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CLAYS, CATIONS, AND GEOPHYSICAL LOG RESPONSE OF GAS-PRODUCING AND NONPRODUCING ZONES IN THE GAMMON SHALE (CRETACEOUS), SOUTHWESTERN NORTH DAKOTA

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Abstract—The Upper Cretaceous Gammon Shale has served as both source bed and reservoir rock for accumulations of natural gas. Gas-producing and nonproducing zones in the Gammon Shale are differentiated on the basis of geophysical log interpretation. To determine the physical basis of the log responses, mineralogical, cation-exchange, textural, and chemical analyses were conducted on core samples from both producing and nonproducing portions of a well in the Gammon Shale from southwestern North Dakota. Statistical treatment (2 sample t-test and discriminant function analysis) of the laboratory data indicate that the producing and nonproducing zones differ significantly in mixed-layer clay content (7 vs. 12%), weight proportion of the clay-size (0.5–1.0 μm) fraction (5.3 vs. 6.3%) ratio of Ca^{2+} to Na^{+} extracted during ion exchange (1.4 vs. 1.0), and abundance of dolomite (10 vs. 8%). The geophysical logs apparently record subtle differences in composition and texture which probably reflect variations in the original detrital constituents of the Gammon sediments. Successfully combining log interpretation and clay petrology aids in understanding the physical basis of log response in clay-rich rocks and enhances the effectiveness of logs as predictive geologic tools.

Key Words—Exchange cations, Geophysical log, Mixed layer, Natural gas, Shale, Statistical analysis.

INTRODUCTION

Mudstones are commonly considered to be source beds for hydrocarbons provided they contain enough organic matter, but they are rarely considered to be reservoir rocks. Future supplies of natural gas will increasingly be derived from highly argillaceous reservoir rocks that are now considered to be uneconomic or marginally economic for gas production. Successful exploration and effective gas recovery from these clay-rich rocks will depend upon predictions of reservoir properties based on interpretations of geophysical log response. The logs, in turn, respond to physical properties that are greatly influenced by the clay mineral suite. In the northern Great Plains of the United States and Canada, marine mudstones of Cretaceous age contain potentially important reserves of natural gas (Rice and Shurr, 1980). These gas-bearing mudstones provide excellent opportunities to evaluate the mineralogical and textural properties which affect the relation of gas production and log interpretation in clay-rich rocks.

The Upper Cretaceous Gammon Shale has served as the source bed as well as the reservoir rock for large quantities of natural gas. The Gammon Shale has experienced only low temperatures during its burial history, insufficient for oil generation or for clay mineral diagenesis. Consequently, the principal gas in the formation is biogenic methane, and the principal clay is highly expandable, randomly interstratified illite/smectite that has not undergone detectable smectite-to-illite transformation. Gas reservoirs in the Gammon Shale consist of thin (<1 cm), discontinuous lenses and laminae of siltstone enclosed in silty shale (Gautier, 1981a). From thick sequences of mudstone considered to contain prospective gas reservoirs, specific zones are selected to be stimulated for gas production on the basis of borehole log interpretation (e.g., Nydegger *et al.*, 1980). This paper presents the results of a case study to determine the physical and mineralogical differences between mudstones of the Gammon Shale that have been classified as productive and nonproductive on the basis of log interpretation.

THE GAMMON SHALE

The Gammon Shale is typical of the clay-rich, gas-bearing strata of the northern Great Plains (Gautier, 1981a) in that it consists mainly of marine siltstone, mudstone, shale, and minor amounts of sandstone deposited offshore during a major regression of the epeiric sea in the Western Interior (Gill and Cobban, 1973). Source areas for the sediment of the Gammon Shale lay to the west in an active orogenic belt and consisted of a mixed terrane of sedimentary, metamorphic, and volcanic rocks (Gautier, 1981b). The Gammon Shale (Figure 1) overlies and intertongues with calcareous shales and marlstones of the Niobrara Formation and underlies organic-rich marine claystones of the Claggett Shale. To the west the Gammon Shale is equivalent, in part, to shoreline deposits of the Eagle Sandstone and continental rocks in the lower part of the Two Medicine Formation. The Gammon Shale thickens to the east

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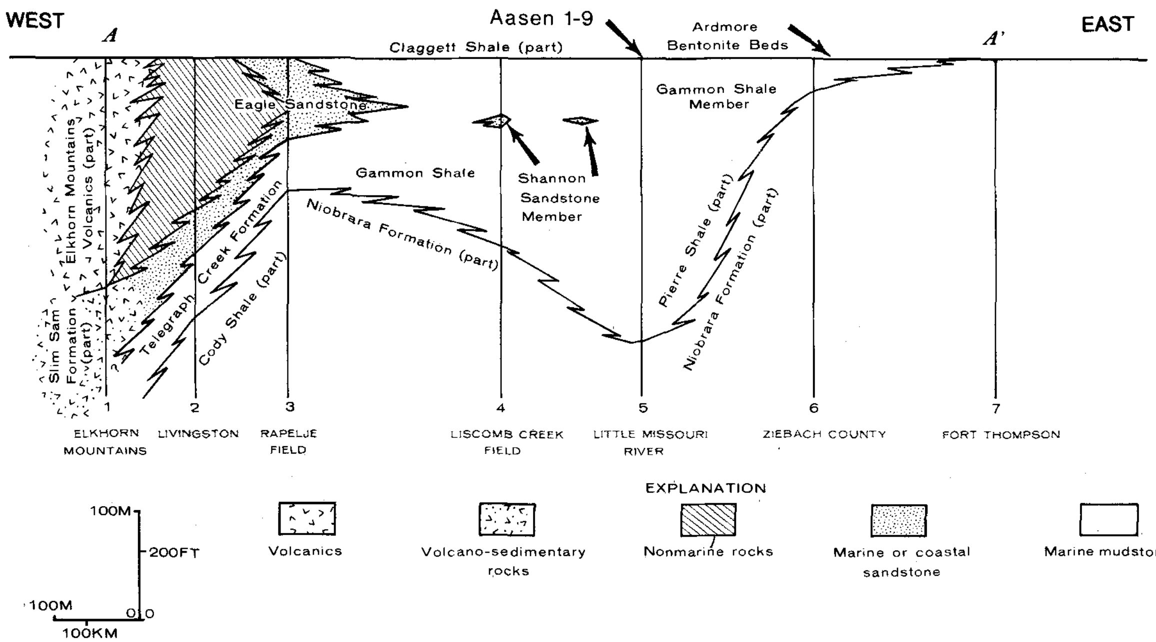

Figure 1. West-east cross section from southern Elkhorn Mountains, Jefferson and Broadwater Counties, Montana, to Fort Thompson, Buffalo County, South Dakota, showing regional stratigraphic relations of Gammon Shale and equivalent and related rocks (from Gautier, 1981a).

(seaward) from about 200 m at its western boundary in central Montana to a maximum thickness of more than 300 m near the Montana-North Dakota border. Eastward in the Dakotas, the Gammon Shale thins to a feather edge and is considered the lowermost member of the Pierre Shale (Schultz *et al.*, 1980).

Gautier (1981a) determined that the Gammon Shale in southwestern North Dakota consists mostly of silt-size (60–70%) and clay-size (30–40%) particles. Randomly interstratified, mixed-layer illite/smectite, discrete illite and mica, kaolinite, and chlorite of undetermined composition constitute the clay suite. The mixed-layer clay is a dioctahedral, aluminous variety, typical of the Pierre Shale in the northern Great Plains (Schultz, 1978). The illite/smectite consists of about 60% smectite-like layers. The smectite layers comprise approximately equal amounts of montmorillonite-like and beidellite-like layers, as indicated by the Greene-Kelly lithium test (Greene-Kelly, 1955). The silt-size fraction is composed of quartz, feldspars, rock fragments, transported dolomite grains, and various detrital phyllosilicates.

FIELD PROCEDURE

The Petroleum Corporation of America (formerly Joseph J. C. Paine and Associates) Aasen No. 1-9 well (sec. 9, T129N, R106W, Little Missouri field, Bowman County, North Dakota) was completed in the thickest part of the Gammon Shale (Figures 1, 2). The well was drilled with KCl-bearing, water-based mud. Economic flows of gas were achieved by perforating and hydraulically fracturing part of the Gammon Shale between depths of 376 and 403 m (Figure 3). Stimulation also utilized water-based fluids containing KCl. A 27-m thick zone, hereafter referred to as the producing zone, was selected on the basis of geophysical log data derived from sonic, neutron, and density tools. The method of log interpretation used in selecting the producing zone was developed for the Bowdoin gas field in north-central Montana and has been described by Nydegger *et al.* (1981). The interval-transit time derived from the sonic log was overlaid on the porosity curve from the compensated neutron log and used as a gas indicator. The sonic porosity log was overlaid on the density porosity log and used as an index of reservoir quality. This second overlay was used as an indicator of clay content. The common crossover of these two overlays was interpreted as indicative of a potentially gas-bearing reservoir rock (Figure 3).

Cores were recovered between 345 and 372 m and between 386 and 393 m in the Aasen 1-9 well, and thus included materials from both the producing and unstimulated zones, respectively (Figure 3). The zone which was bypassed as non-prospective for gas production and thus not stimulated is hereafter referred to as the nonproducing zone.

The cores were sealed and transported to the U.S. Geological Survey Core Library in Arvada, Colorado, where they were preserved in a freezer to prevent dehydration. Visual inspection of frozen and slabbed cores

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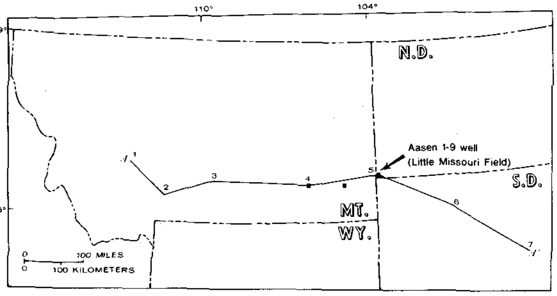

Figure 2. Index map showing location of Aasen No. 1-9 well and cross section (A–A) shown in Figure 1.

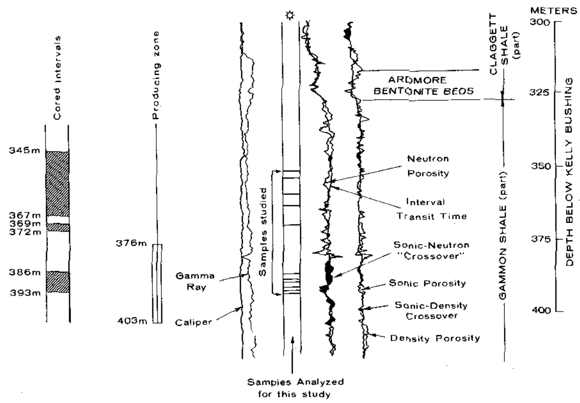

Figure 3. Geophysical log response, cored intervals, perforated and fractured zone, and sample distribution for the Aasen No. 1-9 well. Intervals in which significant log crossovers, used in evaluating reservoir quality, occur are blackened.

and petrographic examination of thin sections revealed no differences between the producing and nonproducing zones with respect to lithology, bedding, or color (Gautier, 1981a), although differences were noted in the basal spacings (air-dried) and peak intensities (after glycolation) of mixed-layer clays.

LABORATORY PROCEDURE

Eleven samples were selected from the Aasen 1-9 cores; six were taken from the producing zone and five were selected from the nonproducing zone (Figure 3). Each sample consisted of rock from a continuous channel along a 0.3 to 0.5-m interval of core. Channel samples were used so that minor lithologic and chemical inhomogeneities would be averaged. The samples were gently crushed, homogenized, and subdivided into several portions for analysis.

One portion of each sample was sieved to remove aggregates larger than 177 μm (80 mesh) and washed several times with a methanol solution to remove soluble salts. Exchangeable cations were replaced with ammonium at pH 7 according to the method of Jackson (1974, p. 269). The resulting supernatant solution containing extracted cations was brought to known volume, acidified to pH 2, and analyzed for Ca, Na, K, Mg, and Fe by atomic absorption in the Water Quality Laboratory of the U.S. Geological Survey, Arvada, Colorado. The ammonium exchanged onto each sample was determined by Kjeldahl distillation.

A second portion of each sample was disaggregated and then dispersed by ultrasonic treatment. The sand-size fraction (>62 μm) was separated by wet sieving. Silt- (2–62 μm) and clay- (<2 μm) size fractions were separated by centrifugation according to Stoke's Law. To identify the clay minerals, it was necessary to fractionate another portion of each sample and to subdivide the clay-size material further into <0.5-, 0.5–1-, and 1–2-μm fractions. Mineralogical determinations were made from X-ray powder diffraction (CuKα radiation) patterns of randomly oriented mounts of the total sample as well as from each of the sand, silt, and clay fractions, and of oriented aggregates from the clay subdivisions before and after various standard treatments. The abundance of minerals in each of the size fractions was determined by means of calculations from diffractogram peak height and peak-area measurements similar to those of Schultz (1964, 1978), as practiced by H. C. Starkey, P. D. Blackmon, and P. L. Hauff, U.S. Geological Survey, Federal Center, Denver, Colorado. Mineralogical data are reported as percentages but, because many factors in addition to mineral abundance may affect diffraction peak intensity, reported values are intended mainly to show relative mineral abundance and to indicate trends. Accuracy of these values is estimated at ±5%, and reproducibility is probably better than ±2%. These values for accuracy and reproducibility are somewhat better than those reported by Schultz (1964). This improvement results from the subdivision of samples into six or more size fractions. The weight percentage of each fraction was determined quantitatively, and each fraction was analyzed individually by X-ray powder diffraction. The results of these analyses were then combined in Table 1. To assure that statistical differences between sample sets were not due to operator bias, samples were given coded identification numbers and submitted at random to the analyst.

STATISTICAL ANALYSIS

Data (Table 1) from producing and nonproducing zones were analyzed in two steps. First, a two-sample t-test of means from independent samples was used to determine whether there were significant differences between the data from the two zones with regard to a particular variable. Second, a discriminant function analysis was employed to answer the following questions:

1. What combination of variables could best distinguish between the producing and nonproducing zones?

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Table 1. Univariate statistics for samples from the Aasen 1-9 well.

Variable	Mean			Standard deviation			Variance			Minimum			Maximum		
	N.	P.	A.S.	N.	P.	A.S.	N.	P.	A.S.	N.	P.	A.S.	N.	P.	A.S.
Depth (m)	—	—	—	—	—	—	—	—	—	351	388	351	372	394	394
Sand (%)	3.36	3.72	3.6	2.16	3.40	2.8	4.65	11.55	7.7	0.70	0.6	0.6	6.30	8.5	8.5
Silt (%)	65.66	67.97	66.9	2.84	2.88	3.0	8.05	8.27	8.8	62.00	62.7	62.0	69.60	71.1	71.1
Clay (%)	30.22	25.42	27.6	2.68	4.95	4.6	7.17	24.54	21.4	26.80	19.9	19.9	34.00	32.0	34.0
Sand + silt (%)	68.8	73.2	71.2	2.8	4.7	4.4	7.7	21.9	19.4	64.3	66.4	64.3	71.8	78.5	78.5
Clay (%)	31.2	26.8	28.8	2.8	4.7	4.4	7.7	21.9	19.4	28.2	21.5	21.5	35.7	33.6	35.7
1–2 μm (%)	6.0	5.1	5.5	1.1	1.2	1.2	1.3	1.4	1.4	4.7	3.8	3.8	7.2	6.9	7.2
0.5–1 μm (%)	6.26	5.3	5.7	0.6	0.7	0.8	0.4	0.5	0.6	5.3	4.4	4.4	6.9	6.1	6.9
<0.5 μm (%)	15.7	13.4	14.5	1.6	2.5	2.4	2.6	6.3	5.6	13.9	10.5	10.5	18.2	17.0	18.2
Dolomite (%)	8	10	9	1.5	1.2	1.8	2.3	1.4	3.4	6	9	6	10	12	12
Quartz (%)	44	45	45	3.7	4.4	4.0	13.7	19.1	15.7	41	38	38	50	50	50
Plagioclase (%)	5	5	5	0.4	1.0	0.8	0.2	1.0	0.6	5	4	4	6	6	6
KSpar. (%)	4	2.5	3	1.7	1.6	1.7	2.8	2.7	2.8	1	1	1	5	5	5
Illite (%)	15	15	15	3.3	2.6	2.8	11.0	7.0	7.9	11	11	11	20	18	20
Chlorite (%)	7	7	7	1.5	1.5	1.5	2.3	2.3	2.2	4	6	4	8	10	10
Kaolinite (%)	4	3.5	4	1.6	0.8	1.2	2.7	0.7	1.5	2	3	2	6	5	6
Mixed-layer clay (%)	12	7	9	2.1	2.2	3.4	4.5	5.0	11.6	9	5	5	14	11	14
Pyrite (%)	Tr	1.5	1	0.4	1.9	1.5	0.2	3.5	2.3	0	0	0	1	5	5
Amphibole (%)	Tr	Tr	Tr	—	—	—	—	—	—	0	0	0	1	Tr	1
CEC (meq/100 g)	15.2	11.8	13.4	2.4	1.1	2.4	5.6	1.2	5.9	11.8	10.6	10.6	17.6	13.4	17.6
Ca (meq/100 g)	8.7	10.1	9.5	1.48	2.9	2.3	0.02	0.1	0.1	6.4	6.0	6.0	10.5	14.0	14.0
Na (meq/100 g)	8.6	7.3	7.9	2.0	1.2	1.7	0.04	0.01	0.0	6.4	5.9	5.9	11.3	8.9	11.3
Mg (meq/100 g)	2.8	3.0	2.9	1.1	0.9	0.9	0.01	0.0	0.0	1.2	2.2	1.2	4.0	4.5	4.5
K (meq/100 g)	0.6	0.5	0.5	0.35	0.2	0.3	0.00	0.0	0.0	0.4	0.3	0.3	1.2	0.7	1.2
Ca/Na ratio	1.0	1.4	1.2	0.1	0.3	0.3	2.2	0.09	0.08	0.9	0.8	0.8	0.3	1.6	1.6
Total cations (meq/100 g)	20.8	20.8	20.8	4.0	4.7	4.2	0.2	0.2	0.2	15.5	16.0	15.5	26.5	26.6	26.6

N. = Nonproducing zone; P. = Producing zone; A.S. = All Samples; Tr = Trace; — = No Value.

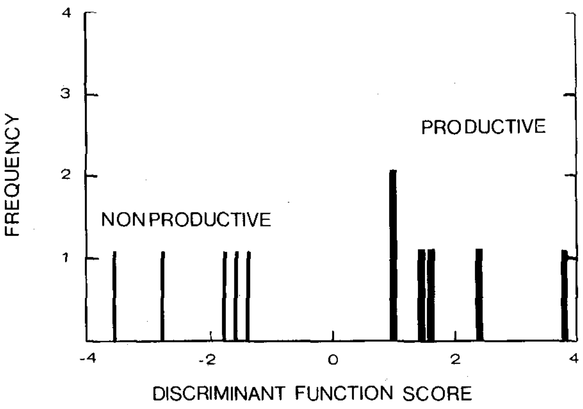

Figure 4. Frequency distribution of discriminant function scores for samples from the producing (2) and nonproducing (1) intervals of the Aasen 1-9 well.

2. How important is each variable in statistically separating samples from producing and nonproducing zones?
3. How successful is the combination of variables at classifying the samples into the appropriate producing or nonproducing group?

The discriminant analysis developed by Fisher (1936) is a classification technique that differentiates populations by means of independent variables. For details of the mathematical treatment of the method the reader is referred to any of several standard references, e.g., Krumbein and Graybill (1965), Wilks (1962), Miller and Kahn (1962). The computer application used in this study (Nie *et al.*, 1975) performs a step-wise regression to determine which variables to include in the discriminant function. Variables are selected to maximize the value of Rao's V, a generalized measure of statistical separation (Nie *et al.*, 1975). Variables are included or excluded from the analysis based on the amount of discrimination they contribute. The discriminant analysis then produces a function which combines the included variables to generate a score that is used to classify the sample.

RESULTS

Cation-exchange capacities (CEC), exchangeable cations, textural data, mineral abundances, and statistical information for the eleven samples and the two sample groups are summarized in Tables 1 and 2. Results from the t-tests (Table 2) indicate that, at the 0.05 level of confidence, samples from the producing zone contain significantly more dolomite and have a higher ratio of extracted Ca to Na than do samples from the nonproducing zone. Also, the producing zone contains significantly less mixed-layer clay and has a smaller percentage of material in the 0.5–1-μm size fraction and a lower CEC than the nonproducing zone.

The discriminant function analysis yielded similar results. The stepwise regression selected four variables as most important for discriminating the producing and nonproducing zones on the basis of the eleven samples. The four variables and their standardized coefficients are listed below:

Variable	Identifier	Standardized discriminant function coefficient
Mixed-layer clay	A	−1.078
1–2 μm material (wt. %)	B	0.862
Dolomite (wt. %)	C	0.794
Ca/Na (wt. ratio)	D	0.500

The following unstandardized function was generated: Discriminant score = −0.494A + 0.741B + 0.595C + 2.077D − 7.448. The score reflects probability of membership of a given sample in one group or another. In this case, a high score indicates a greater probability of membership in the sample group from the producing zone. The absolute values of the coefficients from the standardized equation give the relative weight or "importance" of that variable in the discrimination. The unstandardized coefficients and the constant represent an equation in which the raw values for each variable can be inserted to calculate a classification score for that variable.

The discriminant scores produced a mean of 1.875 for the group of samples from the producing zone and of −2.251 for the group of samples from the nonproducing zone (Figure 4). The sample classification resulting from the discriminant function scores produced no classification errors (Figure 4), indicating no statistical overlap among the samples along the dimension of the discrim-

Table 2. Results of t-test between samples from the producing and nonproducing zones of the Aasen 1-9 well.

Variable	Nonproducing zone	Producing zone	t	Degrees of freedom	Probability
0.5–1.0 μm (%)	6.26	5.32	2.38	9.00	0.041
Dolomite (%)	7.00	10.17	3.09	7.48	0.017
Mixed-layer clay (%)	12.00	6.83	3.93	8.79	0.003
CEC	15.16	11.82	2.91	5.47	0.033
Ca/Na ratio	1.03	1.37	−2.47	7.60	0.039

inant score. The discriminant function resulted in an Eigen value of 5.16 and a canonical correlation of 0.915 between the discriminant function and the grouping.

INTERPRETATION

Statistical analyses indicate that more than 80% of the variance between the samples from the producing and nonproducing zones can be accounted for with a discriminant function stated in terms of the mixed-layer clay content, the weight percentage of part of the clay-size fraction, the abundance of dolomite, and the ratio of calcium to sodium cations extracted during ion exchange (Table 1; Figure 4). This statistical relationship suggests that these four variables are primarily responsible for the difference in geophysical log characteristics used in selecting zones to be stimulated for gas production at the Little Missouri field.

Like most of the Pierre Shale in the northern Great Plains, depth-related burial diagenesis has had little effect on mixed-layer clays of the Gammon Shale (Schultz, 1978). This lack of alteration is probably due to the relatively low temperatures experienced by the sediments during their burial (Gautier, 1981a). Consequently, differences in mixed-layer clay content between producing and nonproducing zones are probably due to variation in original sediment composition. Similarly, inasmuch as most dolomite in the Gammon and equivalent rocks is evidently detrital (Gautier, 1981a, 1981b), variation in dolomite content may also represent original sediment composition rather than diagenetic effects. A similar relationship between detrital dolomite and mixed-layer clay was noted by Schultz *et al.* (1980) in the Pierre Shale as a whole. The larger Ca/Na ratios for the extracted, exchangeable cations from clays of the producing zone are consistent with the greater dolomite content of that zone and may reflect slightly higher Ca and Mg ion activities caused by partial equilibration of interstitial waters with detrital dolomite and selective adsorption of Ca^{2+} by the mixed-layer clay.

Compositional differences between the producing and nonproducing sample groups affect the physical properties and log characteristics in predictable ways. The greater clay-size fraction, mixed-layer clay content, and lower Ca/Na ratio of exchangeable cations in samples from the nonproducing zone are probably responsible for the larger CEC and greater irreducible water content observed in the nonproducing zone (Gautier, 1981a). This higher water content causes crossplots of sonic porosity and density porosity logs (Figure 4) to respond as though the zone was one of lower reservoir quality. In addition, the greater mixed-layer clay content and Na-rich exchangeable cations suggest that clays of the nonproducing zone will hydrate and dissociate to a greater extent in the presence of water-based fluids introduced during drilling and well-completion than will clays of the producing zone. Such hydration and dissociation of clays may effectively reduce the apparent gas effect measured by the neutron porosity-interval transit-time crossplot (Figure 4). Thus, the neutron porosity-interval transit-time crossplot may provide information about clay hydration state as well as about gas effect.

In conclusion, the physical characteristics of the shallow, mudstone gas reservoirs are controlled by detrital, mixed-layer clays as well as by grain size distribution and exchangeable cations. Logs used in predicting gas content and reservoir quality at Little Missouri field evidently respond to subtle differences in grain size, mineralogy, and clay hydration state. The apparent great sensitivity of these logging tools demonstrates their usefulness in predicting reservoir properties in clay-rich rocks. This investigation illustrates, however, the need for mineralogic and petrologic studies designed to specify the physical basis of log response in low-permeability, clay-dominated reservoirs. By successfully combining log interpretation and clay petrology, the effectiveness of logs as predictive tools is enhanced.

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Резюме—Верхний меловый Гаммонский Сланец использовался как источниковый пласт так и порода-резервуар для аккумуляции натурального газа. Продукционные и непродукционные зоны в Гаммонском Сланце различаются геофизической интерпретацией разрезов буровой скважины. Для получения физической основы характеристик разрезов проводились минералогические, катионообменные, текстуральные и химические анализы на образцах из продукционных и непродукционных частей скважины в Гаммонском Сланце юго-западной области Северной Дакоты. Статистическая обработка (2 образца, t-тест и анализ при помощи функции дискриминации) лабораторных данных показала, что продукционные и непродукционные зоны отличаются по: содержанию переслаивающихся глин (7 против 12%), весовой пропорции глиновой фракции размером 0,5 до 1,0 μм (5,3 против 6,3%), отношению ионов Ca^{2+} к Na^{+}, выделенных во время обмена ионов (1,4 против 1,0), и обилию доломита (10 против 8%). Каротаж, повидимому, регистрирует тонкие различия в составе и текстуре, что, вероятно, отражает изменения в начальных детритальных компонентах Гаммонских осадков. Успешное сочетание интерпретации каротажа и петрологии глин помагает понять физические основы данных из разрезов в породах, обогащенных глинами, и увеличивает эффективность разрезов как подсказывающих геологических инструментов. [E.C.]

Resümee—Der Gammon Schieferton aus der Oberkreide hat als Muttergestein und als Speichergestein für Anreicherungen von natürlichem Gas gedient. Gas-liefernde und Gas-nichtliefernde Zonen im Gammon Schieferton werden aufgrund von Geophysikalischen Log-Interpretationen unterschieden. Um die geophysikalische Grundlage für die Log-Aufnahmen zu bestimmen, wurden mineralogische, Ionenaustausch-, Textur-, und chemische Untersuchungen an Bohrkernen aus dem Gasliefernden und -nichtliefernden Gammon Schieferton von SW North Dakota durchgeführt. Statistische Auswertungen (Zwei-Proben-t-Test und diskriminierende Funktionsanalyse) der Labordaten deuten darauf hin, daß die Gas-liefernden und -nichtliefernden Zonen sich erheblich unterscheiden und zwar im Gehalt an Wechsellagerungen (7 vs. 12%), im Gewichtanteil der Tonfraktion (0,5–1,0 μm) (5,3 vs. 6,3%), im Ca^{2+} zu Na^{+}-Verhältnis, das bei Ionenaustausch extrahiert wurde (1,4 vs. 1,0), und im Dolomitgehalt (10 vs. 8%). Die geophysikalischen Logs registrieren offensichtlich feine Unterschiede in der Zusammensetzung und der Textur, die wahrscheinlich Schwankungen in den ursprünglichen detritischen Komponenten des Gammon Sedimentes widerspiegeln. Eine erfolgreiche Kombination der Log-Interpretation und der Tonpetrologie ist eine Hilfe beim Verstehen der physikalischen Grundlage der Log-Aufnahmen in Ton-reichen Gesteinen und vergrößert die Effektivität von Logs bei geologischen Vorhersagen. [U.W.]

Résumé—Le shale Gammon du Haut Crétacé a servi à la fois de lit source et de roche réservoir pour des accumulations de gaz naturel. Les zones produisant du gaz et celles qui sont non-productives sont differenciées sur la base de d'interprétations d'analyses géophysiques. Pour déterminer la base physique des résultats de ces analyses, des analyses minéralogiques, d'échange de cations, texturales, et chimiques ont été faites sur des échantillons de carottes provenant à la fois des portions prôduisant du gaz et de celles qui n'en produisent pas d'un puits dans le shale Gammon du sud ouest du Dakota du Nord. Une analyse statistique (test t à 2 echantillons et analyse par étude du discriminant) des données de laboratoire indique que les zones productives et non-productives sont significativement différentes en ce qui concerne le contenu en argile de couche melangée (7 vs. 12%), la proportion en poids (5,3 vs. 6,3%) de la fraction de taille de l'argile (0,5–1,0 μm), la proportion de Ca^{2+} vis à vis de Na^{+} extraite pendant l'échange d'ion (1,4 vs. 1,0), et l'abondance de dolomite (10 vs. 8%). Les analyses géophysiques enregistrent apparemment des différences subtiles en composition et en texture qui reflètent probablement des variations dans les constituants détritiques originaux des sédiments Gammon. La succès de la combinaison d'interprétations d'analyses géophysiques et de la pétrologie de l'argile aide la compréhension de la base physique des résultats des analyses géophysiques dans les roches riches en argile et augmente l'efficacité des analyses géophysiques en tant qu'outils géologiques de prédiction. [D.J.]