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PLUG GAMMA RAY: KEY TO FORMATION EVALUATION

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Abstract

Core and log data are routinely used for formation evaluation. The scale differences of the two measurements are well understood. Nevertheless, core data, either conventional or sidewall samples, are used to calibrate interpretation models or provide critical model parameters.

We have found that plug gamma-ray measurements greatly facilitate incorporating core data with continuous log data. Plug gamma-ray measurements allow the analyst to derive depth-independent core-log correlations and facilitates the extrapolation of the core data to uncored intervals. We have obtained consistently better correlations between plug gamma-ray- and core-plug-derived petrophysical properties, than between wireline gamma ray and core plug petrophysical properties. Once a functional relationship is established between gamma-ray response and a specific petrophysical property, the depth-dependent property can be inferred by using the wireline gamma-ray log as an independent variable.

Gamma-ray measurements on core plugs are easy to make and should be relatively inexpensive. The measurement addresses two common problems: (1) it minimizes the need for depth alignment between core and log data; and (2) it eliminates the uncertainty in the core-to-log correlations associated with different scales. The plug gamma-ray data can be used to improve both the qualitative and quantitative gamma-ray log driven interpretations. The applications of the plug gamma-ray data are illustrated with numerous examples, including grain size and grain density determinations, gamma-ray permeability cutoff determinations, and shale volume and CEC determination.

Introduction

When the entire reservoir interval is cored, core analysis can provide log-like continuous data, which when integrated with wireline log data on a foot-by-foot basis, results in improved reserve and productivity estimates. However, when only sidewall samples (rotary or percussion) are available, it may be difficult to combine the petrophysical properties derived from the samples with the continuous log data. Sometimes, the core-derived properties are correlated to the wireline gamma-ray response and then extrapolated to uncored or unsampled intervals using the wireline gamma-ray data. However, the functional relationship between wireline gamma ray and the core petrophysical properties may be masked by uncertainties in the core plug depth and/or the natural variability that exists between the small plug and the formation sampled by the wireline log.

Borehole gamma-ray data are used in both qualitative and quantitative log interpretation. From the change in gamma-ray response with depth, geologists may infer the depositional environment. There is an implied or assumed relationship between grain size or change in grain size ("fining upwards") and the wireline log gamma-ray “shape”. Generally, no attempt is made to quantitatively calibrate the log gamma ray to grain size. However, we have found that for some depositional environments, core-plug-derived grain size and gamma-ray data can be used to infer gamma-ray cutoffs for differentiating fine-grained sands from silty-shaly sands.

Log analysts may use the gamma ray to infer reservoir quality or as an independent variable for computing V_{sh} or V_{clay} in shaly-sand evaluations. To infer petrophysical properties from the gamma-ray response, it is necessary to develop models. Typically, these models use gamma-ray response, Gr, as the independent variable; i.e., F= F(Gr). For example, the function F might be $V_{clay} = V_{clay}(Gr)$ or $CEC = CEC(Gr)$.

Whether the function is a simple linear equation or a more complex function (Katahara, 1995), a well-defined relationship must exist between the gamma-ray response and the petrophysical property in order to predict the desired property with the wireline gamma-ray data. Often, universal relationships are sought to decrease the reliance on core; however, in practice, few such relationships exist. For example, mineral substitution can drastically alter the gamma-ray response, as well as the petrophysical property of interest. Furthermore, gamma-ray activity may itself be anomalous due to substitution of U, Th or K. Thus, it is best to seek formation or well specific correlations between specific petrophysical properties and the gamma-ray response. As we will show with examples, formation-specific correlations are best derived from complementary gamma-ray measurements on sidewall or conventional core plugs.

Generally, petrophysicists build wireline data-driven models for key core petrophysical properties by correlating core analysis data and borehole gamma-ray data. Laboratory measurements on core plugs (i.e., grain density, permeability, electrical properties, ...) are correlated to wireline gamma-ray responses, even though it is generally recognized that there exists a large disparity between the volume sampled by a wireline gamma-ray tool and a 1-inch core plug (Enderlin, 1991). The ratio of the volumes investigated by a gamma-ray tool and a 1-inch core plug is typically of order 1,000:1. As most rocks are heterogeneous on scales of 1-inch and greater, it is unlikely that the average value of the log-based gamma ray is comparable to the petrophysical property measured on a 1-inch diameter core plug.

In addition to the scale difference problem, large uncertainties can arise due to core-log depth alignment problems. It is common to align core and logs by correlating continuous core gamma-ray measurements and wireline gamma-ray log data. It is also possible to align core and logs by comparing discrete core porosity measurements and wireline log porosity data. Although great care can be used to align core and log data, it is generally not possible to guarantee alignment much better than 6 inches (15 cm). It may be possible to achieve better alignment by matching small-scale features observed on cores and image log data. However, there is not always a simple one-to-one correspondence between visual features in core and acoustical and/or electrical features evident on borehole image logs. Thus, both depth alignment and sample representativeness limit our ability to extract empirical relationships between wireline gamma-ray and core-derived petrophysical properties.

Instrumentation

To make gamma-ray measurements, we adapted equipment originally assembled to make gamma-ray measurements on drill cuttings (Georgi et al., 1992). This instrumentation consisted of a PC-based 1024-channel spectrum analyzer connected to a 3-inch diameter by 3-inch long NaI detector. While this system is capable of making spectral measurements, the measurements reported here were obtained by summing the spectra to reduce the acquisition time. Gamma-ray measurements on small samples are difficult because count rates are proportional to sample mass, and thus, long counting times may be required to achieve meaningful results. Initial attempts to measuring gamma rays using standard core gamma-ray equipment were found to be totally unsatisfactory due to the poor geometry. The standard core equipment utilized a 4- by 4-inch by 7-inch long NaI detector that proved much too large for measuring these small samples. The background counts using this detector were approximately ten times the counts provided by the 200 API calibration plug.

The well detector chosen for these measurements has a significant advantage over the larger detector used in conventional core gamma equipment because the sample is placed inside the crystal. With this geometry, almost all of the emitted gamma rays interact with the crystal and are counted. All gamma-ray measurements reported in this paper were made with this special gamma well detector (Fig. 1). The detector was shielded with 2 inches of virgin lead containing very little uranium contamination. An additional 2 inches of lead shielding were added to lower the background counts, which permitted us to decrease the total counting time. Typically, the counting times ranged from 10 to 30 minutes per sample. Some measurements reported here were made with an automated system that improved sample throughput. With the automated sample changer, 18 samples could be measured before reloading the changer.

Calibration

If plug gamma-ray data are to be used to calibrate borehole gamma-ray data interpretation or to develop petrophysical models, it is necessary that the plug gamma data are calibrated in a manner traceable to standard wireline gamma-ray calibration standards. The equipment was spectrally calibrated using a cesium 137 source and the span set to measure energy levels up to 3.2 MeV. To calibrate the measurements, we drilled 1-inch diameter samples from a standard KUTh-mix gamma-ray calibration billet. Plugs were drilled from the standard calibration billet (200-gamma API, GAPI) routinely used to calibrate whole-core gamma-ray measurement equipment. In addition, a zero GAPI calibration point was collected with no sample in the well detector. Calibration results are shown in Fig. 2. The zero and 200 GAPI data points (Fig. 2, “ ”) were used to determine the linear scaling for converting counts to GAPI. Linearity checks were made by inserting 200 GAPI blanks of 0.25, 0.5 and 0.75, the weight of the 200 GAPI plug (also shown in Fig. 2, “ ”). With the automated system, each suite of 18 samples included a background and 200 GAPI check. Finally, an independent check of the calibration was made by comparing the gamma well results to the wireline gamma-ray value for a plug drilled from a thick homogeneous shale (~78 GAPI).

Comparison to Wireline Gamma Ray

The plug gamma-ray data compares well to the wireline gamma-ray data. Differences appear to be related to measurement scale differences and averaging associated with the wireline measurements. Shown in Fig. 3 are comparisons of wireline and plug gamma-ray measurements. The plug gamma-ray data generally exhibit much greater variance than do the wireline measurements. This is consistent with the difference in scale of the two measurements. The plug gamma-ray measurement is generally made on a 1.5-inch long, 1-inch diameter sample (~1.2 in.^{3} or ~20 cm^3) weighing about 1.4 oz (~40 gm), while the wireline gamma-ray measurement is influenced by approximately 4,000 in.^{3} (65,500 cm^3) of formation (~288 lb or ~131 kg). Except for minor mass-related attenuation the gamma-ray measurement is simply a volumetric average of the different gamma-ray activities in the sensitive volume and thus, extremes are merely averaged out by the wireline detectors.

Examples

Geological Applications

Often, geologic inferences are made from wireline gamma-ray data. We refer to “fining upwards” and “coarsening” sequences based on the shape of the gamma-ray log (Van

Wagoner et al., 1990). Generally, an increase in gamma ray is associated with a grain size decrease and a clay content increase. Associated with the clays are radioactive elements and minerals that cause the gamma-ray values to increase. Fundamental inferences are made based on the gamma-ray values, assuming that low gamma-ray activity is associated with reservoir-quality sands, and high gamma-ray activity is associated with low-quality, shaley sands that may not be productive. Plug gamma-ray data versus the mean grain size from particle size analysis are plotted in Fig. 4. There is a clear demarcation at 40 GAPI between fine-grained sands (mean grain size > 0.125 mm) and very fine-grained silty-sands (grain size < 0.088 mm).

Often it is desirable to determine the percent sand, silt, and clay to better predict permeability, propensity for formation damage, and to design the completion. Shown in Fig. 5A is the percent sand from laser particle size analysis (LPSA) of percussion side-wall samples versus the wireline gamma-ray values. The correlation is not particularly good (r^2 ~0.28), and the range of wireline gamma-ray values is small (60 to 93 GAPI). When the LPSA data are correlated with the plug gamma-ray data the correlation coefficient doubles (0.28 to 0.57). The linear relationship derived from this correlation can now be used to predict the percent sand from the wireline gamma-ray data. However, it is not recommended that this approach be used if the formation is finely laminated because the average gamma-ray value would not be representative of either the thin sand lenses or the shale breaks.

In the Fig. 6 example, the plug gamma-ray data are used to derive linear relationships for predicting the percent silt and clay. When the LPSA data are correlated with the wireline gamma-ray data, the correlations are not significantly different from zero (e.g., r^2 for silt and clay are 0.1 and 0.28, respectively). However, when correlated with the plug gamma-ray data, the correlation coefficient essentially doubles (e.g., r^2 for silt and clay are 0.49 and 0.43, respectively). The correlation coefficient being significantly less than 1.0 indicates that gamma-ray variations cannot completely explain the variations in grain size. Further, it should be noted that the correlations for percent sand (Fig. 5b), silt and clay (Fig. 6b) are not independent as they are all derived from the same plug gamma-ray data.

We expect permeability to decrease as the degree of shaliness increases and generally, gamma-ray activity is positively correlated with the degree of shaliness (Heslop, 1972). To establish a gamma-ray cutoff value, plug permeabilities are crossplotted against the plug gamma-ray data (Fig. 7). In this case, permeability cannot be directly predicted from the gamma-ray values. However, the gamma-ray data clearly indicate that permeability decreases to unacceptably low values when the gamma-ray values exceed 60 GAPI. It must be stressed that such relationships are not universal. In a second example (Fig. 8) from a California diatomite, reservoir permeability decreases as gamma-ray activity decreases. As the gamma ray decreases, the diatomite becomes purer and the clay and silt content decreases. The silt component is to a large degree responsible for the permeability in these diatomites.

Petrophysical Applications

Borehole log data are comprised of physical measurements. In general, these measurements are not direct measures of the properties of interest. Reservoir geologists and engineers are not interested in the resistivity of the formations per se; they need to know the fluid saturations. Some log measurements can be used directly in calculations (e.g., the integrated bulk density can be used to compute the weight of the overburden), but most require additional ancillary information before the desired reservoir property can be computed (e.g. grain density is required to compute porosity from wireline bulk density measurements). In the examples shown in Fig. 9, the plug gamma-ray data were used to explore the relationship between gamma-ray activity and the degree of dolomitization in the sands. The original comparison of grain densities and wireline gamma-ray data revealed no trend, even though one was suspected. When the data were replotted versus the measured plug gamma-ray data, the expected trend was observed. The relationship between gamma ray and grain density can now be used to interpret the wireline bulk density data. By using the derived relationship, uncertainty in the wireline density porosities are reduced by 10% bulk volume.

Several commonly used resistivity interpretation models require values for the volume percent clay. Generally, petrophysicists derive the required V_{shale} or V_{clay} data from wireline gamma-ray data. In this example, we used FTIR mineralogy data (Harville and Freeman, 1988) and plug gamma-ray data to derive a formation-specific relationship between the gamma ray and clay content. In Fig. 10, the plug and continuous-core gamma-ray data are plotted versus depth. There is no apparent correlation of CEC and continuous gamma ray (Fig. 11A). However, when the CEC data from the 12-titration-based measurements are plotted versus the plug gamma-ray data (Fig. 11B), the expected positive correlation is observed. In Fig. 11C, the FTIR-based clay fraction, illite + smectite, are plotted versus the plug gamma-ray data. When there is little correlation between wireline gamma ray and measured CEC, a log analysts can do little more than use the average CEC value in the resistivity interpretation models. However, when gamma ray and CEC are measured on the same material, scale and depth-shift problems are eliminated and the underlying relationship becomes apparent; it is possible to derive CEC from the wireline gamma-ray data and proceed with the computation of saturation.

Discussion

The plug gamma-ray data are useful as an independent variable. Direct comparison of plug and wireline gamma-ray data can also be used to assess the formation heterogeneity. Differences between plug gamma-ray and wireline gamma-ray data can arise because of differences in the volume of material investigated. If the plug gamma-ray value is much greater or much smaller than the wireline gamma-ray value from the sidewall or percussion core, then the plug material is not representative of the formation that the wireline gamma-ray data represent. If the plug gamma-ray value is much greater than the gamma-ray reading from the wireline log, then the plug sample is probably from a thin shale break and is not representative of the zone. If the plug gamma-ray value is much less than the wireline gamma-ray reading, then the logged interval is most likely much more shaly than the sample indicates and not representative of the formation. On the other hand, if the gamma-ray values are similar, it is probable that the formation is relatively homogeneous and the information obtained from the core plugs is relevant to the formation on a 2-foot scale.

Summary

Plug gamma-ray data can increase the value of routine and special core measurements by facilitating the extrapolation of the sparse core data to the entire cored interval. The data can be used to calibrate geologic inferences of grain size and quantify the differentiation between reservoir sands and nonreservoir shales.

Gamma-ray measurement on core plugs eliminate uncertainties due to depth control as well as uncertainties due to differences in measurement volume. The core-plug gamma-ray measurement is a nondestructive measurement performed on a small plug taken from conventional cores that takes 10 to 20 minutes per sample. The measurement can also be performed on rotary core samples and percussion core samples. Just as the routine measurement of depth in borehole logging is essential to the use of the log data, we believe that the gamma-ray measurement on core plugs is critical to interpreting the petrophysical properties routinely measured on core plugs.

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Figures

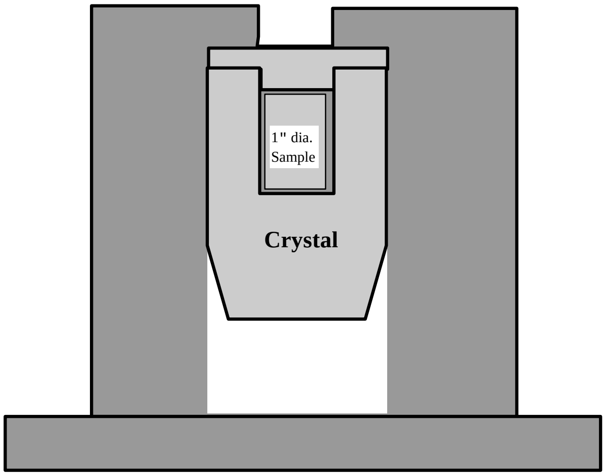


Fig. 1 Schematic of core-plug gamma measurement equipment. The gamma well detector is surrounded by lead shielding to minimize background gamma-ray radiation.

Fig. 2 Calibration of the plug gamma-ray measurements. The background count rate and a 200 GAPI count rate (“ ”) are used to set the linear conversion of gamma counts to GAPI units. The 50, 100 and 150 GAPI (“ ”) data points were obtained with proportionately smaller 200 GAPI standard material. An additional data point (plug gamma and wireline gamma-ray values) from a thick shale is also shown.

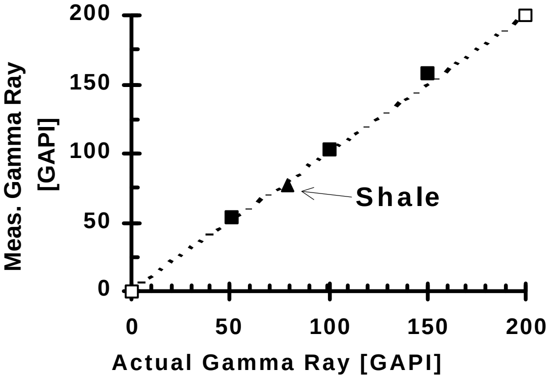
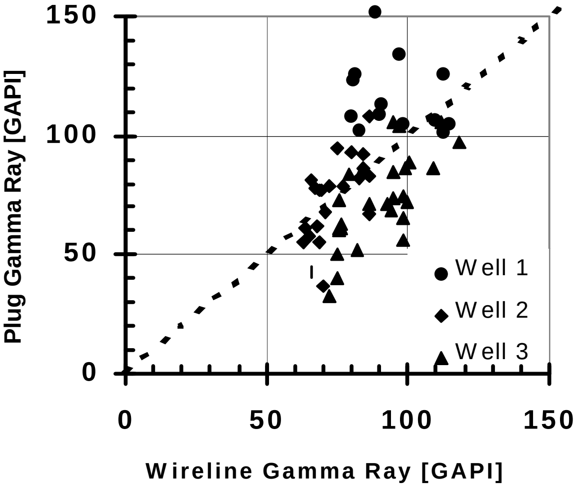


Fig. 3 Plug gamma-ray vs. wireline gamma-ray data from three wells. On average, the plug gamma-ray and wireline gamma-ray values agree. However, the plug gamma-ray data reflect more of the natural variability than the wireline data.



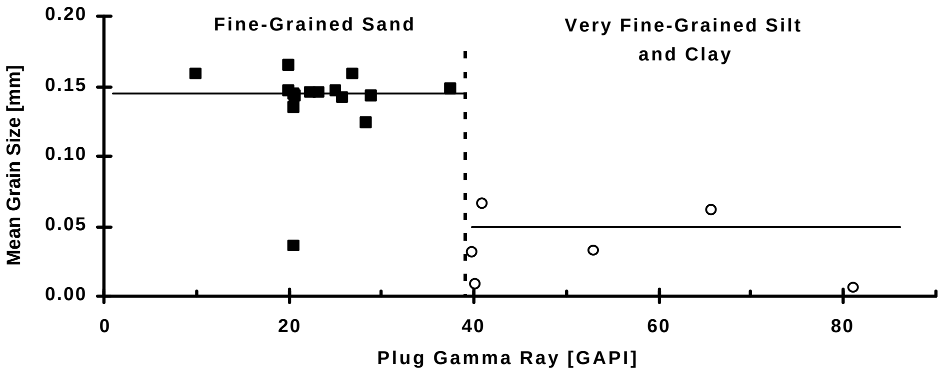


Fig. 4 Plug gamma-ray data vs. mean grain size. The transition from fine to very fine and silty sands occur at a gamma-ray value of 40 GAPI.

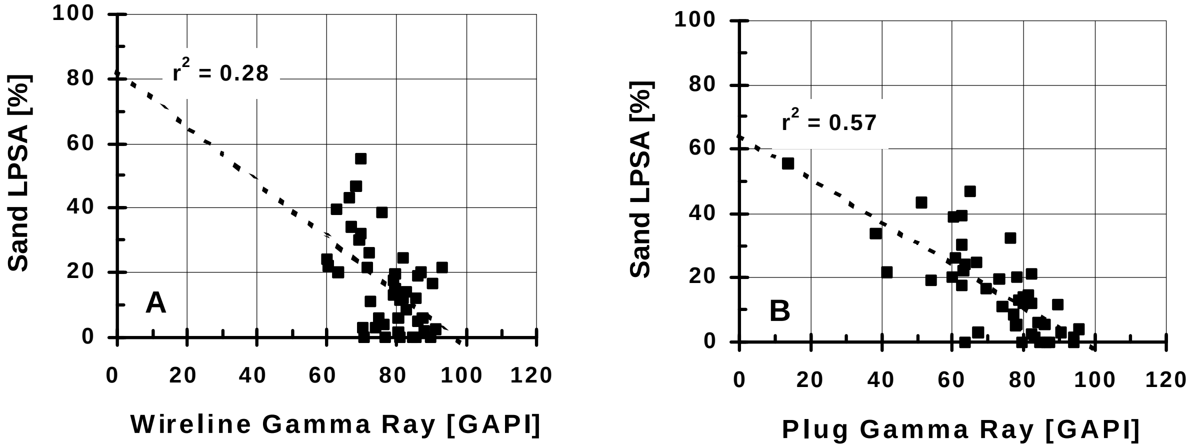


Fig. 5 Percent sand from Laser Particle Size Analysis (LPSA) versus wireline gamma ray (A) and plug gamma ray (B). The plug gamma-ray measurements were made on the same samples as the LPSA measurements. Note that the linear regression coefficient (r^2) doubled, reflecting the better definition of the relationship between the sand content and the plug gamma-ray data.

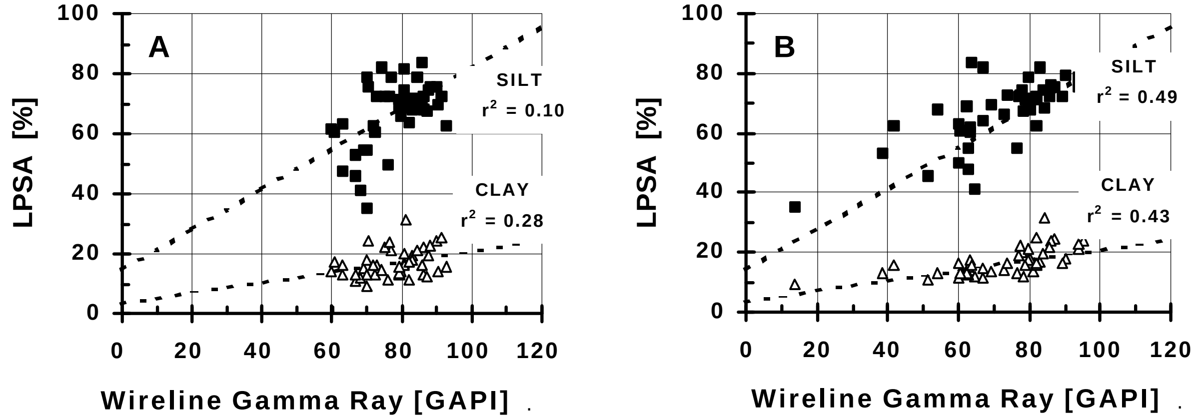


Fig. 6 Percent silt and clay from Laser Particle Size Analysis (LPSA) versus wireline gamma ray (A) and plug gamma ray (B). The plug gamma-ray measurements were made on the same samples as the LPSA measurements. As in Fig. 5, the linear regression coefficient (r^2) doubled, reflecting the better definition of the relationship between the silt and clay content and the plug gamma-ray data.

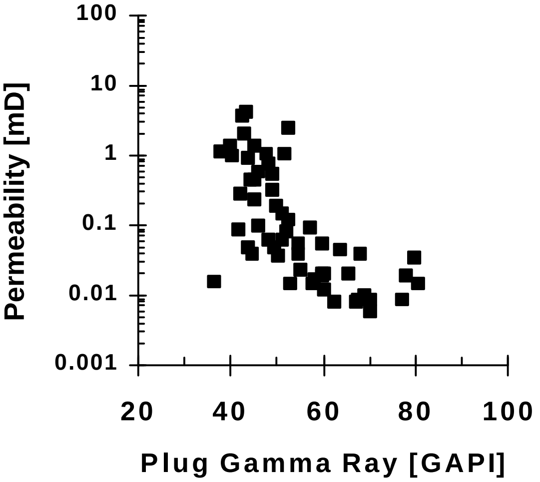


Fig. 7 Permeability versus plug gamma ray. The data indicate that reservoir permeability is unacceptably low when the gamma-ray values exceed 60 GAPI (e.g., the gamma-ray cutoff).

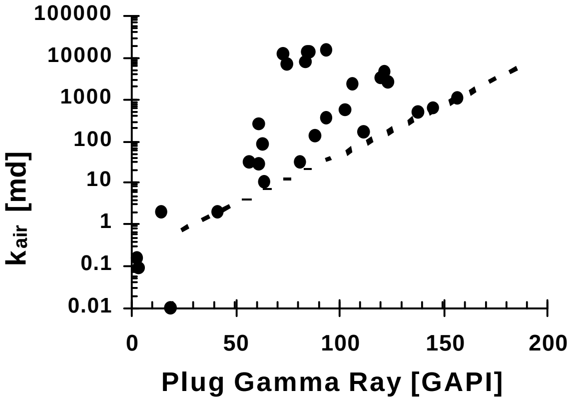


Fig. 8 Permeability versus gamma-ray activity. In the diatomites, permeability increases as the percent of clay and silt content increases. The straight line describes the empirical, expected minimum permeability versus gamma-ray behavior.

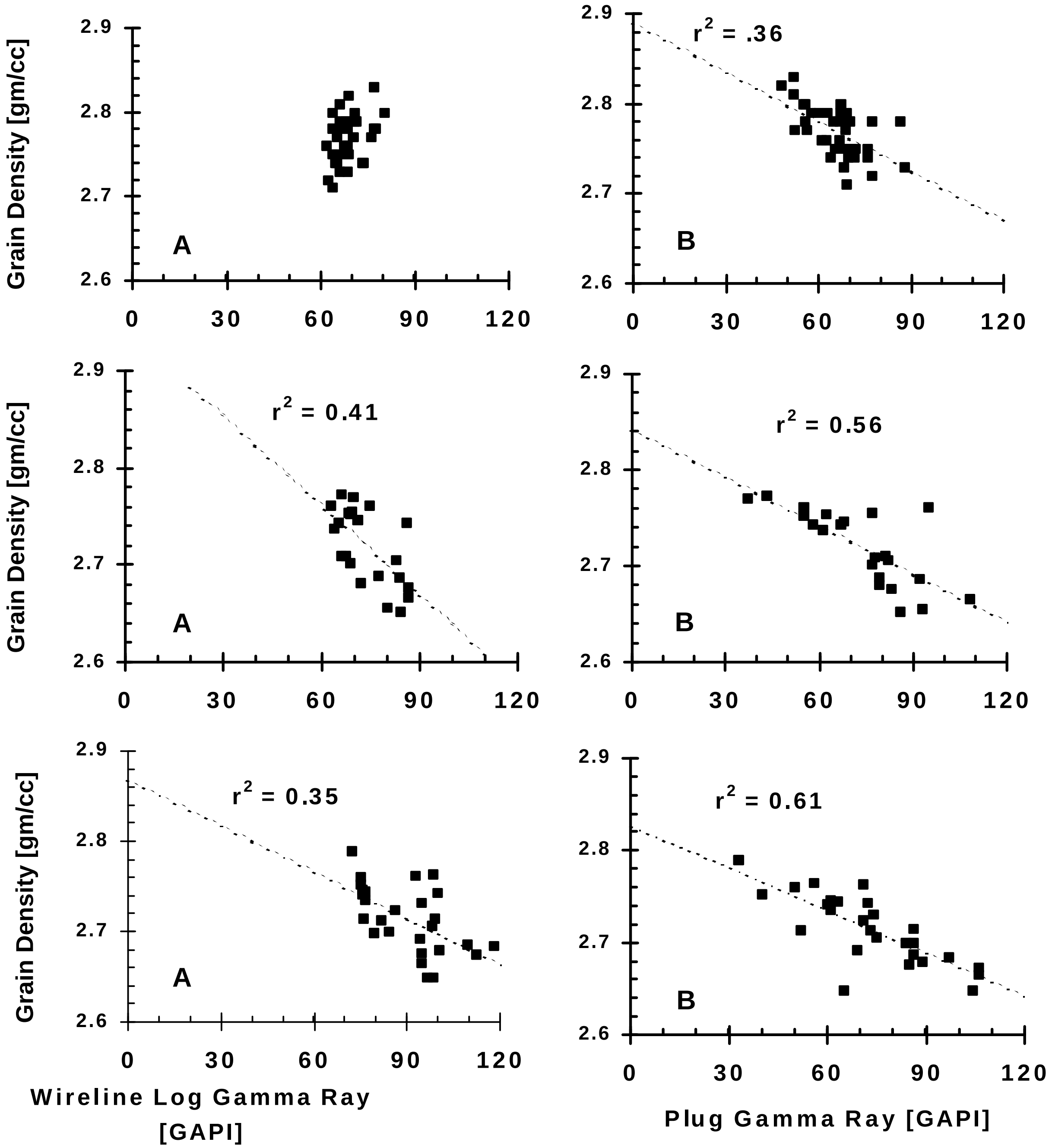


Fig. 9 Grain density versus wireline (A) and plug (B) gamma-ray data.

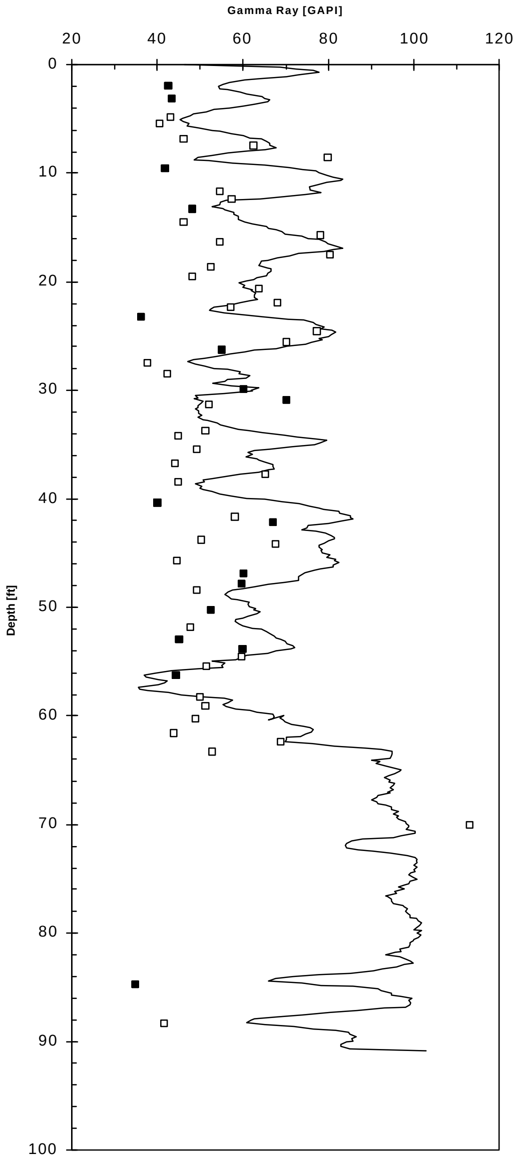


Fig. 10 Continuous core gamma-ray and discrete plug gamma-ray data versus depth. FTIR mineralogy and CEC determinations were made on the samples indicated with filled symbols ( ).

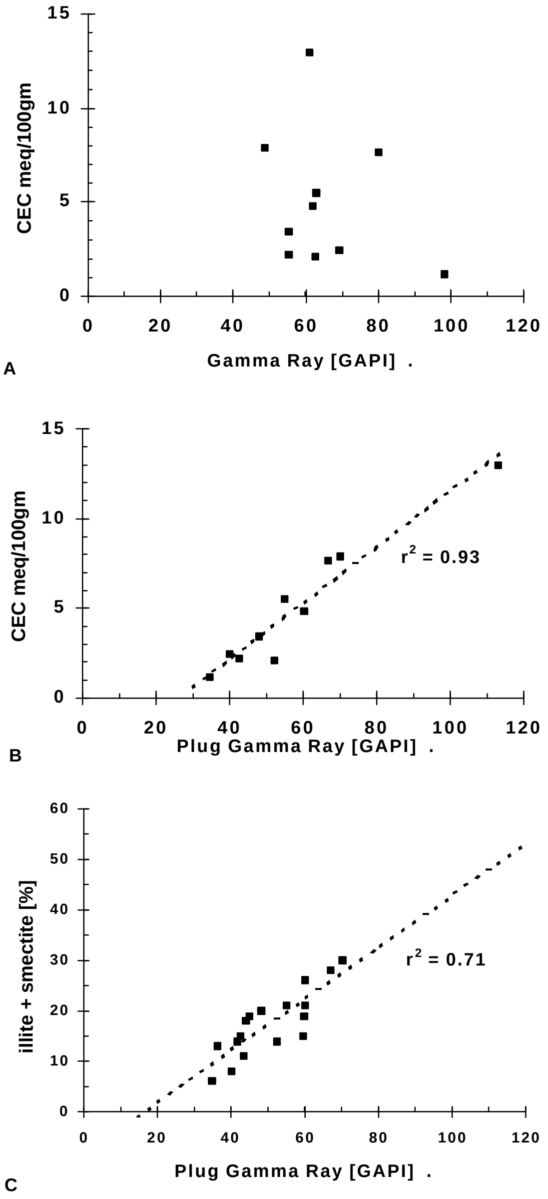


Fig. 11 CEC versus continuous core (A) and plug gamma-ray (B) data and the sum of illite and smectite clay vs. plug gamma ray (C).