The Monte Carlo Method: Versatility Unbounded In A Dynamic Computing World
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MONTE CARLO MODELING OF NATURAL GAMMA RAY LOGGING DEVICES IN DEVIATED AND HORIZONTAL WELLBORES

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ABSTRACT

A Monte Carlo modeling study was carried out to investigate performance of a generic gamma-ray well logging device in vertical, deviated, and horizontal wellbores penetrating earth formations. The general purpose Monte Carlo code, MCNP, was modified with a pseudo-long detector tally and a special distributed source patch. The pseudo-long detector tally was used to simultaneously compute detector responses at a series of logging depths within one Monte Carlo simulation. A source patch was written to describe photon source distributions in laminated formation bed sequences surrounding the wellbore. Simulated gamma ray logs on measured depth in deviated wellbores were depth-corrected. Results show that, in a moderately deviated wellbore penetrating thinly laminated sand/shale formation sequences, the depth corrected gamma ray log can provide identical bed boundary information with what is obtained in a standard vertical wellbore condition. Simulated tool responses in horizontal wells containing thin shale formation beds with various inclination angles indicate that gamma ray logs can be used as a shale bed inclination indicator in horizontal wellbores filled with light drilling fluids. Attenuation of gamma rays in heavy drilling mud and mud weight effects on the tool response were also studied.

Key Words: gamma ray, well logging, Monte Carlo

1 INTRODUCTION

Natural gamma ray logging devices measure radiations from potassium, the uranium and thorium decay chains in earth formations. These naturally occurring radioisotopes tend to be concentrated in impermeable shale formations and are much less concentrated in oil and gas bearing reservoir rocks such as carbonates and sands. Thus, natural gamma ray logs provide valuable bed boundary and shale volume information and are routinely used to enhance lithological correlation and formation evaluation in oil and gas exploration and discovery. In recent years the gamma ray device has become one of the primary logging tools utilized in measurement-while-drilling operations to provide real-time geo-steering guidance in high angle and horizontal wells. However, log data acquired in these wells are often difficult to analyze and evaluate. Physical experiments for these logging conditions are expensive if not entirely impractical to undertake. Monte Carlo simulation provides a useful tool to better understand logging measurement physics and characterize instrument response in complicated logging environments such as this.

The general purpose Monte Carlo code, MCNP4C (Briesmeister, 2000), was used in this study to simulate log responses under various logging conditions. Among the possible natural elements that have unstable nuclides, only ^{40}K, uranium, and thorium are of practical interest in nuclear logging. Potassium is the simplest case in which isotope ^{40}K has an abundance of 0.011% and emits a 1.46 MeV gamma ray (Eent, et al., 1967). Uranium and thorium radiations come from their decay daughter products. Table 1 lists the gamma rays associated with uranium and thorium decay chains. Yields of gamma rays with closely spaced energies beyond the resolution of scintillation detectors are combined to increase the computation efficiency. In this study a generalized shale formation model is assumed to have density of 2.8g/cc and concentrations of radioisotopes are assumed to be 1% by weight of potassium, 1ppm of uranium, and 1ppm of thorium. The sand formations are assumed to be 30% water-filled sandstone with density of 2.155g/cc.

Table I. Uranium and thorium decay chain gamma rays

Uranium		Thorium	
Energy (keV)	Intensity (%)	Energy (keV)	Intensity (%)
63.3	2.8	84.4	6.4
92.8	3.2	129.1	1.2
186.0	3.1	209.4	1.9
295.2	13.3	238.6	19.4
352.0	17.7	270.3	1.6
609.4	20.8	300.1	1.4
665.6	0.7	338.4	6.4
768.4	2.7	463.0	1.9
806.2	0.5	510.7	3.3
934.0	1.5	583.1	12.5
1001.1	0.4	727.3	2.7
1120.4	8.1	794.8	2.0
1238.2	3.7	860.5	1.7
1377.7	2.5	911.1	12.1
1408.0	2.0	968.9	9.6
1509.3	1.5	1587.9	1.5
1661.4	0.6	2614.5	14.5
1764.5	9.7		
1847.6	1.1		
2118.7	0.6		
2204.3	2.6		
2448.0	0.8		

2 PSEUDO-LONG DETECTION MODEL

Natural gamma ray logging instrument usually consists of a cylindrical scintillation detector coupled with a photomultiplier tube and signal processing electronics including amplifiers and a pulse height analyzer. In nuclear well logging operations gamma ray counts are continuously acquired as the instrument string is lowered or pulled up at constant speed in a wellbore. Log data is usually recorded every quarter or half a foot and sampling time per data point varies depend upon the logging speed. Log data is plotted as a function of logging depth.

Direct Monte Carlo calculations to simulate detector movement would be prohibitively expensive as repetitive calculations are required at each logging depth. As an example, a 15-foot formation model is shown in Figure 1 and it consists of a four-foot shale formation bed and two sand formation beds. With direct Monte Carlo calculations at a sampling rate of four acquisitions per foot it would need sixty Monte Carlo simulations to compute the tool response over the formation length.

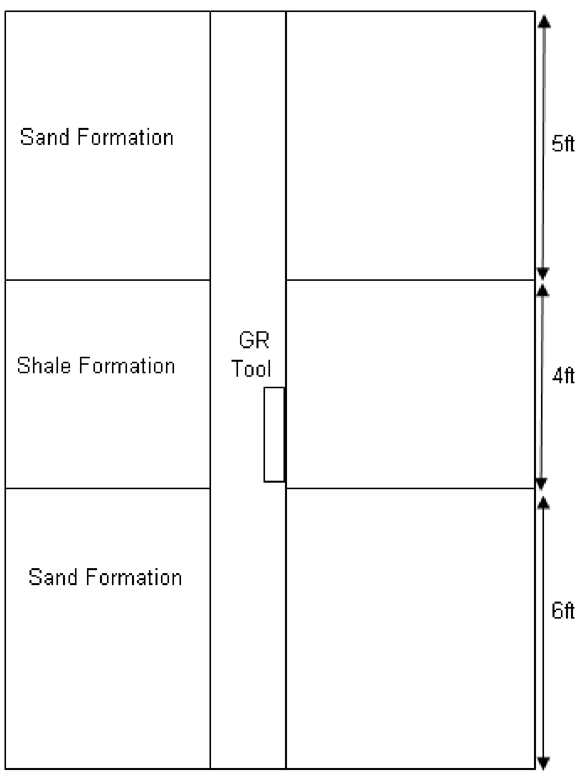

Figure 1: A formation model with conventional single detector model at each detection point

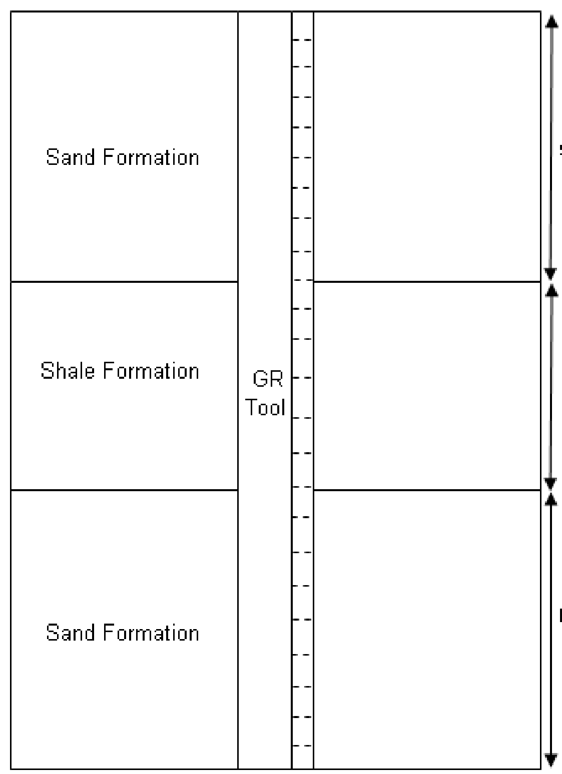

Figure 2: A formation model with a pseudo-long detector model over the entire logging interval

A pseudo-long detector model (Guo, 1995), however, can greatly increase Monte Carlo simulation efficiency. The principle that the pseudo-long detector concept is based on is that response of a finite detector with continuously varying vertical positions is equivalent to the static response of a long detector. As shown in Figure 2, the pseudo-long detector is a stacked set of detectors of reduced length. This approach allows every detection point along the interval of interest to accumulate successful incoming gamma ray counts during a single Monte Carlo simulation. Once gamma rays enter the long detector, particle weights and positions are tracked and recorded. The final tallies of gamma ray counts are calculated using volume of the physical detector.

Validation of the model is carried out using a logging instrument with a 12-in detector and the sampling is done at rate of four acquisitions per foot. A six-inch shale formation bed is sandwiched between two sand formations. The pseudo-long detector model consists of a series of 3-in detectors and its tallies are processed by summing up the count rates of the adjacent four 3-in detectors. Sixty Monte Carlo simulations were also performed to calculate the instrument response with a conventional 12-in detector model. The two tallies are plotted in Figure 3. It shows that the pseudo-long detector tally duplicates the single detector tally at a small fraction of the original computational cost.

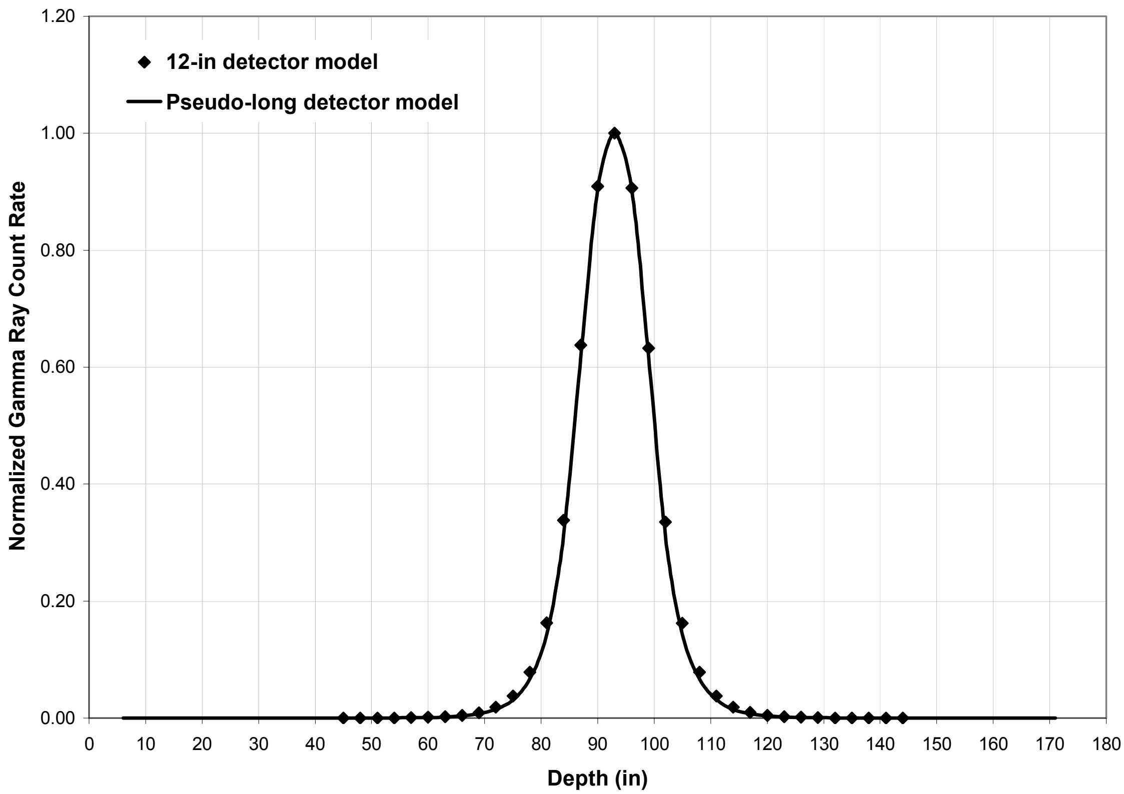

Figure 3: Tally comparison between a pseudo-long detector model consisting of 3 in. detectors and a 12-in detection model

3 SIMULATION OF DEVIATED WELLBORES

3.1 Vertical Wellbore

As a standard logging condition a vertical wellbore model illustrated in Figure 1 was modeled. Log response with a 2x12 CsI tool was plotted in Figure 4. Log data shows a symmetric bell-shaped curve. Since the 4-foot thick shale bed is well within the vertical resolution limits of the12-in. long instrument, the bed boundaries can be accurately determined using the traditional method of inflection point picking as illustrated in the graph.

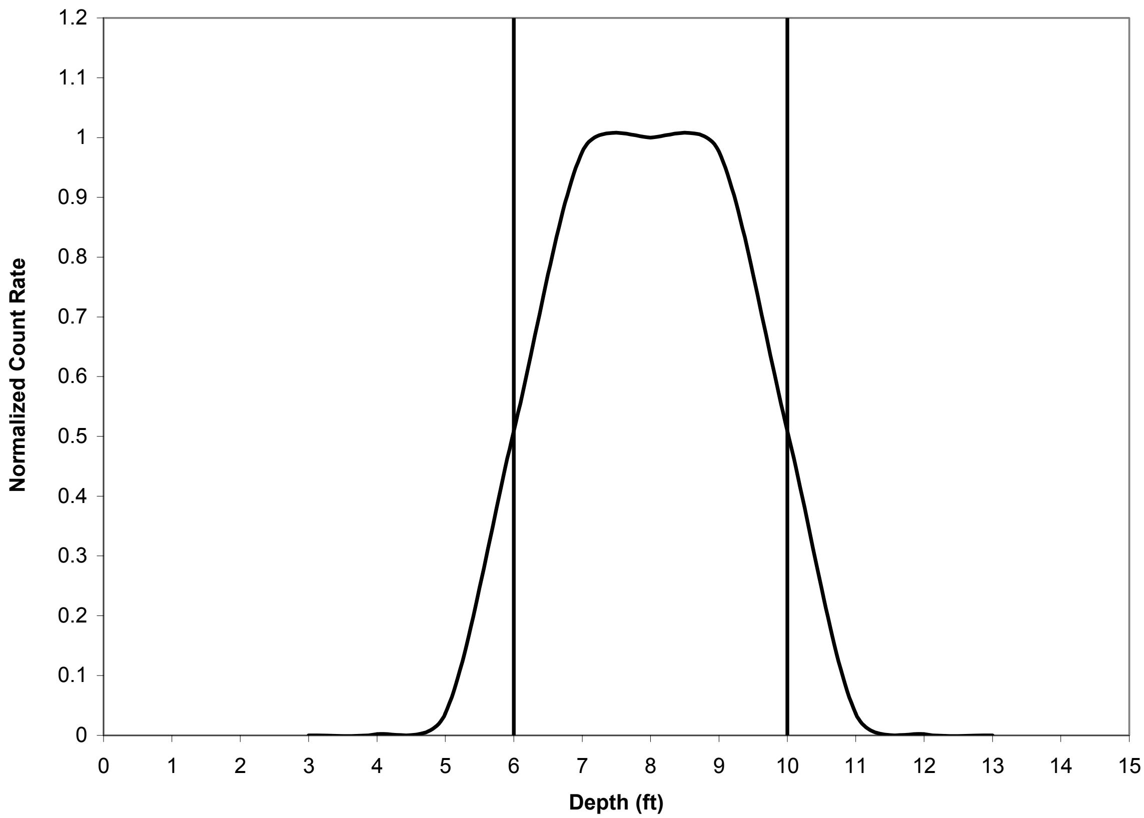

Figure 4: Log response of a 2x12 CsI instrument in a 8-in. vertical wellbore in a sand formation containing a 4-foot shale bed

3.2 70° Deviated Wellbore and Single Shale Bed

Deviated wellbore in a formation containing a single shale bed was studied. Log data was calculated as the instrument logged in a 8-in. deviated wellbore. The 70° deviated well model is shown in Figure 5. The simulated log response is plotted in Figure 6 as a function of the measured depth. An erroneous 15-foot shale bed would be detected if the inflection point method is applied directly.

Depth correction can be made by converting the measured depth into true vertical depth using the deviation angle between the wellbore main axis and the lateral orientation of the formation beds.

$$\text{True-Vertical-Depth} = \text{Measured-Depth} \times \text{COS}(\theta) \quad (1)$$

where θ is the deviation angle.

The depth corrected log data is plotted along with the vertical well log in Figure 7. It shows that log data acquired in deviated well can provide true bed thickness of four feet if corrected to the true vertical depth. However, the bed boundaries would be shifted with an offset of six inches.

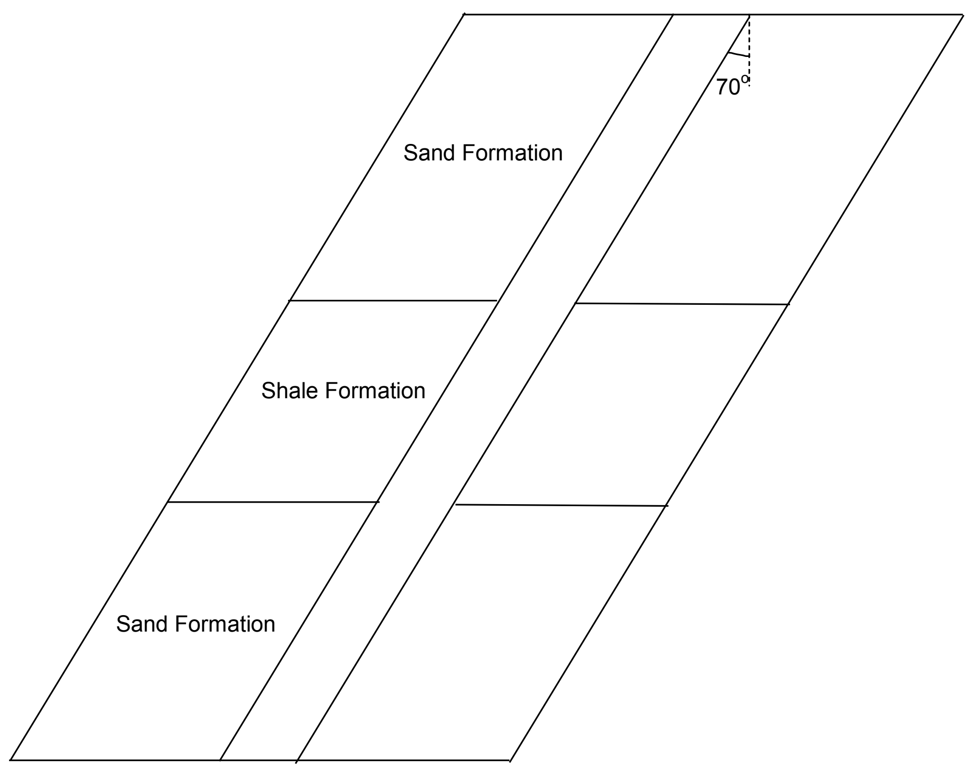

Figure 5: A 70° deviated wellbore in a sand formation containing a 4-foot shale bed.

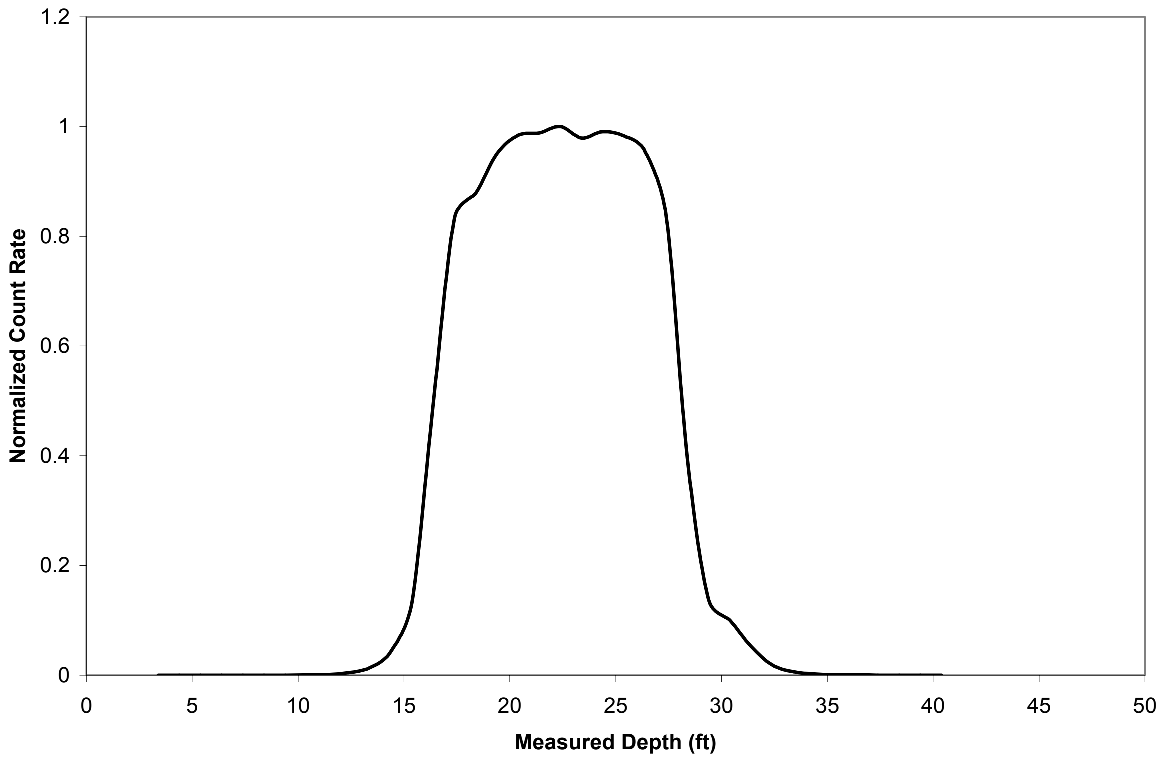

Figure 6: Log data for a 2x12 CsI instrument in a 8-in 70^{o} deviated wellbore

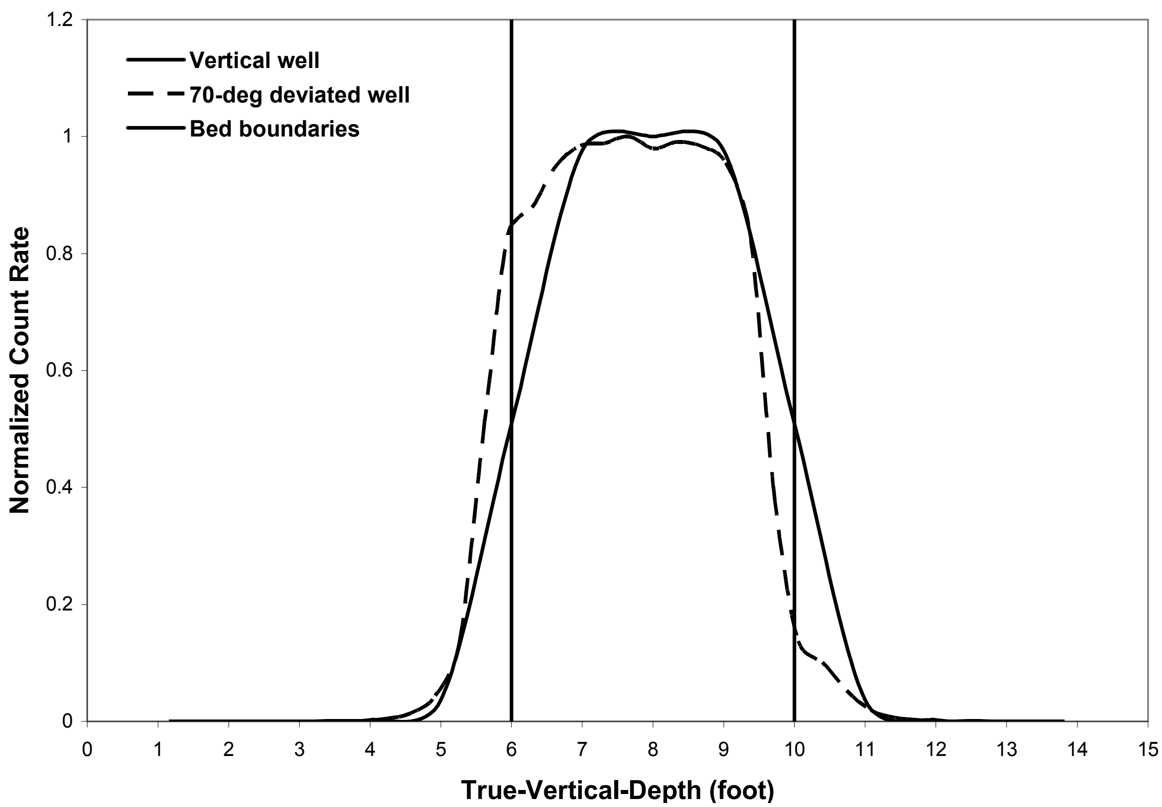

Figure 7: Comparison of vertical well log data and depth corrected deviated well log data.

3.3 30^o Deviated Wellbore and Thinly Laminated Shale and Sand Sequence

A 30-foot long formation model was used to study the gamma ray instrument response in a moderately deviated wellbore. The synthetic earth model consists of thin shale and sand beds with thickness ranging from 0.25in. to 2in. There are 150 thin shale beds in the formation. A source patch was written to describe the volumetric gamma ray source distributions in thin shale beds. A probability density function was defined according to the shale bed volumes and radioisotope concentrations. Source particles are sampled in two steps. First, an individual shale bed was randomly selected. Particle energy and position were then sampled within the shale volume source.

Two sets of log data were simulated. One with the instrument logged in a vertical wellbore and a second from a 30^o deviated wellbore. Shown in Figure 8 is the log data in API units as a function of measured depth. Also shown in the figure are the shale bed boundaries which are plotted in the lower portion of the graph. The shale bed boundaries are well below the vertical resolution limits of the 2x12 CsI instrument.

Depth correction function defined in Equation (1) was applied to log data set in the deviated well. Shown in Figure 9 is the comparison of the depth corrected log data and data from the standard vertical well. The results indicate that depth corrected log data acquired in moderately deviated wells agrees very well with log data obtained in standard vertical wells. The depth corrected log can provide identical information of bed boundaries and thickness.

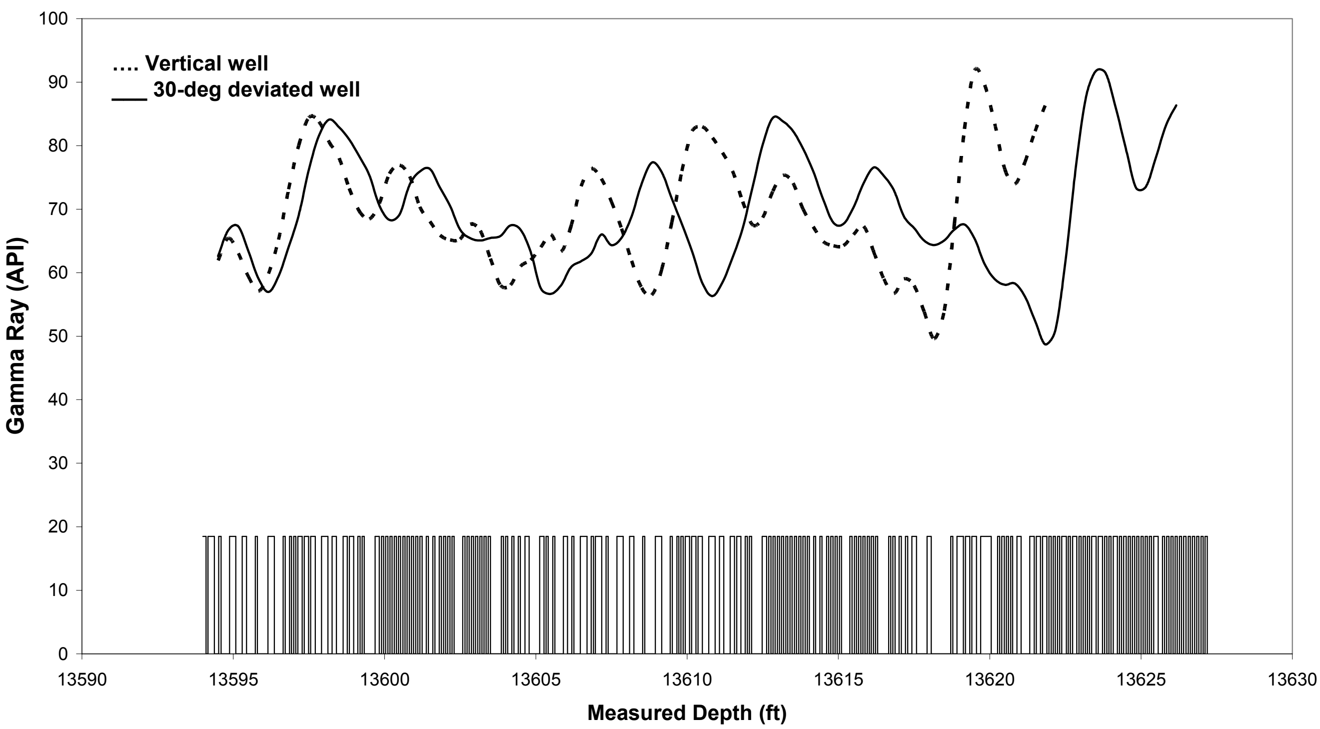

Figure 8: Log data acquired in the vertical and 30^o deviated wells in a 30-foot thin sand and shale formation sequence. Shale bed boundaries are also shown.

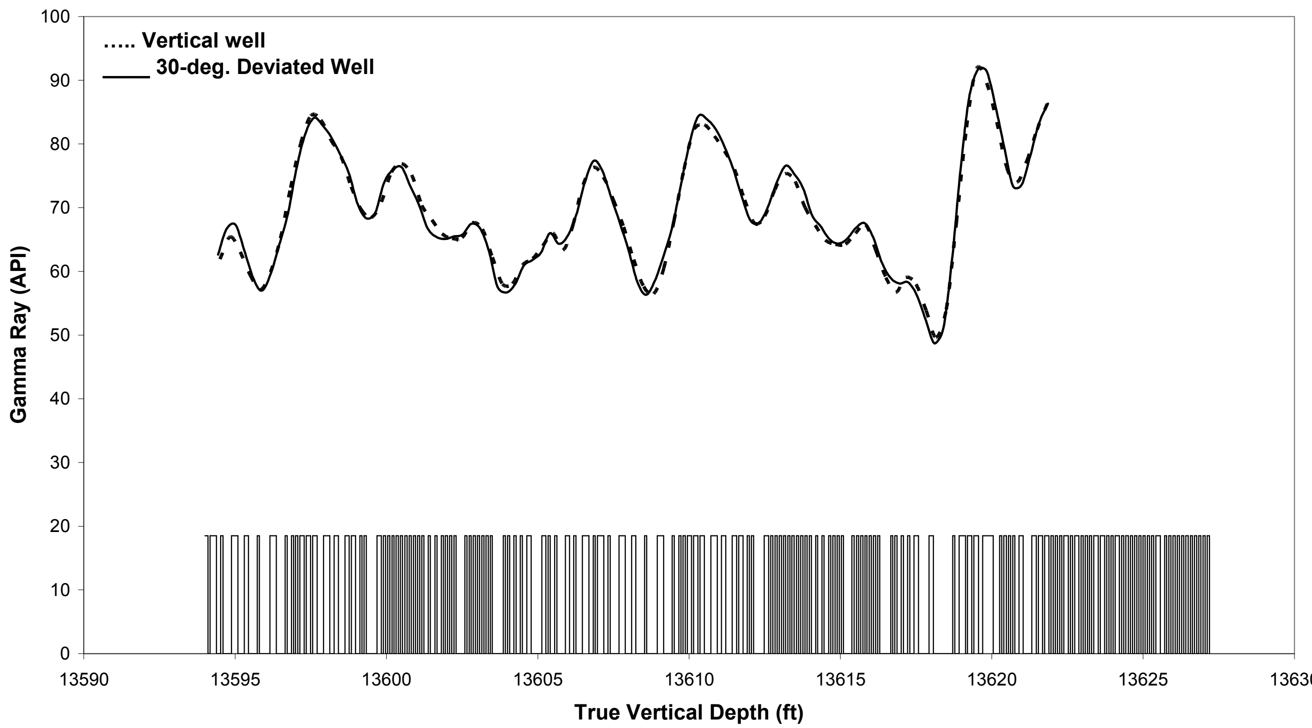

Figure 9: Comparison of the depth corrected log data from deviated well and log data from vertical well. Shale bed boundaries are also shown.

4 SIMULATION OF HORINZONTAL WELLS

In offshore oil field development many extended reach wells are drilled in order to maximize the reservoir oil drainage. Large portions of these wells are high angle and horizontal wells. Study of logging instrument response in horizontal wells can provide important guidance in well drilling operations to optimize the wellbore placement.

Shown in Figure 10 is a 80-foot long and 6-foot in diameter formation model and it includes a horizontal wellbore intersecting a 10^{o} inclined shale bed of 2 in. thick. The 8 in. horizontal wellbore is logged with a 2x12 CsI instrument. The logging depth starts at the depth 0 mark. The simulated log data is illustrated in Figure 11. Two types of wellbore fluid were modeled. The solid line is the log response in fresh water filled wellbore. The highest count rate in fresh water filled wellbore was normalized to one. The dotted line represents the log response in 18 lbm/gal barite mud and it shows that gamma rays are subject to a stronger attenuation effect in heavy barite mud.

There are several observations that can be made regarding Figure 11. First, it can be seen that, as the instrument approaches to the shale bed from the left side, the tool response increases monotonically. While the instrument moves away from the shale bed, an edge effect is observed as the response decreases. The non-symmetric characteristics of the log data would be an important indicator of the inclination direction of the shale bed. Secondly, the sensitivity depth interval is 20 feet long. Thirdly, wellbore fluid weight affects the tool response.

Figure 12 shows the log data from horizontal wellbore intersecting with 1^o inclined shale bed. The bed thickness is 2 in. The same edge effect is observed. However, the sensitivity depth interval is 260 ft long. A 5^o inclined shale bed case was also modeled. Listed in Table II is a summary of the sensitivity depth interval and inclination angle.

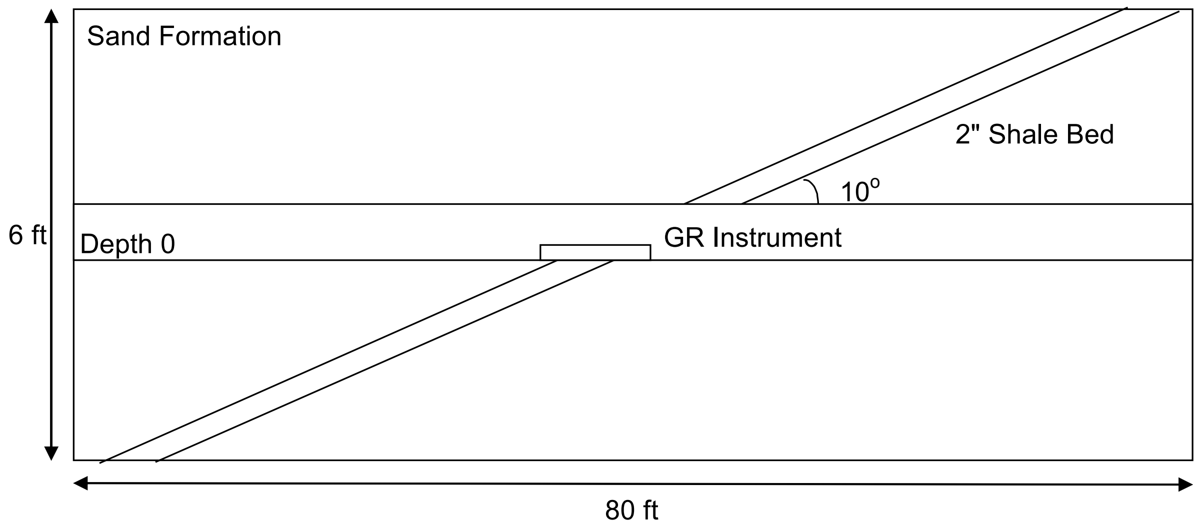

Figure 10: A 6 feet in diameter and 80 feet long sand formation with a 8 in. horizontal wellbore and a 10^o inclined shale bed. A 2×12 gamma ray instrument is shown.

Table II. Sensitivity Depth Interval and Inclination Angle

Inclination (deg)	1	5	10
Depth Interval (ft)	260	40	20

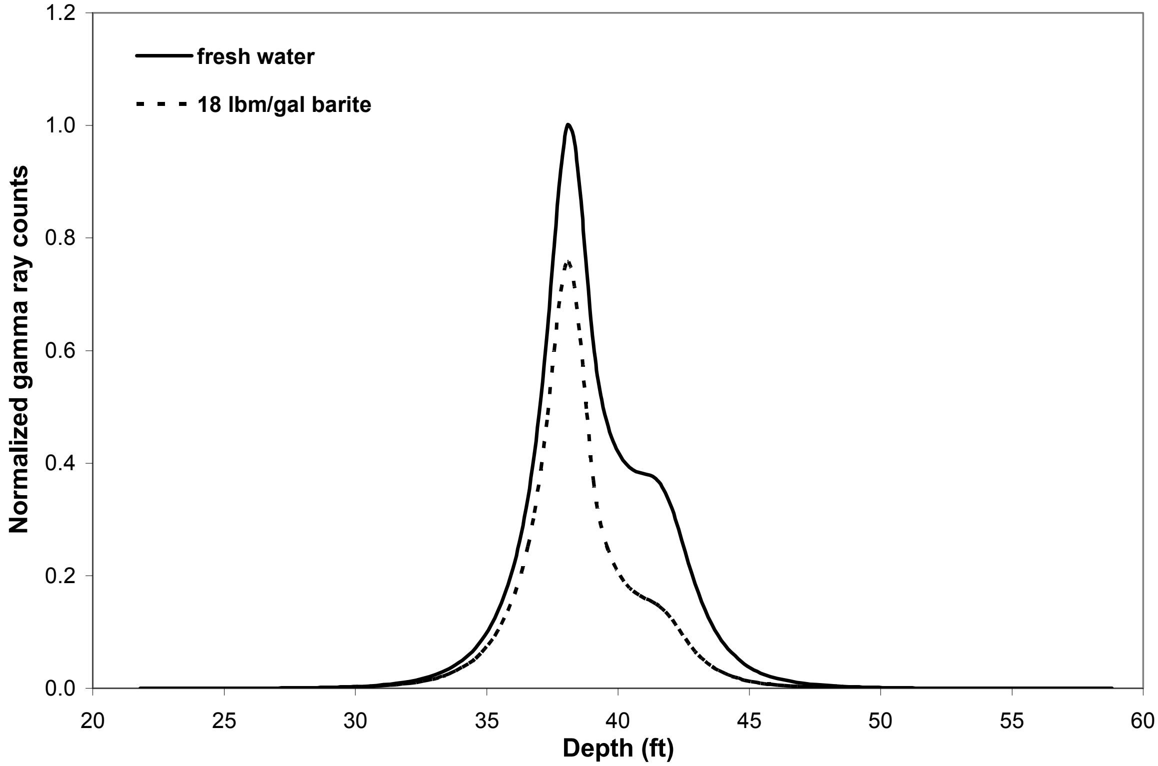

Figure 11: Log data from a 10° inclined 2 in. thick shale bed

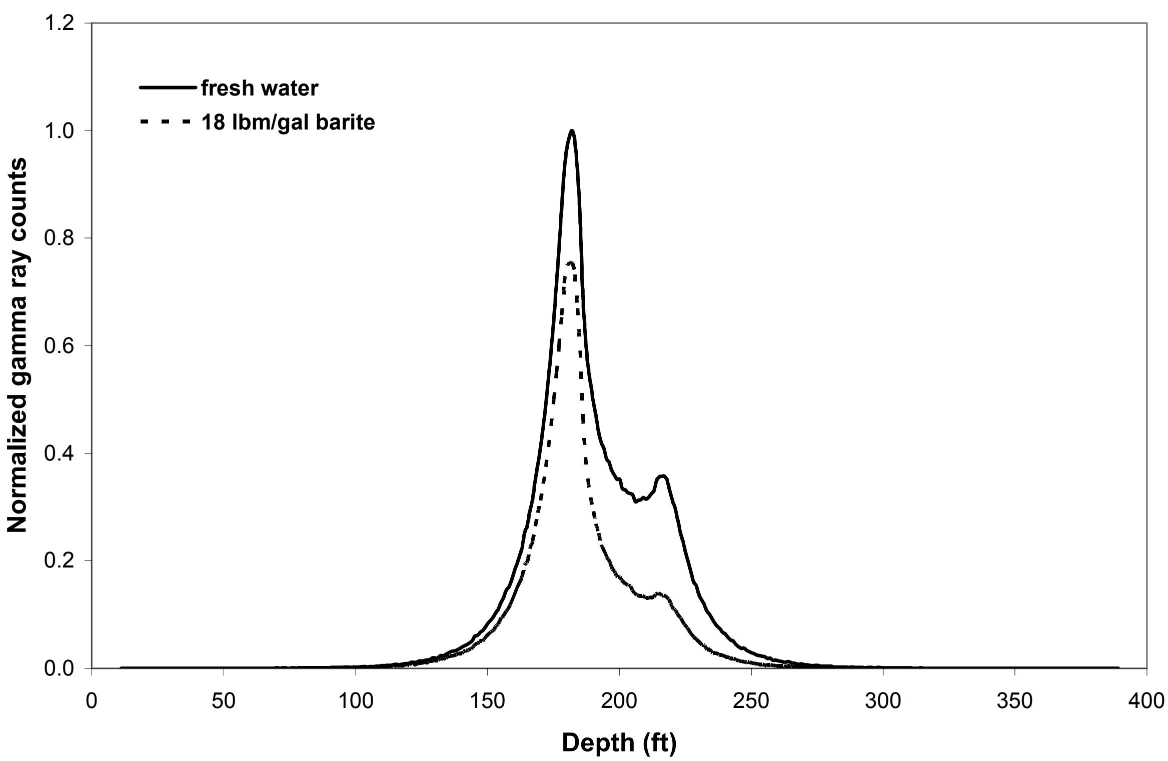

Figure 12: Log data from a 1° inclined 2 in. thick shale bed

5 CONCLUSIONS

An extensive Monte Carlo modeling study was carried out to investigate performance of a generic gamma-ray well logging device in vertical, deviated, and horizontal wellbores. With a pseudo-long detector tally and source patch describing the distributed gamma ray sources the instrument responses in complicated logging conditions were modeled with the MCNP code in a very efficient fashion. Earth formations containing single shale bed and thinly laminated sand/shale sequences were studied. Modeling results show that the depth corrected gamma ray logs in moderately deviated wells can reproduce log data acquired in standard vertical wells. In 70^o or highly deviated wells the depth corrected logs provide the identical bed thickness information with a small shift in bed boundaries. Simulated tool responses in horizontal wells intersecting thin shale formation beds with various inclination angles indicate that gamma ray logs can be used as inclination indicators and provide important guidance in drilling applications.

6 ACKNOWLEDGMENTS

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7 REFERENCES

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