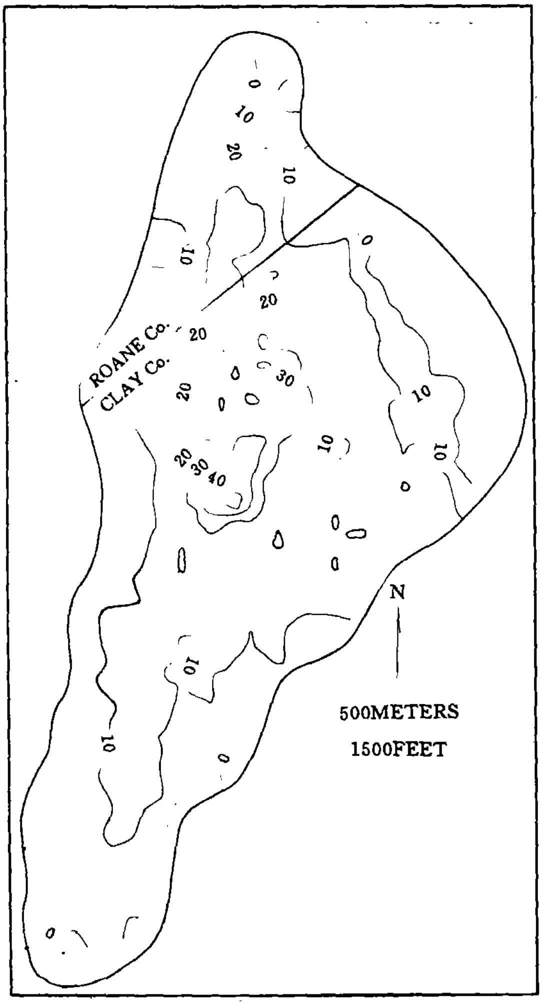

Fig. 9 Contour map of cumulative ten-year production of oil from Granny Creek field. Contour interval is 10,000 barrels (1 barrel = 0.159 m^3)

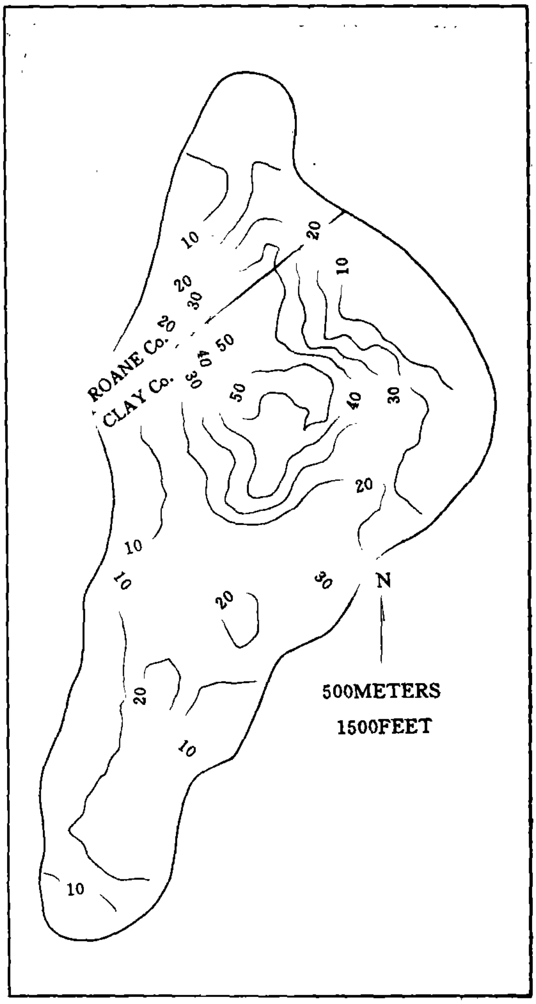

Fig. 10 Contour map of recovery efficiency. Contour interval is 10% efficiency

were drawn as cross sections that highlighted the discontinuity between wells. Geophysical log data and core descriptions were used to compute discriminant functions and to classify log readings among four lithofacies. The resulting cross sections showed the east-to-west, offlapping, distributary mouth bars that constitute the reservoir. Estimates of original oil in place combined with cumulative production data to give well-by-well estimates of recovery efficiency; maps of these variables generally show the same north-south trend observed on lithofacies maps.

REFERENCES

Alger, R., Raymer, L., Hoyle, W. and Tixier, M., 1971. "Formation density log applications in liquid-filled holes".

In:*Well Logging*,Society of Petroleum Engineers Reprint Series No. 1,pp. 185—196.

Britton,J. Q. ,1993. Petrographic heterogeneities of the Big Injun sandstone in Granny Creek Oil Field,Clay and Roane Counties,West Virginia[unpublished M. S. thesis]. Morgantown, West Virginia,West Virginia University,p. 119.

Bruner,K. and Smosna,R. ,1992. "Reservoir sedimentology of a fluvial-deltaic system:the Mississippian Big Injun sandstone from six wells in the Granny Creek and Rouzer oil fields,West Virginia". unpublished report to D. Patchen, West Virginia Geological and Economic Survey,Morgantown,p. 39.

Carll, John,1890. Oil and Gas Fields of Western Pennsylvania. Geological Survey of Pennsylvania seventh report,p. 356.

Davis,J. ,1973. *Statisitcs and Data Analysis in Geology*:John Wiley and Sons,New York,p. 550.

Hohn, M. ,1988. *Geostatisitics and Petroleum Geology*;Van Nostrand Reinhold,New York,. p. 264.

Hohn,M. ,McDowell,R. R. , Vargo,A. ,Matchen,D. ,Heald,M. T. and Britton,J. Q. ,1993. Petroleum geology and reservoir characterization of the Big Injun Sandstone(Price Formation)in the Granny Creek Field,Clay and Roane Counties,West Virginia. West Virginia Geological and Economic Survey,Bulletin B-44,p. 91.

Kruskal,J. ,1964. "Non-metric multidimensional scaling:a numerical method". Psychometrika,Vol. 29,pp. 115—129.

Norusis,M. ,1992. *SPSS for Windows-Professicnal Statistics, Release* 5;SPSS Inc. , Chicago,p. 348.

Overby,W. K. ,Tucker,R. C. and Ruley,E. E. ,1993. Recent Developments in the Big Injun Horizon in West Virginia. Producers Monthly,Vol. 27,No. 7,pp. 18—22.

Schlumberger,1989. *Log Interpretation-Principles/Applications*. Schlumberger Educational Services,Houston.

Smosna,R. and Bruner,L. ,1991. "Reservoir sedimentology of the Mississippian Big Injun in West Virginia". Unpublished report to D. Patchen,West Virginia Geological and Economic Survey,Morgantown,p. 26.

Swales,D. L. ,1988. Petrology and sedimentation of the Big Injun and Squaw sandstones,Granny Creek Field,West Virginia [unpublished M. S. thesis]. Morgantown,West Virginia,West Virginia University,p. 128.

Tyler,N. ,Galloway,W. E. ,Garrett,C. M. ,Jr. and Ewing,T. E. ,1984. Oil accumulation,production characteristics, and targets for additional recovery in major oil reservoirs of Texas. Bureau of Econmic Geology,Geological Circular 84-2, p. 31.

Whieldon,C. and Eckard,W,1963. West Virginia oilfields discovered before 1940. U. S. Bureau of Mines Bulletin 607,p. 187.