Detection of Late Cretaceous and Cenozoic sequence boundaries on the Atlantic coastal plain using core log integration of magnetic susceptibility and natural gamma ray measurements at Ancora, New Jersey

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[1] Magnetic susceptibility (MS) and natural gamma ray (NGR) were measured on middle Miocene to Cenomanian coastal plain strata from a continuously cored (356 m total depth; 86% recovery) borehole at Ancora, New Jersey (Ocean Drilling Program Leg 174AX). These measurements were integrated with lithologic descriptions and a downhole NGR log. A simple linear model explains most of the variation of the downhole NGR and the core MS as a consequence of the previously described lithologic variation. Spectral NGR at selected levels shows that NGR activity is mostly due to ^{40}K associated with glauconite and mud, sediment components that also tend to give high MS values. Abrupt deviations from the average values of NGR activity and MS determined by the linear model can be interpreted as due to singular lithologies. For example, an anomalous level with high NGR but not a parallel increase in MS was found at the Navesink/Mount Laurel formation contact and can be attributed to high uranium concentration in phosphorite. Most (27 of 33) of the sequence boundaries independently identified at the Ancora site have sufficient lithological contrasts to be expressed in the NGR and/or MS logs. *INDEX TERMS:* 0915 Exploration Geophysics: Downhole methods; 1512 Geomagnetism and Paleomagnetism: Environmental magnetism; 4556 Oceanography: Physical: Sea level variations; 5109 Physical Properties of Rocks: Magnetic and electrical properties; 8105 Tectonophysics: Continental margins and sedimentary basins; *KEYWORDS:* sequence boundaries, magnetic susceptibility, natural gamma ray, linear model, sea level changes, downhole log

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1. Introduction

[2] The Ancora borehole was drilled and continuously cored at Ancora, New Jersey, as part of the New Jersey Coastal Plain Drilling Project (Ocean Drilling Project (ODP) Leg 174AX [*Miller et al.*, 1999a]) (Figure 1). The goal of Leg 174AX drilling was to study the response of passive continental margin sedimentation to sea level changes during the Late Cretaceous to early Eocene. Sedimentary sequences (i.e., unconformity-bounded units associated with baselevel lowering (definition of *Miller et al.* [1998] modified after *Mitchum* [1977]) are important geological signatures of sea-level changes [e.g., *Haq et al.*, 1988]. Because of their sensitivity to lithology, downhole and core log data can be used to help identify particular sedimentary sequence boundaries. Such boundaries are often, although not always, associated with high gamma radiation [*Sugarman et al.*, 1993]. Until now, it has not been possible to determine unequivocally the cause of high gamma radiation at sequence boundaries. Possible causes are concentrations of authigenic minerals (e.g., glauconite or phosphorite) and scavenging of radioactive isotopes at exposure surfaces.

[3] Natural gamma ray (NGR) measurements provide a powerful tool for sequence stratigraphy [e.g., *Van Wagoner et al.*, 1990]. NGR is a standard downhole logging measurement used for correlation and as an indicator of relative contents of clay and sand [e.g., *Wahl*, 1983; *Dewam*, 1983; *Serra*, 1984, 1986; *Haack et al.*, 1990; *Huenges et al.*, 1997]. NGR can also be measured on cores [e.g., *Blum et al.*, 1997; *Metzger et al.*, 1997], but to obtain results comparable to downhole logging in terms of counting statistics, it often requires very long measuring times. Our strategy at Ancora was to use detailed core NGR measurements in selected intervals to obtain a precise depth registry of the core with downhole logs. The downhole NGR can then be used more precisely for lithologic interpretation,

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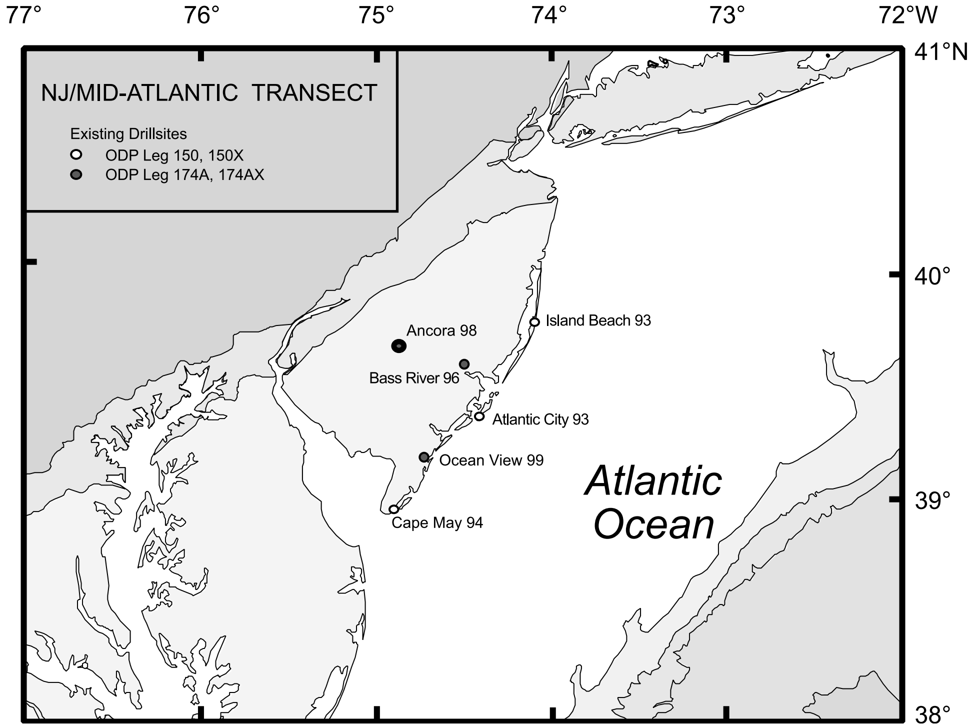


Figure 1. Location map showing the Ancora site with respect to other core location of the New Jersey coastal drilling project.

taking advantage of its good counting statistics, continuity and accurate depth scale.

[4] Magnetic susceptibility (MS) can be easily measured on cores providing lithological information independent from NGR. Variations in the MS and NGR logs have a broad correspondence to the lithology of the core, and such logs are often used to identify first-order lithologic changes. The availability of two records (NGR and MS) gives more complete information that may be used in a more quantitative approach to resolve ambiguities in discriminating lithologic changes. Finally, NGR spectrometry is used to identify the major radioisotopes at different core depths.

2. Methods

2.1. Lithostratigraphic and Sequence Stratigraphic Studies

[5] Lithostratigraphic, sequence stratigraphic, biostratigraphic, and isotopic studies were conducted on the Ancora borehole by the Leg 174AX scientific party [*Miller et al.*, 1999a]. Lithostratigraphic studies included descriptions of sedimentary textures, structures, colors, fossil content, lithologic contacts, quantification of the grain sizes, and identification of the standard New Jersey coastal plain lithostratigraphic units [*New Jersey Geological Survey*, 1990]. Quantitative cumulative percentages of the sediments were computed from samples washed for paleontological analysis (typically $\sim$1.5 m sample spacing). Each sample was dried and weighed before washing, and the dry weight was used to compute the percentages of medium-coarse quartz sand, fine quartz sand, mud (clay and silt), mica, glauconite, foraminifers, and shells. Though other components were sometimes identified (e.g., phosphorite, siderite, opaque minerals, indurated zones), they were not quantified.

[6] Sequence stratigraphic studies of the Ancora section followed standard procedures developed in drilling previous New Jersey boreholes at Island Beach, Atlantic City, and Cape May [*Miller et al.*, 1994] using principles developed in global studies by *Vail et al.* [1977], *Mitchum* [1977], *Van Wagoner et al.* [1990], and *Sugarman et al.* [1993] in New Jersey. Unconformities were identified on the basis of physical stratigraphy, including irregular contacts, reworking, bioturbation, major facies changes, and paraconformities inferred from biostratigraphic breaks. For the nonmarine and nearshore sections, primarily in the Miocene and younger section, lithofacies interpretations provide the primary means of recognizing unconformities and interpreting paleoenvironments. For the neritic (shelf) sections, primarily in the Paleogene and Upper Cretaceous, biostratigraphic and biofacies studies provide an additional means of recognizing unconformities and the primary means of interpreting paleoenvironments.

[7] Lithofacies changes within onshore New Jersey sequences generally follow repetitive transgressive-regressive patterns [*Sugarman et al.*, 1993, 1995] that consist of (1) a basal transgressive glauconite (in Cretaceous-Paleogene sections) or quartz (in Neogene sections) sand equivalent to the transgressive systems tract (TST) of *Posamentier et al.* [1988] and (2) a coarsening-upward succession of regressive medial silts and upper quartz sands equivalent to the highstand systems tracts (HST) of *Posamentier et al.* [1988]. Lowstand systems tracts (LSTs) are usually absent in the coastal plain, and the TSTs are generally thin. Because the TSTs are thin, maximum flooding surfaces (MFS) are difficult to differentiate from unconformities. Both can be

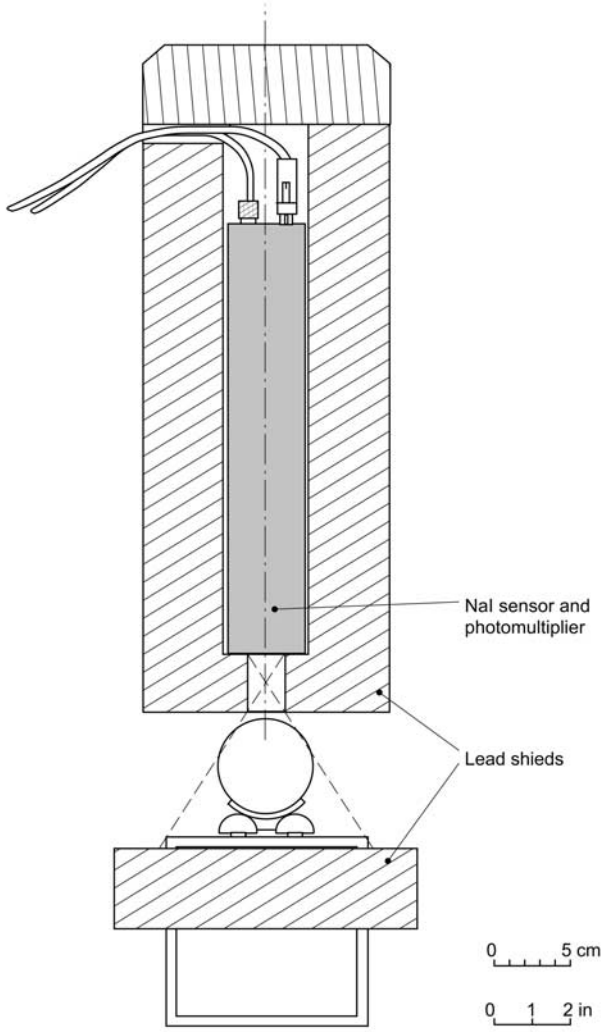


Figure 2. Sketch of the geometry of the NGR sensor used on the Rutgers MST.

marked by shell beds and gamma ray peaks [e.g., *Sugarman et al.*, 1993]. Flooding surfaces, particularly MFSs, may be differentiated from sequence boundaries by the association of erosion and rip-up clasts at the latter, lithofacies successions, and benthic foraminiferal changes. The transgressive surface (TS), marking the top of the LST, represents a change from generally regressive to transgressive facies; because LSTs are generally absent, these surfaces are generally merged with the sequence boundaries. Notable exceptions include the base of the Navesink Formation in outcrop and the borehole at Bass River [*Miller et al.*, 1999b] as well as the Ancora borehole (this study).

[8] The identification of phosphorite in coastal plain sections is pivotal for the discussions below. Phosphorite is occasionally common near sequence boundaries, generally as individual black sand-sized apatite grains [*Miller et al.*, 1999a, 1999b]. Apatite grains may also be disseminated within the uppermost part of sequences just below sequence boundaries. However, phosphorite is generally rare at most sequence boundaries, with the exception of the Navesink/Mount Laurel Formation disconformity [*Miller et al.*, 1994, 1998, 1999a, 1999b]. In outcrop, this contact is marked by a phosphorite pavement or high concentrations of apatite pellets, interpreted as a period of submarine exposure following a major eustatic lowering and subsequent rise [*Miller et al.*, 1999b]. A result of this study demonstrates that the high natural gamma ray peak in downhole logs that is often associated with the Navesink/Mount Laurel contact [*Miller et al.*, 1999a] is due to the activity of uranium-bearing phosphorite.

2.2. Core NGR

[9] Core measurements were made using a fully automated multisensor track (MST) equipped with NGR and MS sensors. The MST is designed to measure a contiguous series of core segments with each segment butted against the other to avoid data artifacts at the ends of core sections. Optical gates control the stepper motor-driven belt and prompt the operator to add additional cores.

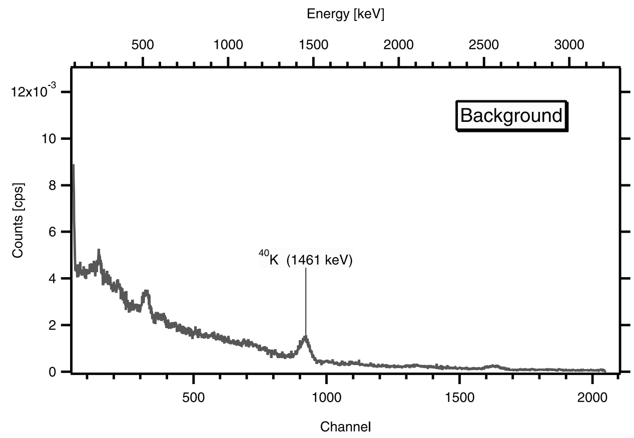
[10] The core NGR measurement system consists of a Canberra model 802, 5 $\times$ 5 cm cylindrical NaI(Ti) crystal gamma ray detector and photomultiplier tube, housed in a lead shield. Data are acquired through a PC computer using a Canberra ‘‘AccuSpec NaI Plus’’ board with 2048-channel memory, on-board analog to digital converter, and high-voltage power supply. The geometry of the gamma-ray detector is depicted in Figure 2.

[11] A mixed nuclide standard source is used for the hardware calibration of the gamma ray detector. Our standard source contains a ^{109}Cd radionuclide with an emission line at 88 keV, ^{137}Cs with an emission line at 662 keV and ^{60}Co, which has two typical emission lines at 1332 keV and 1172 keV. The gamma ray spectrum of the calibration sample illustrates these peaks (Figure 3b). In the calibration and all measurement procedures the high-voltage bias of the photomultiplier was set to 850 V. A gamma ray energy spectrum of the calibration sample is acquired and adjusted by tuning the amplifier gain and the zero of the analog to digital converter to match the two ^{60}Co peaks of the calibration sample at channels 740 and 840, the ^{137}Cs peak at channel 410, and the ^{109}Cd peak at channel 40. The actual calibration slope and the offset are calculated using a linear regression on these four peaks. The described setting allows the measurement of gamma ray energy ranging from a few keV to $\sim$3200 keV and is used for spectral acquisition [*Hoppie et al.*, 1994; *Blum at al.*, 1997]. For routine total gamma ray counting, a lower energy range up to $\sim$1600 keV is used and obtained simply by doubling the amplifier gain. No attempt was made to have an absolute calibration of the NGR detector in terms of radioisotope concentration per core volume.

[12] Zero background counts in the NGR measurements originate from a combination of cosmic radiation able to bypass the lead shield, impurities in the detector crystal, and contamination (dust) inside the shield. This background can be determined by a zero (i.e., no sample) measurement and must be subtracted from the sample total signal or spectrum before the analysis. The zero background spectrum of our instrument (Figure 3a) was obtained with a measurement time of 42 hours to collect a significant number of counts in each channel.

2.3. Total NGR Measurements

[13] A continuous record of the total NGR for the stratigraphic section is available from downhole logging. The downhole NGR log was obtained by J. Curran (New Jersey



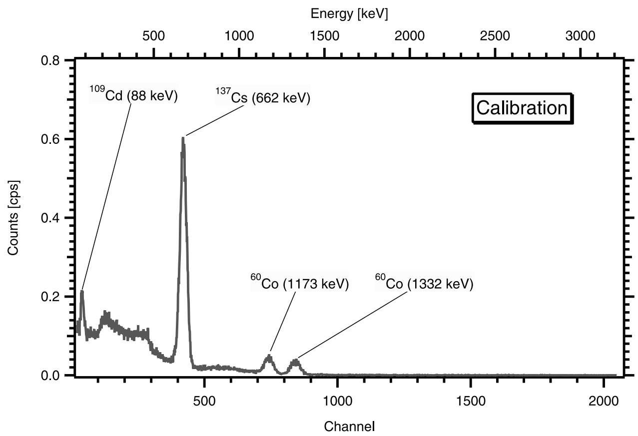
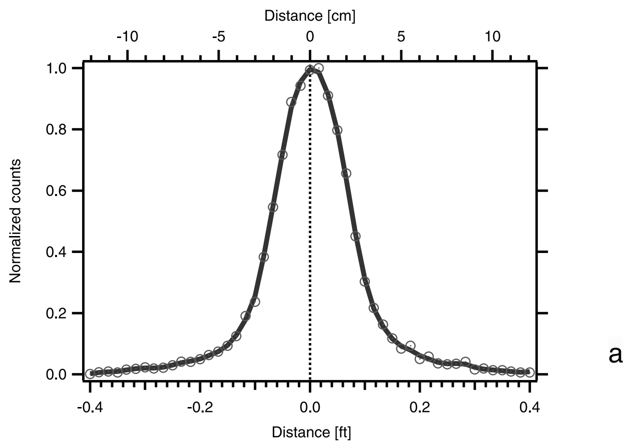


Figure 3. (a) Zero-background spectra with the ^{40}K potassium peak at 1461 keV energy. (b) NGR spectra (counts versus channel) of the calibration standard containing ^{109}Cd, ^{137}Cs, and ^{60}Co. Total measurement time was 36,000 s. Emission peaks with the corresponding radioisotope and gamma ray energy are indicated. The top horizontal axis shows the calibrated energy scale.

Geological Survey) using a MGX 2 logger with a 22.22 mm diameter by 76.2 mm long NaI gamma detector recorded digitally. The downhole NGR log was acquired continuously by moving the gamma tool at 9.1 m per minute. The acquisition time was 0.6 s (i.e., measurement effectively every 9.8 cm) resulting in an average of ~45 counts in each measurement. The log was obtained through the 10-cm-diameter drill rods because of concerns with hole stability and time constraints. Though this undoubtedly results in a damping of gamma log amplitude, comparison of logs obtained through the rods with those obtained on formation at another drill site at Ocean View, New Jersey, reveals minimal differences in relative amplitude.

[14] NGR measurements on the core were made at selected intervals to ensure a good depth registry between the downhole log and the actual core [e.g., *Zimmermann et al.*, 1991]. For this purpose we measured several short ~3-m core intervals where a clear peak or a sharp gradient in the NGR was expected from and could be compared to the downhole NGR log. The quality of the total NGR measurements on the core is a function of vertical (stratigraphic) resolution and counting precision. The vertical resolution of the NGR detector depends on its geometry (see Figure 2). In our detector the aperture in the lead shield is only 2.5 cm diameter for the 5 cm NaI(Ti) crystal. This gives the detector a very good vertical resolution at the expense of high counting rate. The vertical resolution of the detector was determined by measuring the total gamma ray counts of the standard source, which can be considered as a point source, at different positions with respect to the detector axis. A plot of the response function (Figure 4a) shows that the resolution achieved in the present configuration is characterized by 95% of the total counts falling within 6 cm and 90% of the total counts falling within 4.5 cm from the detector axis. In the measuring routine the sample increment was set to 7.5 cm so that each measurement is virtually independent while still attaining a good vertical resolution.

[15] Radioactive decay is a random process that follows a Poisson distribution, and this is the most important factor limiting the precision of the NGR measurements. Because of the random process, a sufficient number of counts must accumulate to obtain a robust estimate of the mean counting rate. The standard statistical error is expressed by $\varepsilon = \sqrt{N}/N$, where N is the number of counts in each measurement.



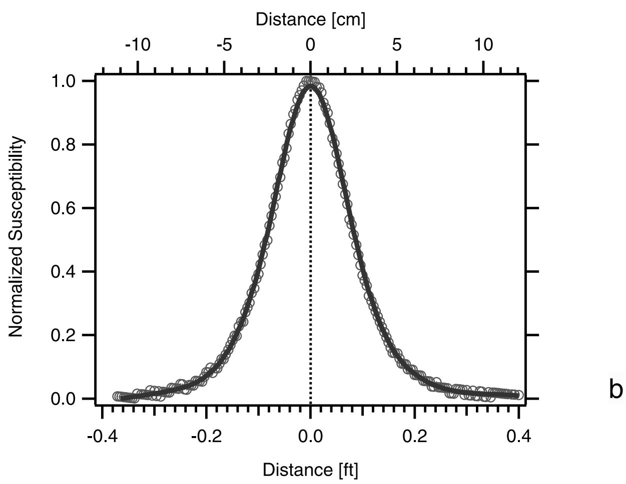


Figure 4. (a) Response function s plotted versus distance from the sensor axis of the NGR sensor using the calibration standard and (b) 100-mm-diameter Bartington susceptibility loop sensor using a thin disk of diabase.

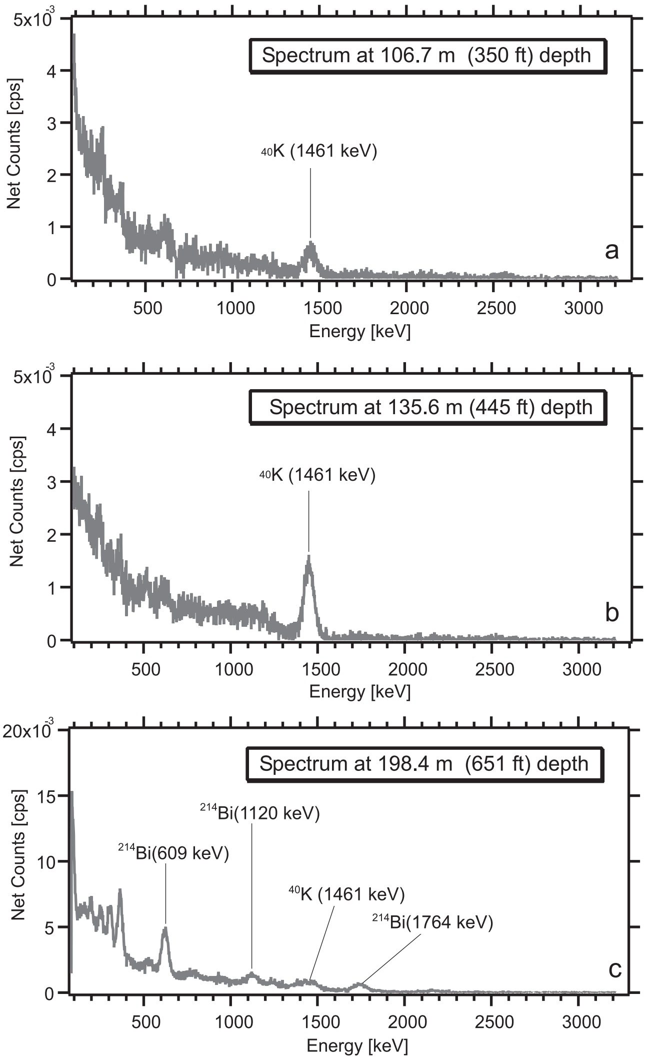


Figure 5. NGR spectra after background subtraction for selected Ancora core samples. Results from (a) 106.7 m (350 foot) depth and (b) 135.6 m (445 foot) depth in the Shark River Formation show typical spectra characterized by potassium-rich minerals (^{40}K peak) predominantly in mud and glauconite, respectively. (c) Results from 198.4 m (651 foot) depth showing an additional high concentration of uranium daughter product (^{214}Bi peaks). Note the different vertical scale in Figure 5c due to the higher activity.

Therefore N can be set to obtain any desired precision, although in weak sources such as sediments the acquisition time can be prohibitively long. We set the acquisition time for the Ancora core measurements at 200 s; this usually corresponds to $\sim$100 or more total counts above background in each measurement for the weakest sediments and to a standard error that is consequently <10%.

[16] The zero background noise of the NGR sensor in the total counts configuration was extensively measured at different times, and no trend or long-term variations were found. The overall mean of the zero background is 2.5 counts per second (cps), and its statistics are in excellent accord with the expected $\sqrt{N}/N$ Poisson relationship. As part of the measurement routine, the background is measured at the beginning and at the end of each measurement session. We did not attempt to compensate for small volume changes due to shrinkage, sampling, etc., found in the Ancora core, which are another source of variability.

2.4. NGR Spectrum Measurements

[17] NGR spectrometry gives information on the relative concentrations of radioactive elements which, in natural rocks, are mainly ^{40}K, the ^{238}U series, and the ^{232}Th series [e.g., *Adams and Gasparini*, 1970; *Blum et al.*, 1997]. The main factor limiting the extensive use of this technique in natural samples is the time required to acquire a number of counts in each channel sufficient to obtain the necessary precision [see also *Hoppie et al.*, 1994]. Because of the low activity of our samples, the acquisition time ranged from 50 to 60 hours. This obviously made it important to select intervals that would give meaningful spectra.

[18] NGR spectra were measured at selected core depths of 106.7, 135.7, and 198.4 m (Figure 5). The depth levels at 106.7 m, within a dominantly mud lithology of the Shark River Formation, and 135.6 m, within a glauconitic level of the Shark River Formation, were chosen on the basis of their representative lithologies, mostly muds (69% mud and 9% glauconite) at 106.7 m and mud (41%) and glauconite (47%) at 135.6 m, in order to estimate their relative radioisotope composition. The core NGR spectra taken at these two depth levels in the core show only the ^{40}K peak at 1461 keV (Figures 5a and 5b). This suggests that most of the natural radioactivity in these sediments is due to ^{40}K and that high NGR counting rates are expected for potassium-rich sediments. The more pronounced ^{40}K peak at 135.6 m emphasizes that different counting rates can produce spectra that are otherwise identical. This is expected because of the higher activity of the abundant glauconite in this level and is predicted by the linear models (see below).

[19] In contrast, the NGR spectrum for the base of the Navesink Formation at 198.4 m, which had a very high NGR activity that corresponds to an anomalous high NGR peak in the downhole log, could not be explained only by the presence of glauconite and mud. The NGR spectrum in fact detected several emission lines of ^{214}Bi which is characteristic of the uranium series (Figure 5c). This is most probably due to a local horizon particularly enriched in phosphorite, which is a uranium-bearing mineral. Core and outcrop descriptions of the basal Navesink Formation contact note the presence of phosphorite pellets and phosphorite pavements, respectively [*Miller et al.*, 1999a, 1999b].

2.5. Core Magnetic Susceptibility

[20] Magnetic susceptibility measurements provide information on the concentration of ferromagnetic, mainly iron oxides and iron sulfides, and paramagnetic minerals [e.g., *O'Reilly*, 1984]. The paramagnetic and ferromagnetic contribution to susceptibility may greatly vary depending on lithology. In terrigenous sedimentary rocks, clay minerals constitute a common paramagnetic source of susceptibility that are likely to be important especially when the coarse-grained fraction is largely devoid of iron minerals as in the quartz sands in the Ancora borehole.

[21] Magnetic susceptibility was measured on cores with the MST using a Bartington MS2 magnetic susceptibility

meter and the MS2C-type loop sensor with a 100-mm diameter. The Bartington meter operates in conjunction with a computer through a RS232 serial interface. Readings were taken on the 1x range in cgs units and adjusted per factory calibration curves for a core diameter assumed to be a uniform 5 cm. The response function of the loop sensor was determined by measuring a thin 5-cm-diameter disc of highly magnetic Palisade diabase. The results (Figure 4b) show that the response of the susceptibility sensor is similar in width and shape to that of the NGR sensor.

[22] The MS readings are subject to a slow drift mainly due to thermal effects that is more or less monotonic over times of 30 min or so and must be subtracted from the measurements. Blank measurements were taken before and after each set of measurements, and their difference was used to detrend linearly the measured susceptibility with respect to the measurement time. To avoid unacceptable high drifts, we made sure that the time elapsed during any set of measurements did not exceed 15 min before another blank reading was obtained.

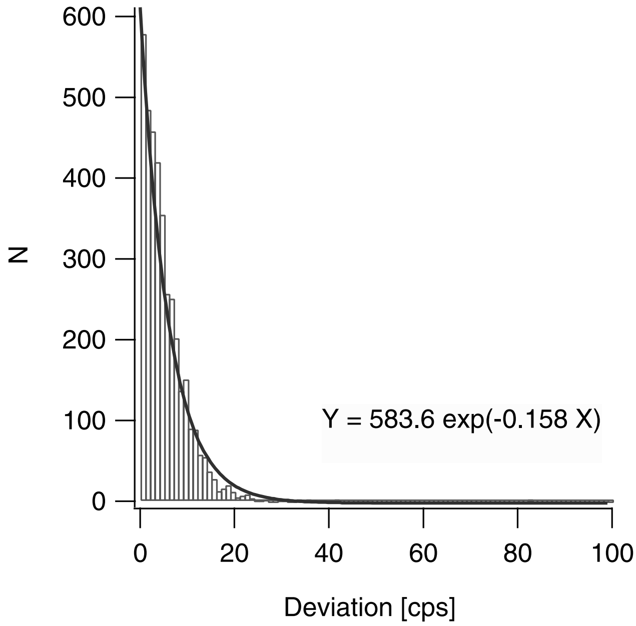


Figure 6. Histogram of the absolute values of residuals after smoothing of the downhole NGR log with 10-point Gaussian filter compared with an exponential function.

3. Data Analysis

3.1. Regularization

[23] Data regularization was considered necessary to reduce data scatter, especially in the NGR logs where the relatively low counting resulted in an average standard error of ~17%. In contrast to the geometry of the core NGR the crystal detector in the downhole NGR measurement senses radioactive decays from a sphere of influence whose diameter *d* depends on the energy of the gamma rays and the density of the surrounding rocks. The value of *d* is found to be ~0.5–1 m for terrigenous sediments [*Wahl*, 1983] where ~90% of the radioactive contribution comes from a *d* of 20–40 cm. This is a major factor limiting the vertical resolution in the downhole NGR. Measurements taken at intervals smaller than *d*, therefore, cannot be treated as independent. Moreover, each measure is subject to the intrinsic statistical error ε that generates noise in the record.

[24] The high scatter in the downhole NGR logs can be reduced using a smoothing function that considers these factors. The vertical sampling of the downhole NGR measurements in the Ancora borehole is 6 cm. We chose a 10-point Gaussian (binomial) smoothing function which corresponds to 60 cm in-depth, compatible with the expected *d*. The distribution of residuals should approximate the Poisson error distribution and thus should have an exponential distribution. The histogram of the absolute value of the residuals (Figure 6) shows that this expectation is fulfilled for a binomial smoothing function of 60 cm. For consistency, the same 10-point smoothing window was applied to the core NGR data. The smoothing procedure used for the core MS data was similar to that used in the downhole NGR; here we arbitrarily chose a smaller window of 5 points.

3.2. Depth Registry

[25] We acquired only a small set of precise core NGR measurements to check the depth registry so that the continuous, well-defined downhole NGR log could be used for lithologic interpretation. Acquisition time for obtaining core NGR measurements at a sampling rate and counting precision comparable to the downhole NGR record would have been prohibitive. Also, the continuity of the core NGR is inherently limited by core recovery which was excellent (86%) but nevertheless not complete at Ancora. Where taken, the core NGR measurements compared well to the downhole NGR measurements except for the absolute scale. Peaks or gradients measured in the core NGR were replicated in the downhole NGR, and the two records were very well registered within 0.3–0.6 m of tolerance (Figure 7). Therefore, no corrections were made to the core depths and the core logs and lithology can be directly compared to the downhole NGR.

3.3. Lithological Dependence

[26] A lithological description based mainly on grain-size analysis is available for the Ancora core [*Miller et al.*, 1999a]. The NGR and MS logs appear to be strongly related to the dominant lithologies. The NGR log data have an approximately bimodal distribution that reflects the dominant sandy and clayey lithologies in the core. At a closer look, the NGR seems to correlate mainly with the clay-silt and glauconite contents that are by far the major contributors to NGR activity. This is confirmed by the NGR spectra from clay-rich and clay-glauconite-rich sedimentologies (i.e., Figures 5a and 5b). A small NGR contribution may also come from the fine-sand fraction. However, there are some very high NGR values that do not seem related to the described lithology, for example, at 198.4 m depth. In this particular case, the NGR spectrum indicates the presence of a localized enrichment of uranium-bearing phosphorite (Figure 5c).

[27] As found in similar New Jersey coastal plain cores from ODP Leg 150X [*Metzger et al.*, 1997], the concentration of glauconite is the factor that mostly controls the magnetic susceptibility. To a much lesser extent, the mud concentration is the next most important factor. As a

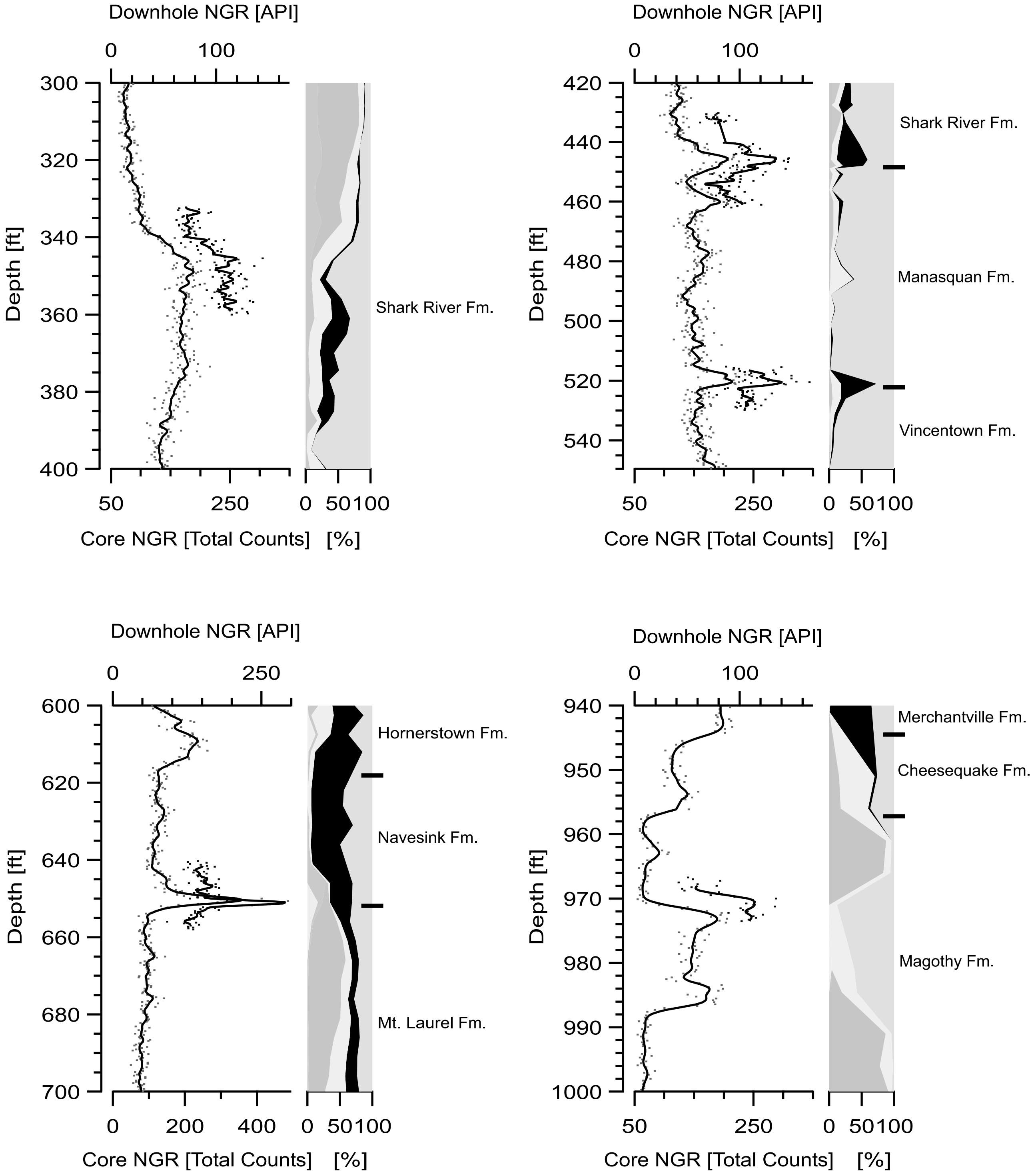


Figure 7. Downhole and core NGR data in selected intervals demonstrating good depth registry between the core and the downhole logs. The lithology logs use the same symbols as in Figure 9. For smoothing details, see text.

consequence, the MS has a spiky appearance where the maxima correspond to sporadic intervals with high concentrations of glauconite. Concentrations of other common magnetic minerals such as magnetite may also give high MS values. The best example at Ancora is found in the interval within 164.6 and 173.7 m, where a high concentration of fine-grained magnetite in the sediment, as confirmed by magnetic hysteresis parameters, largely accounts for the anomalous increase in MS (Figure 8).

3.4. Linear Models

[28] The good visual correspondence of lithology with NGR and core MS at Ancora (Figure 9) suggests that a very simple lithological dependency can account for most of the

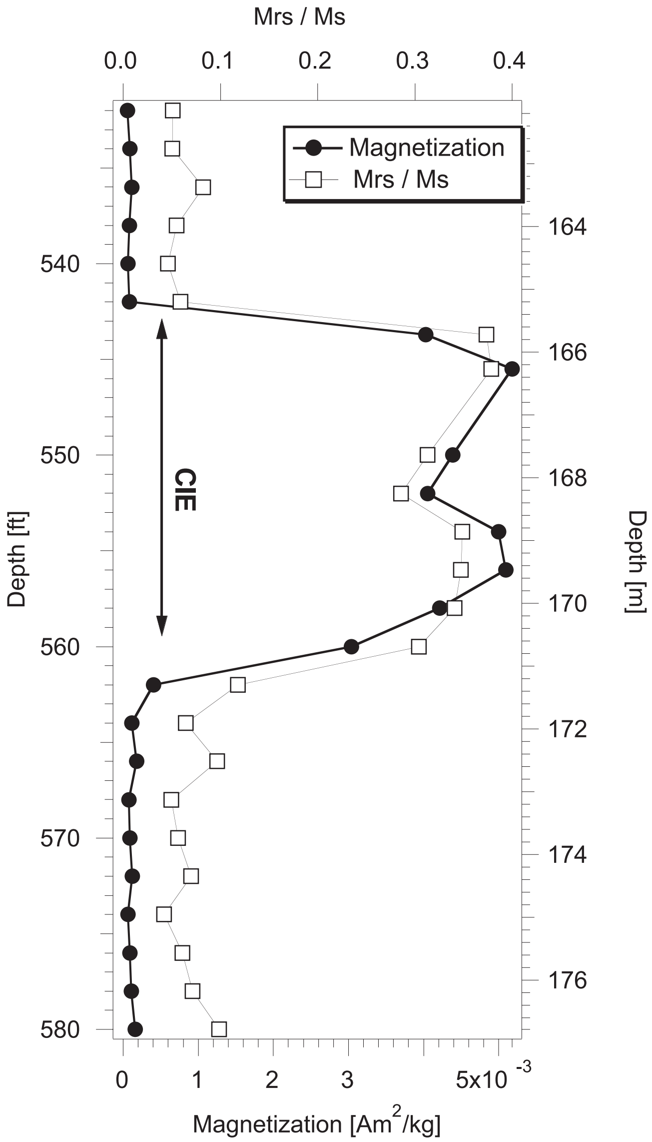


Figure 8. Saturation remanent magnetization (J_r) and the ratio between saturation remanence and induced magnetization (J_r/J_s) after standard correction for paramagnetic component from hysteresis measurements on bulk samples using Model 2900 AGFM. The magnetic data indicate an abnormally high concentration of very fine grain magnetite particles across the interval comprising the late Paleocene Carbon Isotope Excursion.

variation in NGR and MS. The apparent lithologic dependence of NGR and MS can be explained more quantitatively using a simple linear model. Although all the various described lithologies can be included in the model, we just use glauconite, clay-silt, and fine-sand fractions to model them. This is based on the visual comparison of logs and lithology, on numerical tests made using different combinations of lithologies, and on the observation that except for sand most of the other lithologies are not volumetrically important at Ancora.

[29] The model can be described as

$$\mathrm{MS} = S_{\mathrm{mud}}\, F_{\mathrm{mud}} + S_{\mathrm{glauconite}}\, F_{\mathrm{glauconite}} + S_{\mathrm{fine-sand}}\, F_{\mathrm{fine-sand}}$$

$$\mathrm{NGR} = G_{\mathrm{mud}}\, F_{\mathrm{mud}} + G_{\mathrm{glauconite}}\, F_{\mathrm{glauconite}} + G_{\mathrm{fine-sand}}\, F_{\mathrm{fine-sand}},$$

where F is the estimated relative fraction of each lithological component (mud, glauconite, and fine-sand) and S and G are constants that represent the MS and NGR activity, respectively, of the lithologies that can be calculated by nonnegative least squares minimization. The nonnegative constraint, meaning that the S and G coefficients are forced to be ≥ 0, is used because diamagnetic (negative) susceptibility is negligible, and negative NGR counts are not physically plausible. In this case, the best fit values of the S and G coefficients were calculated using all available samples for which lithological descriptions and MS and NGR measurements were available. This procedure gives the mean values of MS and NGR activity of these lithologies for the entire core (Table 1). The fitted results can be compared to the actual data (Figure 9). The goodness of the linear fit can be tested using the Pearson correlation coefficient between the actual data and the computed model. The correlation coefficient is highly significant for both the NGR and the MS models (see Table 1).

4. Discussion

[30] Linear models give a quantitative relationship between gross lithology and the NGR and MS logs, which is described by the G and S coefficients. The most important contributors to total NGR are the glauconite and mud fractions. The average NGR activity or G coefficients of these two lithologies is 112 cps and 70 cps, respectively, indicating that glauconite activity is on average 35% higher compared to mud. A small contribution to NGR also comes from the fine-sand fraction, which has a G of $\sim$38 cps, suggesting the presence of some potassium-rich mineral such as plagioclase. With an average MS of $\sim 222 \times 10^{-6}$ SI, glauconite is by far the highest contributor to magnetic susceptibility. The S parameter for mud is $\sim 40 \times 10^{-6}$ SI, while the susceptibility of fine-sand is negligible. Models that included medium quartz sand show that this sediment component is virtually inert, with no significant contribution to NGR and MS.

[31] Although there are several departures of the actual data from the model, the correlation of MS with glauconite and NGR with mud and glauconite is well established together with their mean contributions. Similar results were obtained for New Jersey sites using a more qualitative method by *Metzger et al.* [1997]. A relatively minor long-trended deviation of the actual data from the models can be explained as gradual mineralogical changes, especially in clay mineralogy, along the core. Sharp departures of the data from the model are most likely explained by singular concentrations of very radioactive (e.g., phosphorite) or highly magnetic (e.g., magnetite) minerals that were not explicitly quantified in the lithological and mineralogical descriptions. For instance, this is obvious for the NGR peak at 198.4 m core depth where the NGR spectrum indicates a large concentration of uranium which subsequent inspection of the core indicates was related to the presence of phosphorite. Because such unusual occurrences may have paleoenvironmental significance, we suggest that the departures from the model could be used to identify them.

[32] At Ancora the interpretation of the NGR and MS logs allows the identification of most of the sequence boundaries found in the core. This is because the strati-

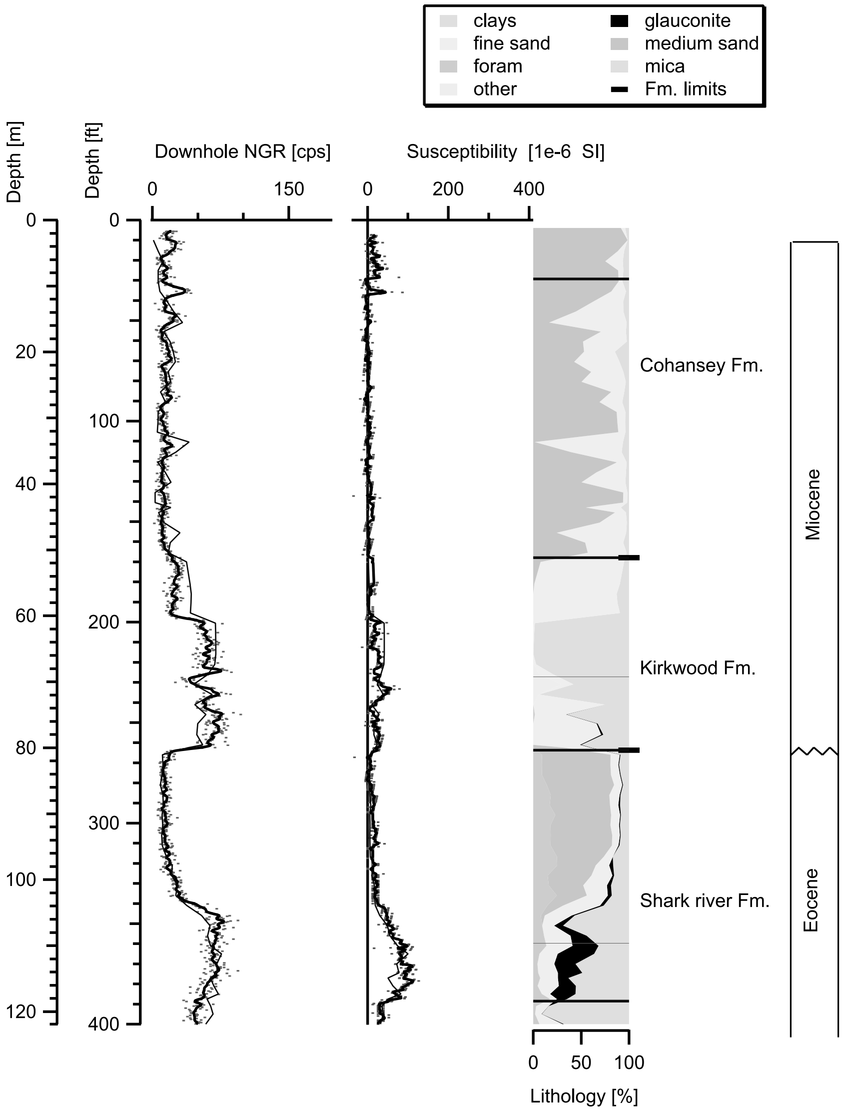


Figure 9. Downhole NGR log and core MS log compared with linear models and core lithology. Dots represent the actual measurements, the thick line is a smoothing function described in the text, and the thin lines represent the linear models. Sequence boundaries identified on the basis of direct lithological and physical description are indicated in the lithology column as horizontal lines; dashed lines mark formation limits [*Miller et al.*, 1999a].

graphic sequences generally are reflected in lithological changes and the log properties are mainly a result of the lithology. For instance, glauconite sand beds, which are typical markers of the transgressive system tract in an idealized depiction of Eocene and Cretaceous sequences of the New Jersey coastal plain [*Miller et al.*, 1998], can be readily recognized in the MS log because of the high susceptibility of glauconite. Maximum flooding surfaces can also be interpreted at the upper part of the MS peak. Sharp changes of NGR point to lithological variations that can also be understood as sequence stratigraphic boundaries or unconformities. In actual sequences, however, the glauconite sand can be detrital, redeposited, and mixed with the overlying mud and silt that constitute the lower HST or occasionally in quartz sands at the upper HST. This makes interpretation of the NGR log alone more ambiguous, although extensive reworking of glauconite is generally restricted locally to Oligocene sections [*Miller et al.*, 1998]. The redeposition of glauconite also makes it difficult to use NGR logging for interpreting the mud to sand ratio because the detrital glauconite sand has a high NGR activity, similar to that of mud.

[33] With these caveats in mind, a comparison with the sedimentological analysis made independently on the recovered core [*Miller et al.*, 1999a] shows that only a few sequence boundaries were apparently missed in the log interpretation. (Note that to avoid registry problems inherent in unit conversions (rounding errors, etc.), we also quote the depths in feet in parentheses because that was the primary unit of measure for all the published core descriptions, logs, and the depths of the sequence boundaries [*Miller et al.*, 1998, 1999a]). The sequence boundaries at 8.9 m (29.25 feet) in the Cohansey Formation and at 140.5 m (461.2 feet) in the Manasquan Formation have very little lithologic

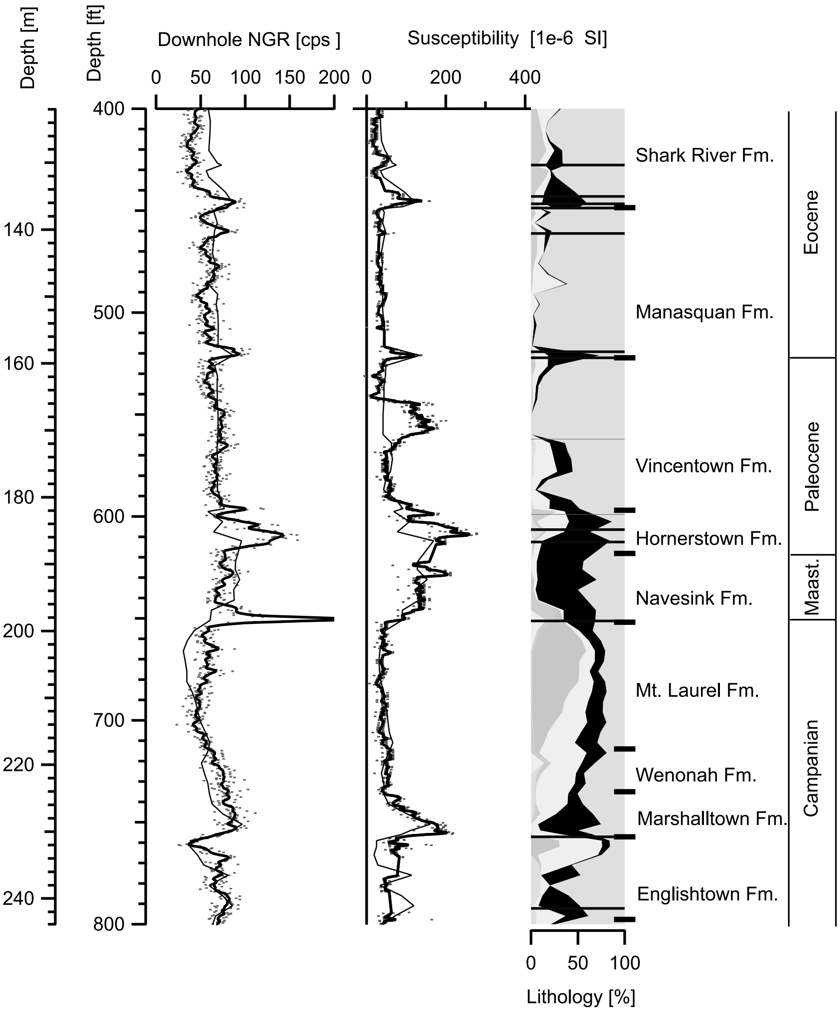


Figure 9. (continued)

expression and thus not surprisingly do not have an obvious signature in the NGR or MS logs. The only sequence boundaries that have a clear expression in the lithology column but do not show up well in the logs are those within the Englishtown Formation at 241.5 m (792.3 feet) and the Bass River Formation at 338.6 m (1110.9 feet). This may occur because local concentrations of mica are masking the NGR and MS expression of the sand to mud ratio.

[34] The closely spaced sequence boundaries within the Hornerstown Formation at ~185.9 m (610 feet) depth have only a subtle expression in the geophysical logs as broad NGR and MS peaks which do not clearly reflect major lithological change(s). This is also the case for the NGR peak at 198.4 m (651 feet) depth, as shown by the large discrepancy between the data and linear model (Figure 9b). The misfit is probably due to minerals like phosphorites that were not included in the lithology log. Recognition of the three closely spaced sequence boundaries at 137.2 m (450 feet) and of two closely spaced sequence boundaries at 158.5 m (520 feet) is based mainly on biostratigraphic analysis [*Miller et al.*, 1999a]; these groups of sequence boundaries are resolved only as single boundaries in the log interpretation.

[35] An uncertain sequence boundary that has a very clear expression in the MS log was found at 171.3 m (562.1 foot) depth in core, a level that coincides with the base of the late Paleocene Carbon Isotope Excursion [*Zachos et al.*, 1993]. From this level to 165.2 m (542 feet), the intensity of saturation remanent magnetization (J_s) in the sediment increases by a factor of 10 compared to the adjacent sections (Figure 8). Magnetic hysteresis parameters (e.g., ratio of saturation remanence, J_r, to J_s generally >0.3) indicate that the high magnetization corresponds to an increased abundance of very fine grain magnetite [*Day et al.*, 1976]. These unusual magnetic properties may be due to the presence of biogenic magnetite [*Konhauser*, 1998; *Stolz et al.*, 1990; *Moskowitz et al.*, 1993] and are the subject of further investigation.

[36] Two sequence boundaries identified at Ancora by *Miller et al.* [1999a] lack NGR and/or MS signatures, in the Kirkwood Formation at 69.2 m (227.2 feet) and the Shark River Formation at 109.7 m (359.8 feet). However, both of these levels were identified only as possible sequence boundaries and further study is needed to verify their significance [*Miller et al.*, 1999a].

5. Conclusions

[37] The measurement strategy in the Ancora core was to use the continuous downhole NGR log for lithology

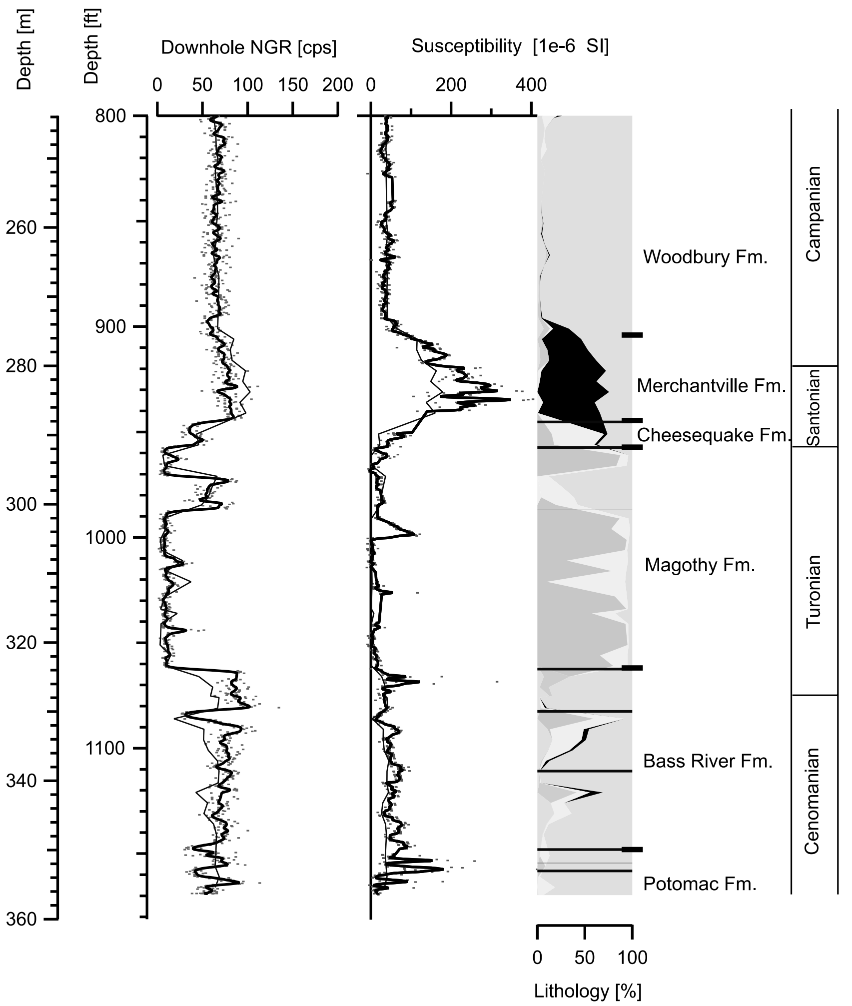


Figure 9. (continued)

interpretation and detailed core NGR measurements in selected intervals for depth registry and identification of major lithologic contributors to the NGR signal. Good results were obtained in fitting NGR and core MS logs to a very simple parameterization of the lithologic description of the section using a linear model. The quantitative model demonstrates that the NGR and MS logs at Ancora are strongly controlled by sediment lithology. The model provides a predictive tool for sedimentological and mineralogical aspects that may be not otherwise be immediately apparent. The ability to use geophysical logs to identify sequence stratigraphic boundaries was tested in the Ancora core. Twenty-seven of 33 of the sequence boundaries previously identified at Ancora using conventional sequence stratigraphic criteria correspond to major variations in the NGR and/or MS logs. Although core recovery at Ancora was excellent, the techniques illustrated here can be used to predict the locations of sequence boundaries in sections with poor or discontinuous recovery. However, this study also shows that prominent features in the NGR and/or MS logs may also reflect substantial lithological variations that do not obviously correspond to sequence boundaries.

Table 1. Linear Model Coefficients

	Correlation Coefficient	Mud	Glauconite	Fine Sand
NGR, cps	0.81	$G_{mud} = 70.2$	$G_{glauconite} = 112$	$G_{fine\text{-}sand} = 38.5$
MS, 10^{-6} SI	0.81	$S_{mud} = 40.3$	$S_{glauconite} = 222$	$S_{fine\text{-}sand} = 9.3$

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