CHARACTERIZATION OF A SLIM-HOLE GAMMA-RAY SONDE FOR POTASH EXPLORATION APPLICATIONS IN A SIMPLE TEST PIT ENVIRONMENT

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Abstract

Prior studies of gamma-ray tools have all been focused around instruments that typically evaluate sandstone, shale, and limestone formations that are encountered in oilfield logging. For this study, a set of experiments were conducted to characterize the lateral and vertical response functions for a slim-hole gamma-ray sonde used in the mining industry to locate potash mineral deposits.

The experiments were conducted in an indoor warehouse environment utilizing a set of large plastic tanks that were filled with light evaporite minerals (granular halite and sylvite) in differing arrangements to simulate various possible formation configurations. Measurements were taken while using a centralized slim-hole gamma ray tool in an air filled 4.5 inch plastic borehole.

Sequential tests were run to establish the linearity of tool response, the radial depth of investigation, the vertical response function, and the repeatability of the measurement. Radial depth of investigation was measured using concentric radioactive rings of increasing diameter with two possible intermediary substances, air and halite. To test vertical response a column structure was built using halite as the bottom “bed” and a sylvite layer was systematically added in known quantities to acquire a response function of increasing thicknesses. Repeatability of the measurements was verified by logging several points with multiple tools of the same model for all the various experimental setups.

Results were corrected for background radiation to predict the response in solid subsurface conditions without incident surface radiation seen in the experiments. The findings were also corrected for the differences between low porosity subsurface conditions and the unconsolidated granular products that were used in the simulated formation.

The experimental results were surprisingly close to theoretical tool response for an oil field sonde, as well as to published specifications of major oilfield logging vendor’s tools. Consequently, gamma-ray logs collected with a slim-hole tool in shallow mineral core holes should be directly comparable to oilfield gamma-ray tools run in open-hole wellbores, once corrections for borehole size and fluid content using best practices are applied.

Introduction

Gamma-ray logging has been applied to mineral exploration problems for many years, including uranium exploration (e.g. Dodd, 1966; Hawkins & Gearhart, 1968) and the evaluation of potash deposits (Alger & Crain, 1965; Crain & Anderson, 1966; Tixier & Alger, 1967). In the context of the latter the most useful tool has proven to be the gamma-ray log, because it responds directly to the potassium content of the formation.

While the underlying physics of these methods are straightforward, all applications of geophysical logging suffer from certain common problems including characterizing the volume of investigation or resolution of the measurements; motion of the logging tools as the data are captured; calibration of the tools; and a variety of environmental effects related to the presence of a borehole, its size and shape, the properties of fluids filling the borehole, presence of any steel casing and cement sheath between the borehole and the formation of interest, etc. This study was instigated to better understand the vertical and horizontal resolution of a typical mineral industry gamma-ray logging tool Once the basic tool response is established, other effects such as tool motion and the borehole can be incorporated into a quantitative model.

Gamma-ray logging is based on the decay of naturally occurring radioisotopes. The most common radioactive isotopes in the Earths' crust that contribute to natural gamma radiation are potassium-40 (K^{40}), uranium-238 (U^{238}), and thorium-232 (Th^{232}). Other radioactive isotopes, such as U^{235}, naturally occur but only in minute amounts. Both U^{238} and Th^{232} decay through a series of 10 or more intermediate products to stable lead, with gamma radiation emissions of different energies at each step (Bassiouni, 1994). K^{40}, which constitutes about 0.01% of all potassium, decays by both beta decay and electron capture. The latter decay process constitutes about 11% of all decays and yields Ar^{40} plus a 1.46 MeV gamma-ray. The natural gamma radiation is detected using a sodium iodide crystal within a scintillation device, where a sensitive photomultiplier mechanism attached to one end of the crystal records the individual light flashes that result when a gamma-ray photon interacts with an atom of the crystal. These are amplified, counted, and the resultant count rate is directly proportional to the gamma-ray flux through the crystal. The absolute count rate is a function of detector size, efficiency and the shielding provided by the surrounding tool body; consequently the counts must be calibrated to a source of known radioactivity to use the data in a quantitative manner. This is accomplished by logging a test pit with blocks of some standard material. The primary logging reference pit for gamma-ray logging is located in Houston, Texas (Belknap et al, 1959), and several secondary standard pits have subsequently been established around the U.S. Modern gamma-ray detectors of the type used in this study are extremely sensitive and detect nearly all of the gamma photon interactions with the NaI crystal. In a total gamma-ray tool all counts from gamma-rays of any energy are summed together; in a spectral gamma-ray tool the counts are separated into bins based on the intensity of the light flashes which are proportional to the energy of the incident gamma photons. This study utilized a total gamma-ray tool.

We conducted a series of laboratory tests in a warehouse environment using a slim-hole gamma-ray tool and granular potash product (both sylvite and langbeinite) in air background and shielded by granular halite (NaCl), Tests were designed initially to obtain an approximate volume of investigation in air so as to determine tank size and amount of product required for subsequent tests; followed by a simple test to verify the response of the tool varies linearly with the amount of surrounding radioactive material. We then conducted several experiments in large plastic tanks with a plastic pipe borehole, using spacers made of thin sheet plastic to make confined horizontal layers and radial nested cylinders. Details of the test arrangements and apparatus are given below.

Methods

Intrepid Potash purchased a 2PGA-1000 gamma-ray probe from Mt Sopris Instruments[1]. The probe is a slim hole tool 1.63 inches in diameter, weighing 7 lbs, with a 3 inch x 0.875 inch NaI crystal detector similar to those used in standard oilfield gamma-ray logging tools. Because the tool diameter and housing materials are different than tools that have been characterized in the literature, and because the detector is not precisely the same, we expected the tool response to be similar, but not identical, to a typical oilfield tool. The tool output was recorded in counts/sec, and has been calibrated to equivalent API units using the Houston, TX test pits to be 1 CPS = 1.19 API units as shown in Figure 1. Two additional tools of identical design and manufacture were rented and used to assess the repeatability of the measurements and variation between tools.

The materials used for tests were provided by Intrepid Potash as 50 lb. bags of unconsolidated halite, sylvite, and langbeinite. All materials were from single plant runs so the variation of materials between sacks is thought to be minimal. Each bag of potash was individually weighed prior to use to verify the exact amounts of radioactive material used. Because these products are granular, all the materials include some unknown amount of air filled voids. The bulk density for each loose material, without tamping or otherwise packing, was therefore determined by weighing a known volume of material. By comparison to the known grain density of the mineral phase, we estimate the porosity of the granular products we used to be 33% in sylvite, 39% in halite, and 43% in langbeinite. The variations in porosity between materials result from differing grain size and shapes of the crushed commercial product.

All tests were conducted in a warehouse located in central Denver, about 3 miles NE of the downtown area. The surficial deposits are thin Pleistocene eolian deposits overlying bedrock Paleocene and Upper Cretaceous Denver Formation shales (Trimble & Machette, 1979; Moore et al 2001). The background radioactivity in the area is relatively high, averaging ~82 cps as determined by a tool hung in air 4 ft above the concrete floor of the building. The background radiation increased to ~93 cps when the tool was adjacent to the floor. These are equivalent to air readings on the order of 95-110 API units.

Three sets of tests were conducted. Initially, the tool response hanging in air was measured using 50 lb. bags of sylvite (referred to as “product”) arranged radially around the tool, where the number of bags of product and diameter of the ring of bags from the tool was varied (Figure 2). All readings were taken with a stationary tool for a period up to 1200 seconds. These “bag tests” were used to 1) determine the time required to get a statistically stable reading; 2) verify linear response of the tool with the amount of radioactive product; and 3) determine the approximate volume of investigation to aid in the design of a test tank for the subsequent experiments.

The second set of tests were designed to determine the radial depth of investigation of the tool in air and when shielded by a volume of halite surrounding the tool. These are referred to as the “radial tests”. A constant volume of sylvite (14.73 cu ft; or ~23 sacks = 1150 lbs) was used for all tests so the amount of radioactive source material was held constant. These tests were conducted in a 7 ft diameter x 3 ft tall plastic tank (Figure 3A). An air filled borehole was constructed by securing a 4.5 inch O.D. length of PVC pipe to the floor of the tank with a plastic pipe flange. The tool was centered in the plastic borehole using Styrofoam standoffs (Figure 3B), and a 12.5 inch tall Styrofoam block was placed in the bottom of the tube so that the NaI detector was centered in the tank, 18 inches off bottom. Concentric rings of Plas-Tex, a thin and flexible waterproof plastic wall paneling material, were used to confine the granular sylvite in a ring surrounding the tool and the plastic borehole. Because the material is weak, plywood forms were used at the top and bottom to hold the cylinder in place when filled with product (Figure 4). The number of different rings and the largest

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[1] Mt Sopris Instrument Co, 4975 E 41st Ave, Denver, CO 80216; http://www.mountsopris.com/

outer diameter was limited by the amount of material available to fill the ring with sylvite and the inner cylinder with halite. A total of five rings were constructed (*Table 1*), beginning with sylvite immediately surrounding and in contact with the borehole up to a midpoint of the ring radius of 3 ft. The width of the ring had to be varied so as to accommodate a constant volume of radioactive material.

The third experiment was designed to determine the vertical resolution of the tool. Only a single bed contact is required to characterize this response, so a 6 ft. tall x 2.5 ft radius test tank was constructed and filled with halite to a depth of 3 ft (Figure 5). The tool was then logged across this surface in a series of 25 station measurements 3 inches apart (6 ft total tool movement). Sylvite product was then added on top of the halite layer in initially 1 inch increments and then 2 inch increments until a total sylvite layer of 32 inches was achieved. The entire 6 ft. vertical hole was logged again after each incremental increase in the thickness of the radioactive material.

All measurements were collected with a stationary tool in “time mode” for a period of 30 seconds and do not mimic the response of a moving tool. Gamma-ray counts from the detector were summed for a period of 1 second, written to file as counts/sec, the buffer flushed and measurement cycle repeated to yield a stream of 30 data points or more per station measurement. In an actual logging job data would be collected in “depth mode”, where the tool would be in motion and after each selected depth increment (e.g. 0.5 ft) the summed counts would be divided by the elapsed time for that increment, the value written to file as counts/sec, and the next measurement cycle started. For a typical oilfield logging speed of 1800 ft/hr, the tool would move approximately 0.5 ft per second.

Results

Initial air tests (“bag tests”)

The bag tests were used to assess how long the tool needed to be held on station to achieve a statistically stable answer. This is shown in Figure 6 for one test, where the X axis is the time on station, *t*, for one experiment, and the Y axis shows the standard deviation of the average from 0 to *t* in counts/sec. The tool exhibits significant instability in the readings for several seconds, then settles to a value near the long running average of 75.5 cps after about 50 seconds. The initial 5-10 seconds instability appears related to cold starting the data collection process and is not a factor once the tool has begun acquiring data. From this experiment we determined a minimum run of 30 seconds on station, and better 60 seconds, was required to get an accurate reading.

A second test was run as a simple verification of the linear response of the tool to the amount of radioactive material surrounding the tool. This was accomplished by laying 7 bags of product in a 1 foot radius circle surrounding the tool hanging in air. After measuring the response for 400 seconds, a second layer of 7 bags was added and the measurement repeated, and so forth until the stack was 5 bags tall (35 bags total, or approximately 1750 lbs of KCl. The response was absolutely linear with an R^2 of 0.998 (Figure 7), projecting back to an air background of 72 cps.

Other tests were run to determine the approximate volume of investigation in air and when the tool was surrounded by salt in order to design a suitable test tank for the subsequent experiments. These experiments were not evaluated quantitatively.

Radial (horizontal) response tests

The radial response function of the tool was determined by a series of measurements of a constant weight/volume of KCl in five concentric rings. Because the volume of radioactive material was held constant, the only variables in the test were the radius of the successive rings and the material occupying the void space between the ring and the borehole. One set of measurements were made with air in the inner cylinder, and a second set with halite in the inner cylinder.

The results of these two experiments are show in Figure 8. The uppermost set of points are the data collected with an empty inner cylinder; while the points just below them are the same readings with background radiation contribution subtracted out. The background correction varies with the radius of the ring because the sylvite ring itself acts as shielding to radiation coming from outside the ring. Therefore as the ring gets smaller a greater amount of background radiation was shielded by the geometry of the experiment relative to a large ring where significant radiation comes up through the floor of the inner cylinder; the larger the inner air filled ring, the larger the background counts received. The bottom two sets of points represent the raw readings with the inner ring filled with salt, and those readings that were background corrected. In this case the background corrections are small because most radiation was shielded by the salt and sylvite surrounding the tool. We estimated an average of 10 cps results from radiation coming directly up the axis of the borehole from the floor, plus a small amount of ambient radiation passes through the salt when the ring is small. Only three readings were taken with salt in the inner cylinder due to a limited volume of halite available for the experiment.

The generalized relationship for attenuation of gamma-rays in a medium is given by:

$$N = N_0 e^{-\mu\rho x} \qquad [1]$$

where N is the gamma-ray flux at the detector, N_0 is the total gamma-ray flux, μ is the mass adsorption coefficient of the medium, ρ is the material bulk density, and x is the distance over which gamma-rays are being attenuated (Ellis, 1987). In this experiment, the gamma-ray flux was measured; the bulk density of the medium and the attenuation distance are known; and the total gamma-ray flux (N_0), while unknown, was held constant by using a fixed quantity of radioactive material (sylvite). The mass adsorption coefficients of the medium are thus the only unknowns. By regression analysis of the raw data we are able to determine the quantity $\mu\rho$ for the two experiments (inner cylinder air; inner cylinder of halite), then correcting for the measured porosity of the granular medium and the density of solid salt, we compute the radial geometrical factor for three cases: air, salt with 39% air filled porosity, and solid salt. The J functions are shown in Figure 9. In the present experiment, with a centered slim tool in a 4.5" borehole, 90% of the response in dense salt (density 2.16 g/c3) is at 31 cm (12.2 inches) and the 50% point is at 11.5 cm (4.5 inches). The mass adsorption coefficient for halite estimated from these data is 0.039 cm2/g.

Our measured tool response is similar to, but not identical, to the published J function for 1.46 MeV K^{40} gamma-rays obtained by Monte Carlo modeling (Wahl, 1983), where the 50% cumulative response is shown to be 15 cm (5.9 inches) from the center of an 8 inch borehole, and the 90th percentile is at 27 cm (10.6 inches). This is shown by the heavy solid line in Figure 9. Wahl modeled a formation density of 2.2 g/c3, a liquid filled borehole, with a borehole eccentered tool. Although he did not state the mass adsorption coefficient, we determined it is ~0.047 cm2/g based on our curve fit to the published illustration and assuming the lithology was porous limestone. For comparison, we show an additional curve computed using a solid quartz sandstone density of 2.65 g/c3 (0% porosity) and assuming the mass adsorption coefficient for quartz is similar to that determined for salt. This is a reasonable approximation for matter composed of light elements. The 50% response point for sandstone is at 9.5 cm (3.7 inches) and the 90% point at 25 cm (9.8 inches). Note that our sandstone curve and the Wahl curve converge at approximately 28 cm (11.0 inches).

The curve offsets <28 cm apparently result from the difference in borehole size, tool positioning, and borehole liquid. Also our curve is empirically determined, whereas the Wahl curve is a model assuming some hypothetical tool/detector configuration. Our prediction for sandstone with 27% porosity, with a bulk density of 2.2 g/c3, is very close to the solid salt line shown on Figure 9.

Vertical resolution tests

The vertical resolution of a logging tool can be determined by logging a sharp interface between two materials. Logging a second interface, for example across a thick bed, is unnecessary because the upper interface is just a mirror image of the response across the lower interface.

For this experiment, we filled a plastic tank as described previously with 3 ft of granular halite. An initial logging run to determine the baseline response without any radioactive layer was run and is shown as the heavy dashed line on Figure 10. The minimum reading of ~16 cps was attained when the sensor was 23.5 inches off bottom. Readings closer to the floor are higher, and the response slowly increases towards the salt-air interface at 36 inches then increases to an air background of 77 cps when the tool is 5 ft off bottom.

These data were interpreted as gamma radiation from the earth beneath the tank is largely shielded by the salt in the tank, but some radiation comes directly vertically through the air filled borehole and is counted by the sensor. When the tool was positioned at the midpoint of the salt, it had the maximum shielding from ambient radiation, and as it logged out the top of the salt section it received increasing radiation reflected off the building and the air coming down the top of the borehole. The maximum reading of 77 cps reflects an air reading with the ground below partly shielded by the salt filled tank.

Accordingly, these background readings were subtracted from the subsequent experiments to attain a background corrected log. These are shown by the solid lines in Figure 10. The data were collected as a series of 30-second station measurements at 3 inch increments from tool on tank bottom (where the sensor is located 5.5 inches above tool measure point) to 6 ft off bottom, for a total of 25 stations. Initially sylvite was added in 1 inch increments, with a "logging run" between each additional buildup of the radioactive layer. After 6 inches, material was added in 2 inch increments up to a total of 32 inches. For graphical clarity only selected curves are shown on Figure 10.

The 1 inch KCl curve on Figure 10 illustrates the response to a very thin radioactive layer after baseline correction. The bottom and top part of the log show a base-lined response near 0 cps, and the peak reading was 56 cps at the 38.5 inch station immediately above the KCl layer. This remains true up to a layer thickness of 6 inches, after which the peak reading starts to migrate slowly higher with increasing KCl layer thickness until a 26 inch layer is attained, at which point the peak readings stabilize at 46.5-49.5 inches above tank bottom. The peak reading of 700 cps is constant in the subsequent experiments up to a layer thickness of 32 inches, at which point the readings had clearly reached a flat plateau. This clearly defines a thick bed for this tool.

Above 40 to 50 inches off bottom, depending on the layer thickness, the readings drift back to lower values up to the top of the log at 75.5 inches off bottom. The position of the inflection point is related to the thickness of the KCl layer, and the readings start to drop back when the sensor is close to or above the KCl-air interface. The readings never dropped back entirely to the zero baseline because the tool sees an air response to the thick radioactive layer below when it is raised above the KCl layer.

Figure 11 shows the tool response to the 28 inch thick KCl layer with the top and base of the sylvite layer marked. The log is slightly asymmetric because it is salt below and air above this layer, with the upper half space tailing off more slowly than the lower half space into salt. Overall this curve shows full response at the midpoint of the 28" bed. The vertical resolution of the tool is estimated at 68 cm (27 inches), and the shoulders on either side of a bed boundary are located 13.5 inches above and below the bed boundary respectively. At the midpoint of the bed, the tool reads the peak reading of 700 cps and thicker beds do not increase this value. All of these numbers are based on granular material with 33-39% air filled porosity, as described previously. Based on the results of the horizontal depth of investigation tests, we expect the bed resolution in solid material will be slightly sharper due to the greater attenuation of non-porous materials. The estimated bed resolution in solid halite is 49 cm (19 inches), using the mass adsorption coefficient for halite determined previously.

Linear response test for mixtures of potash and salt

A simple test in a small tank was conducted to verify the linearity of tool response to various mixtures of halite and sylvite. Five readings were taken in a very large plastic garbage can with a 4.5 inch borehole in the middle. The annular volume was filled with mixtures consisting of 100% halite; 75% halite/25% sylvite; 50% halite/50% sylvite; 25% halite/75% sylvite; and 100% sylvite. All mixtures were based on weights, and the granular product was well mixed prior to filling the tank. A single station measurement with the tool sensor centered in the test tank was used to determine the counts. The tank used was sufficiently large to include the 90% depth of investigation based on the prior radial testing.

The results of this experiment are shown in Figure 12. Like the simple bag test to verify linearity of response with amount of radioactive material, this test reveals a highly linear response function ($R^2 = 0.998$) and projects to a background reading in salt of 62 cps, or 65% of the reading in air. From this test we conclude sylvite and halite have essentially identical mass adsorption coefficients, and %K_2O content of a mixed sylvite-halite ore body can be determined with high precision without correction for different gamma-ray adsorption characteristics of the two components.

Tool repeatability test

Three different gamma-ray sondes, all of the same tool manufacture and model, were available to us during the testing phase of this project, although not all at the same time. Several tests were run with a tool hung in air around an array of bags of product to assess the variability in readings between tools. These included background radiation readings with various amounts of halite surrounding the tool as shielding; and product tests with variable amounts of KCl arrayed around the tools hung in air. The results of this are shown in Figure 13. The tool response was remarkably similar, with all tools reading within +/- 3 cps of the same value for each experiment. Repeatability of a single tool to measurements under the same conditions were similarly precise. For a typical peak reading of 700 cps in a thick sylvite layer, the precision and repeatability exceeds 0.5%. Accuracy, of course, is a function of the tool calibration, the model used to convert tool counts to % K_2O, and the thickness of the layer compared to the vertical resolution shown in Figure 11. For a typical measurement in a thick (>28 inch) sylvite layer, with a stationary or slowly moving tool so the average count time per station exceeds 1 second[2], the precision of the counts should be better than 1% and the corresponding %K2O determination within 0.18%.

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[2] The tool should not be logging any faster than 0.5 fps or 30 ft/min in order to count for 1 sec over each 0.5 ft increment, assuming standard oil field logging resolution. For high resolution logging to resolve thin ore zones (e.g. 0.2 ft sampling rate) we recommend not more than 12 ft/min = 720 ft/hr. Obviously, only the section of interest needs to be logged at a reduced rate for high resolution data and the remainder of the section can be pulled at normal logging speeds.

Discussion

Comparisons to published oilfield tool responses

Table 2 summarizes the characteristics of the mineral logging sonde used in this study alongside the published specifications for several modern oilfield logging tools. This list was compiled from company brochures and websites and is not comprehensive. Also shown are the specifications taken from the computer modeling approach taken by Wahl (1983). We suspect many of the published tool specifications were actually estimated by modeling rather than measured as was done in this study. Figure 14 is an example log that shows the gamma ray response of the Mount Sopris tool (solid green line track 3 converted to API units) overlaid by the total K2O results from the mineral assay analysis (lime green bars in track 3) .

From this, we conclude the Mt. Sopris logging sonde is quite similar in response to typical oilfield tools deployed by the major service vendors. Although borehole size, borehole fluid, positioning of the tool in the borehole, etc. will vary between the test environment used here and actual field logging conditions and for that matter from well to well, the overall response functions should be very close. We find no fundamental or theoretical barriers to cross-calibrating the mineral logging data, which is commonly tied to core analyses, to oilfield tool responses collected in either open-holes or cased-holes. Borehole environment corrections and normalization will be required to reconcile the data from well to well, these procedures are well established in the log interpretation community and are routine. Constructing a simple test pit with a large borehole for oilfield sonde testing would greatly facilitate the direct comparisons of these data sets.

Conclusions

Based on the experiments described above, we found:

1. A typical slim-hole, minerals logging gamma-ray sonde has similar (but not identical) response characteristics to a standard oilfield gamma-ray tool.
2. The depth of investigation in pure, solid salt is 11.5 cm (4.5 inches), defined as the 50% cumulative response. The 90% cumulative response is at 31 cm (12.2 inches).
3. The vertical bed resolution is 68 cm (27 inches) in granular product and was estimated to be 49 cm (19 inches) in solid salt. Vertical resolution is defined as the minimum bed thickness required to measure a full peak response (for the radioactivity of the surrounding source) at the midpoint of the bed.
4. The gamma-ray tool response is absolutely linear with respect to the amount of radioactive material within the volume of investigation, to a high degree of precision. This was verified by both varying the total amount of radioactive material in the volume of investigation, and by determining the gamma-ray counts for varying mixtures of radioactive and non-radioactive evaporate.
5. The mass adsorption coefficients of sylvite (KCL) and halite (NaCl) are nearly identical, and are very close to sandstone (SiO_4). In the absence of significant heavy elements, differences in mineralogy can likely be ignored for potash ore grade determination.
6. The tool response experimentally determined in this study is in agreement with published modeling studies of gamma-ray logs.
7. There are no fundamental limitations or barriers to the application of gamma-ray logs to determine the potassium content of potash and langbeinite ores.

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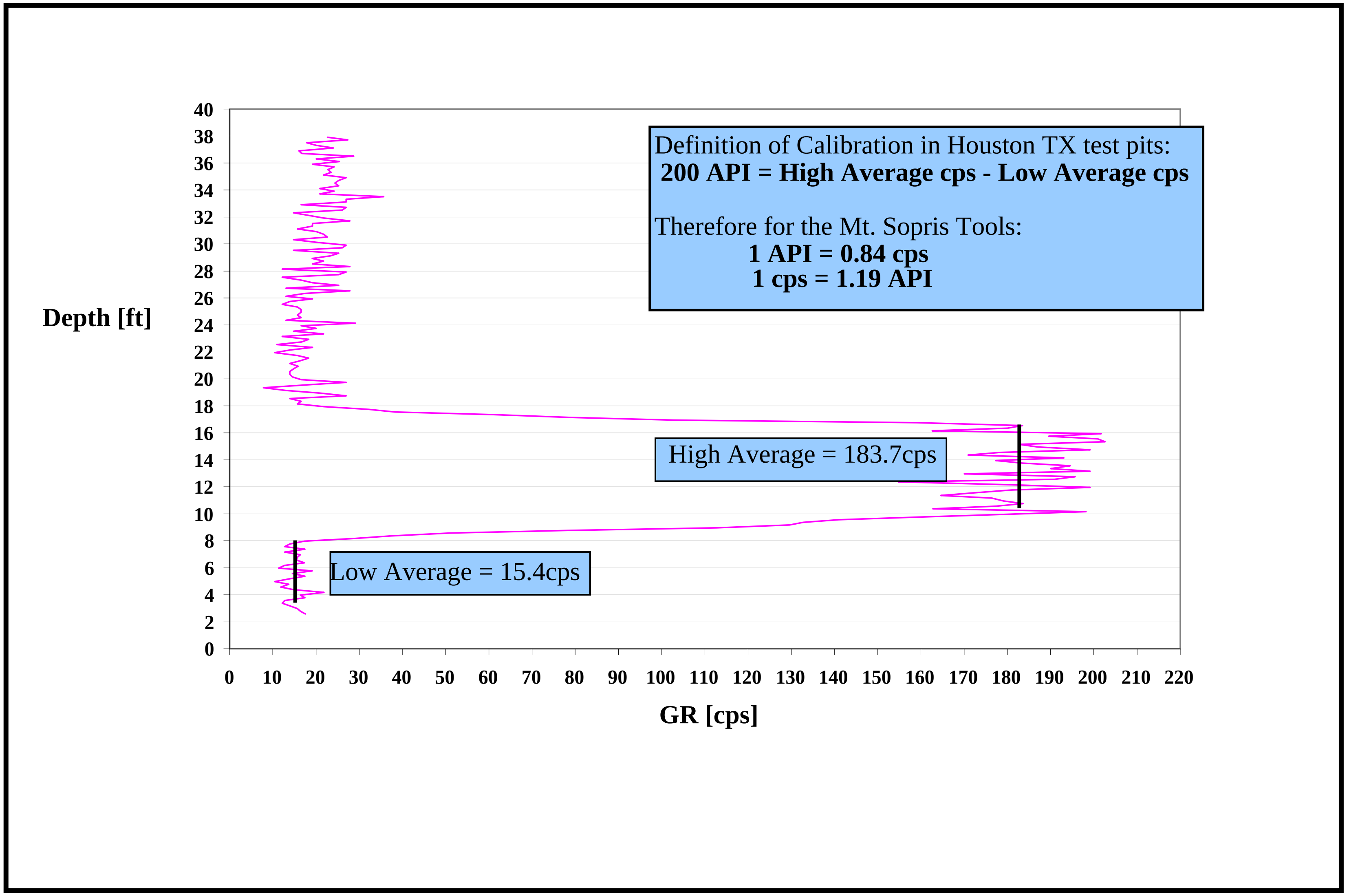


Definition of Calibration in Houston TX test pits:
200 API = High Average cps - Low Average cps

Therefore for the Mt. Sopris Tools:
1 API = 0.84 cps
1 cps = 1.19 API

High Average = 183.7cps

Low Average = 15.4cps

Figure #1: API Calibration Test Pit in Houston, TX

Figure #2: Photos of the initial “bag tests”

Figure #3A: Empty test tank with 4.5” borehole

#3B: Gamma-ray sonde with Styrofoam centralizers

Figure #4A: Test tank set up for radial depth of investigation tests showing plywood forms and nested cylinders, prior to filling with product.

Figure #4B: Radial tank set up after filling with product.

Figure #5: Test tank set up for vertical resolution experiments.

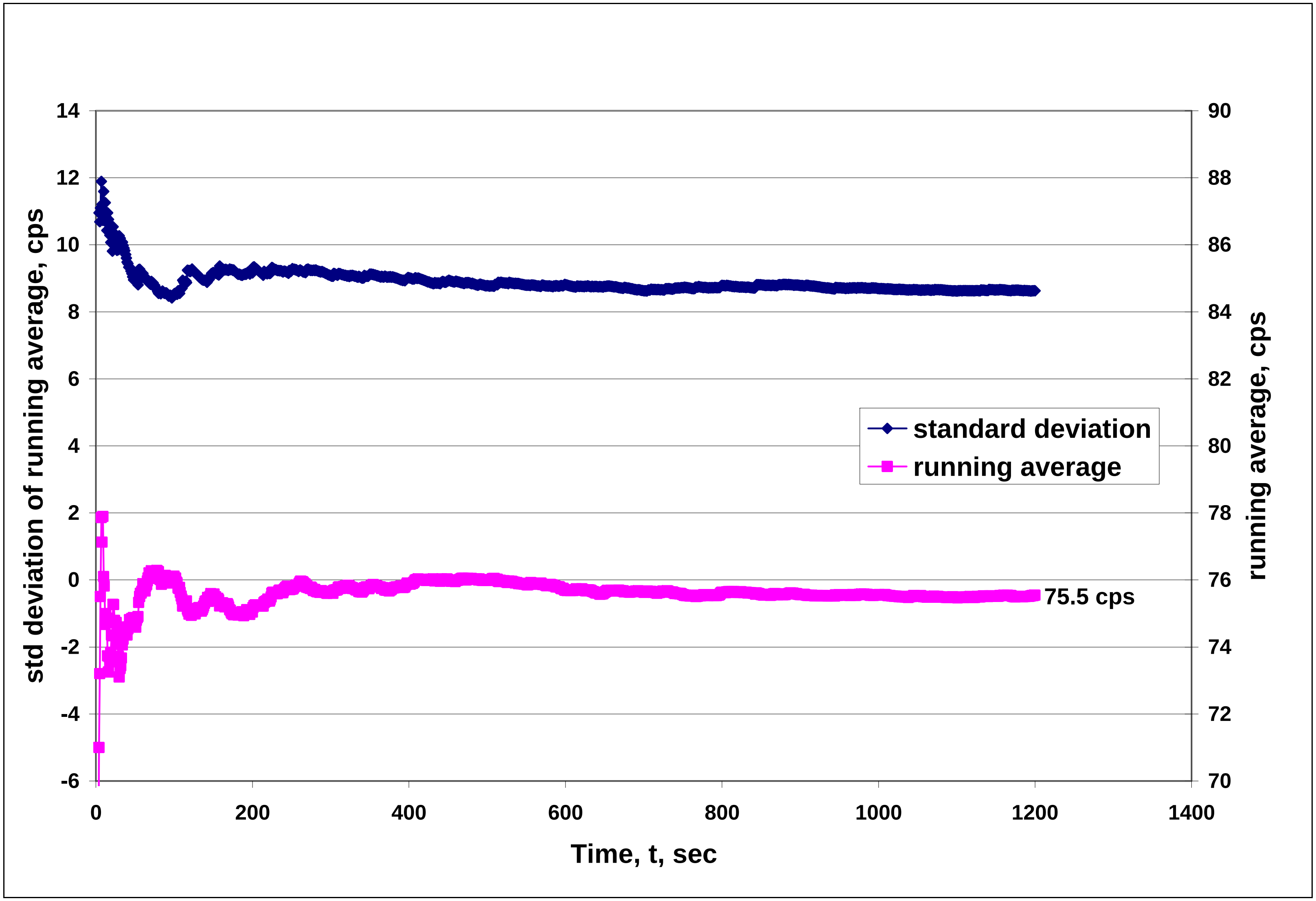


Figure #6: Bag test showing raw data for a 20-minute single station measurement.

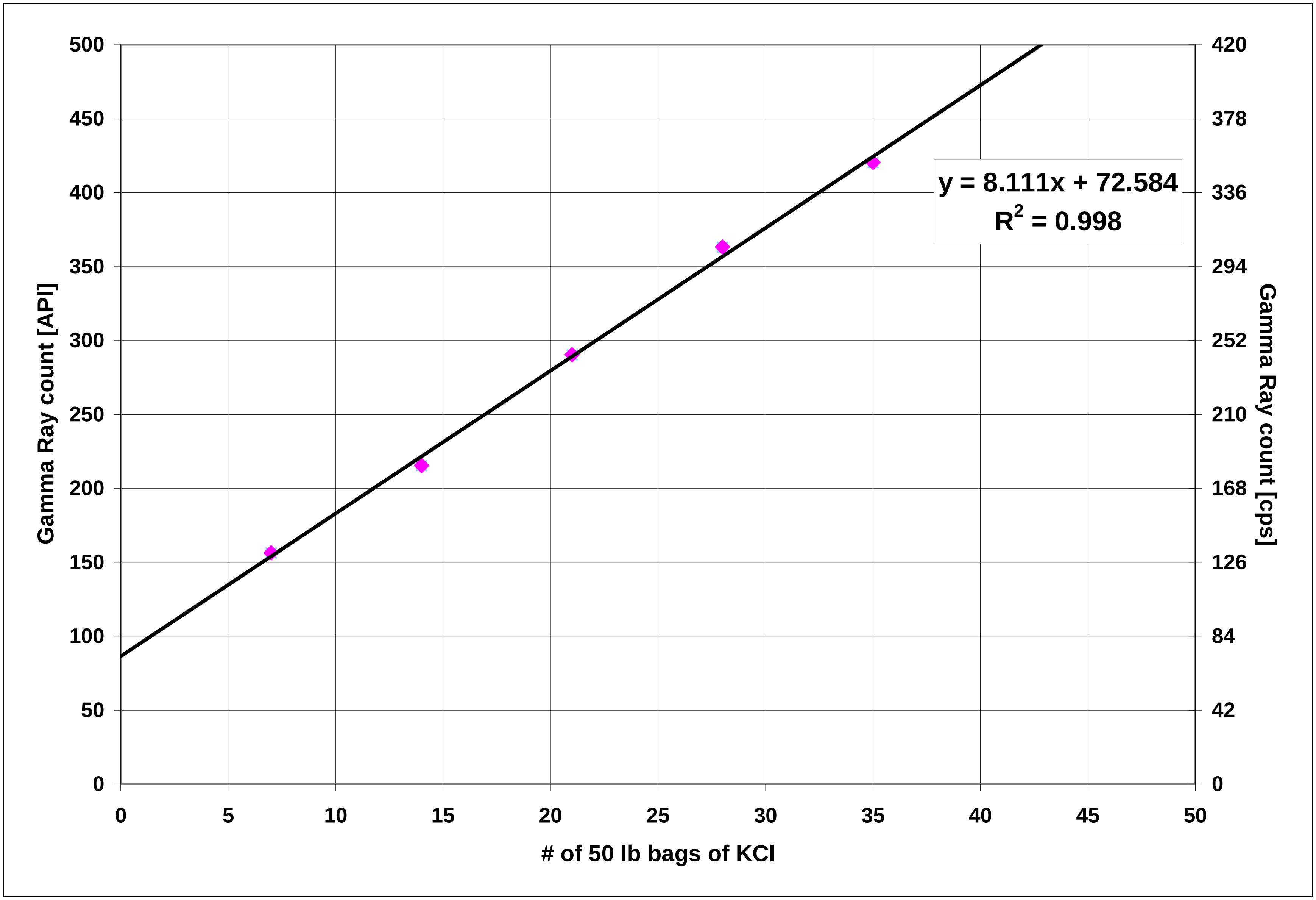


Figure #7: Response linearity test using 7 to 35 bags of product in a 1 ft radius array around tool hung in air.

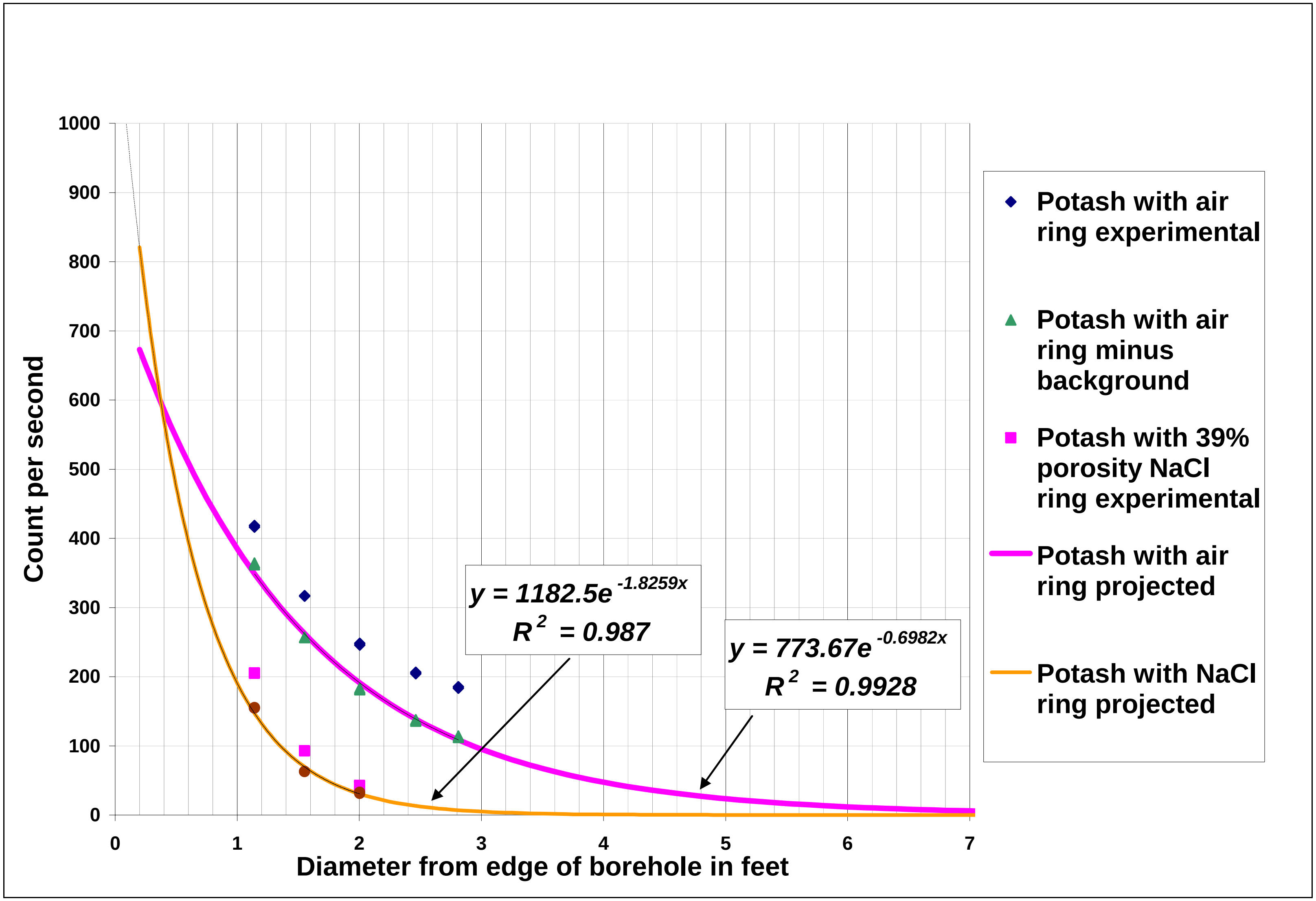


Figure #8: Radial response tests raw and background corrected data.

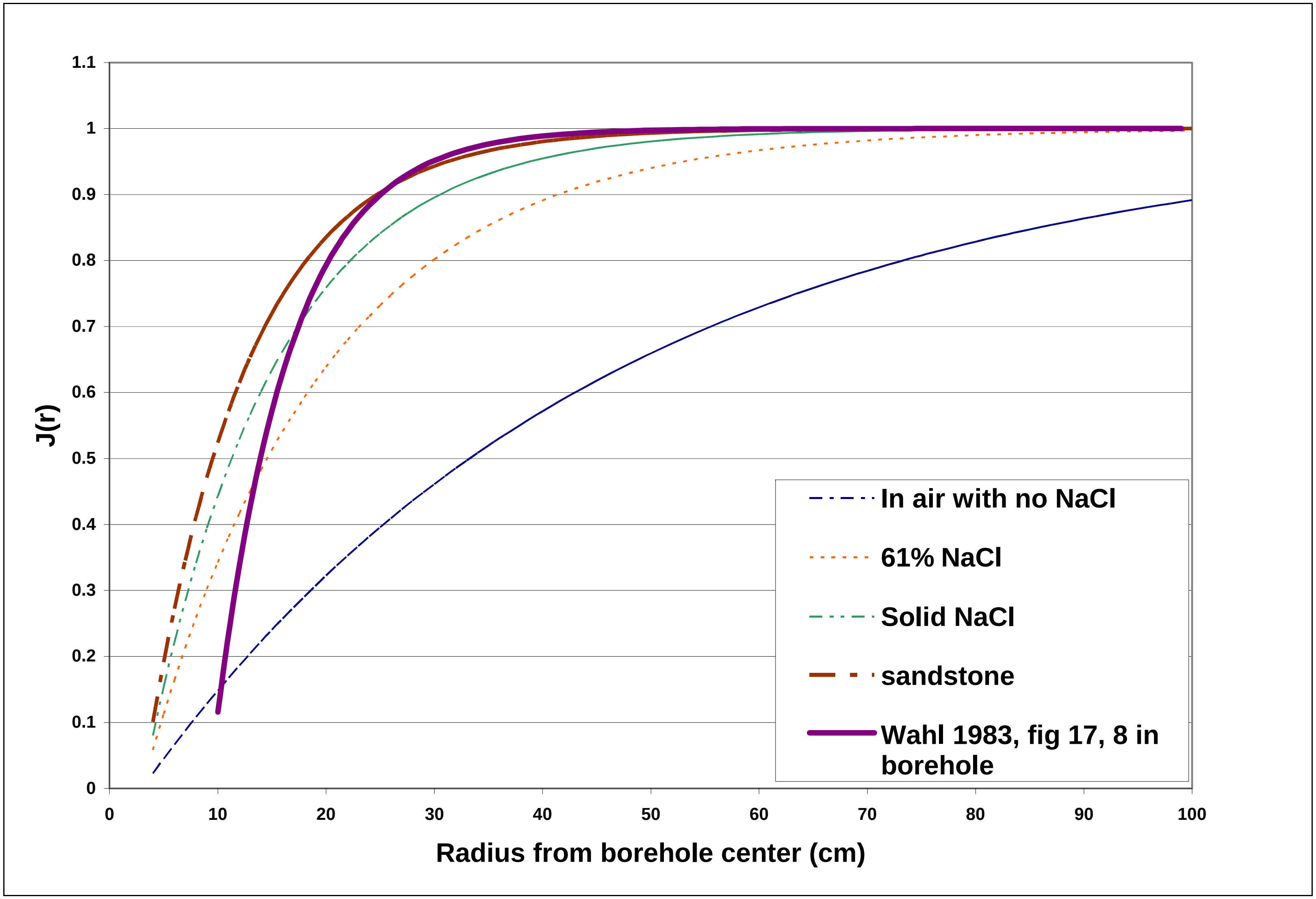


Figure #9: Radial depth of investigation (J function).

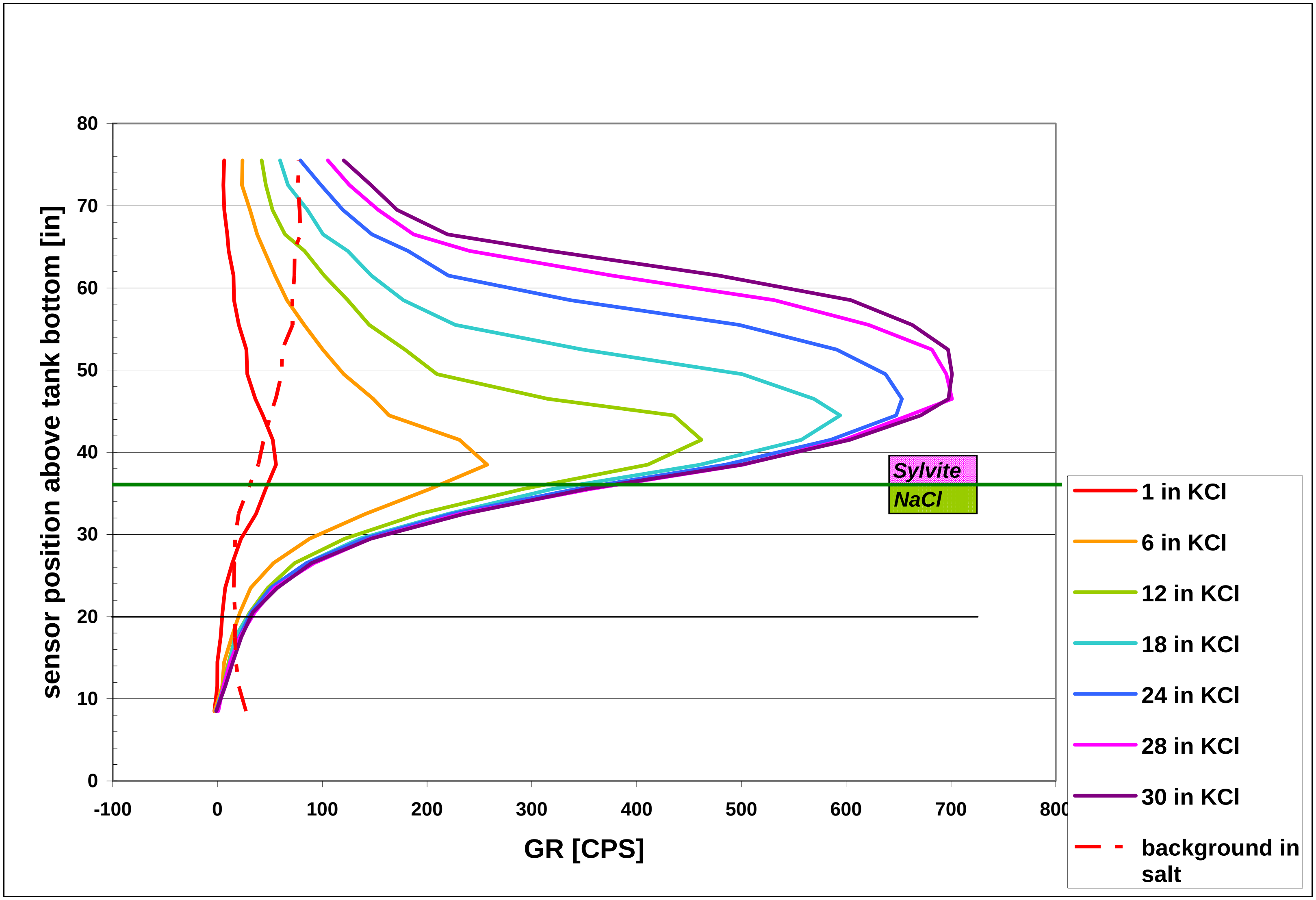


Figure #10: Vertical resolution tests (background corrected) for 1-32 inches of KCl on a 36 inch salt base.

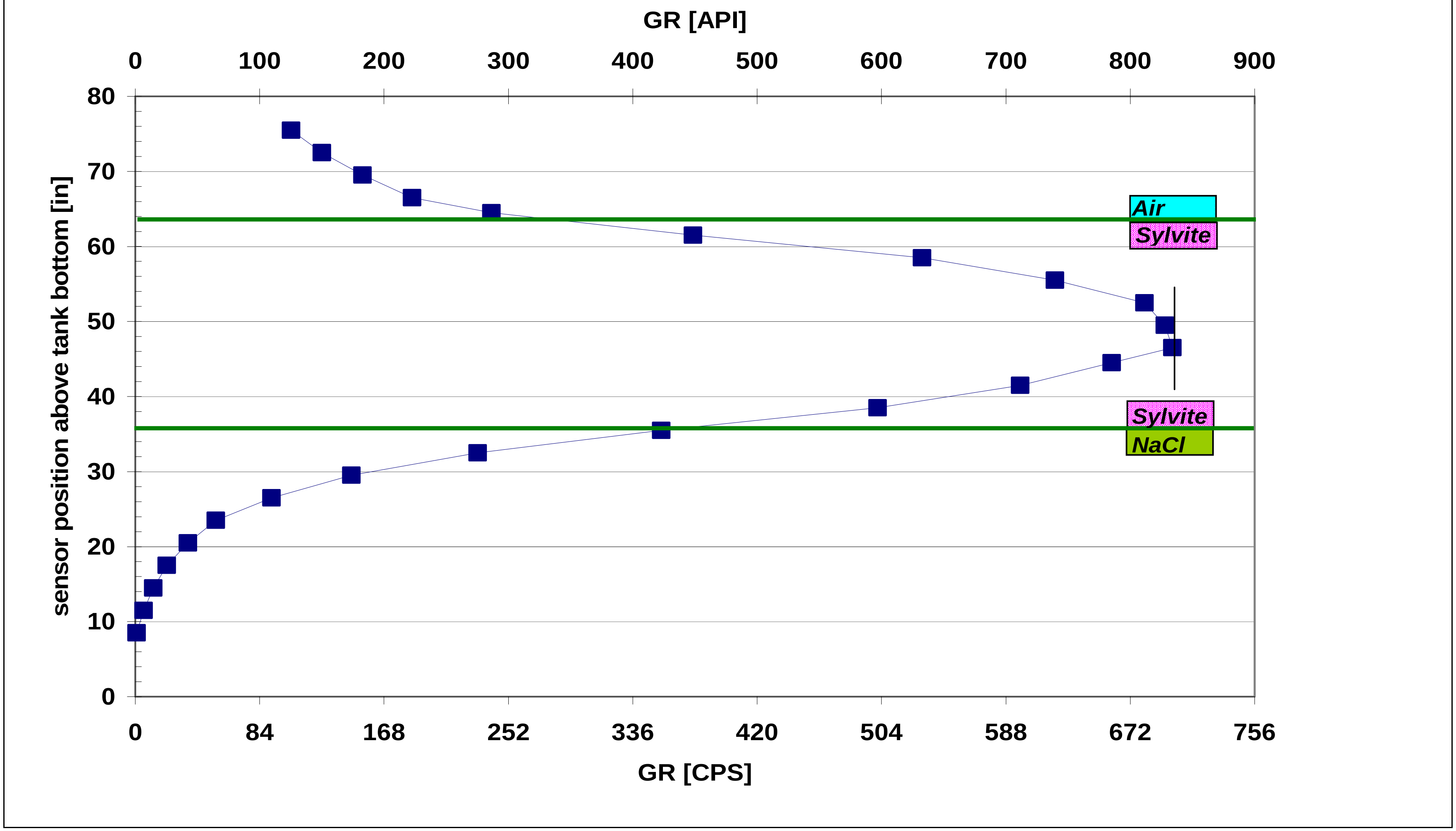


Figure #11: Baselined vertical response function for 28 inch layer of granular KCl. This is essentially a vertical J function for this tool in a porous evaporite media.

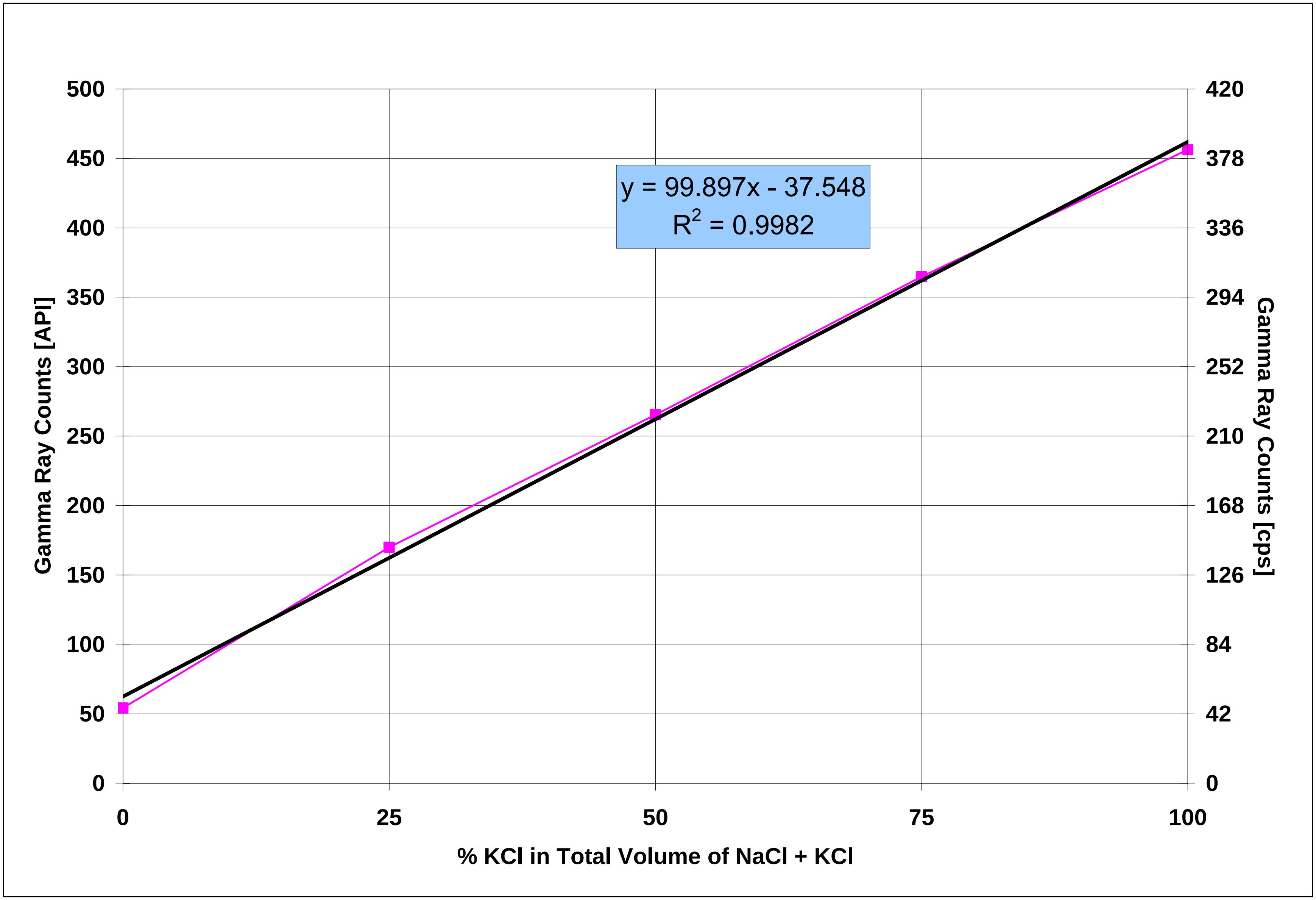


Figure #12: Linear response test for several mixtures of potash and salt.

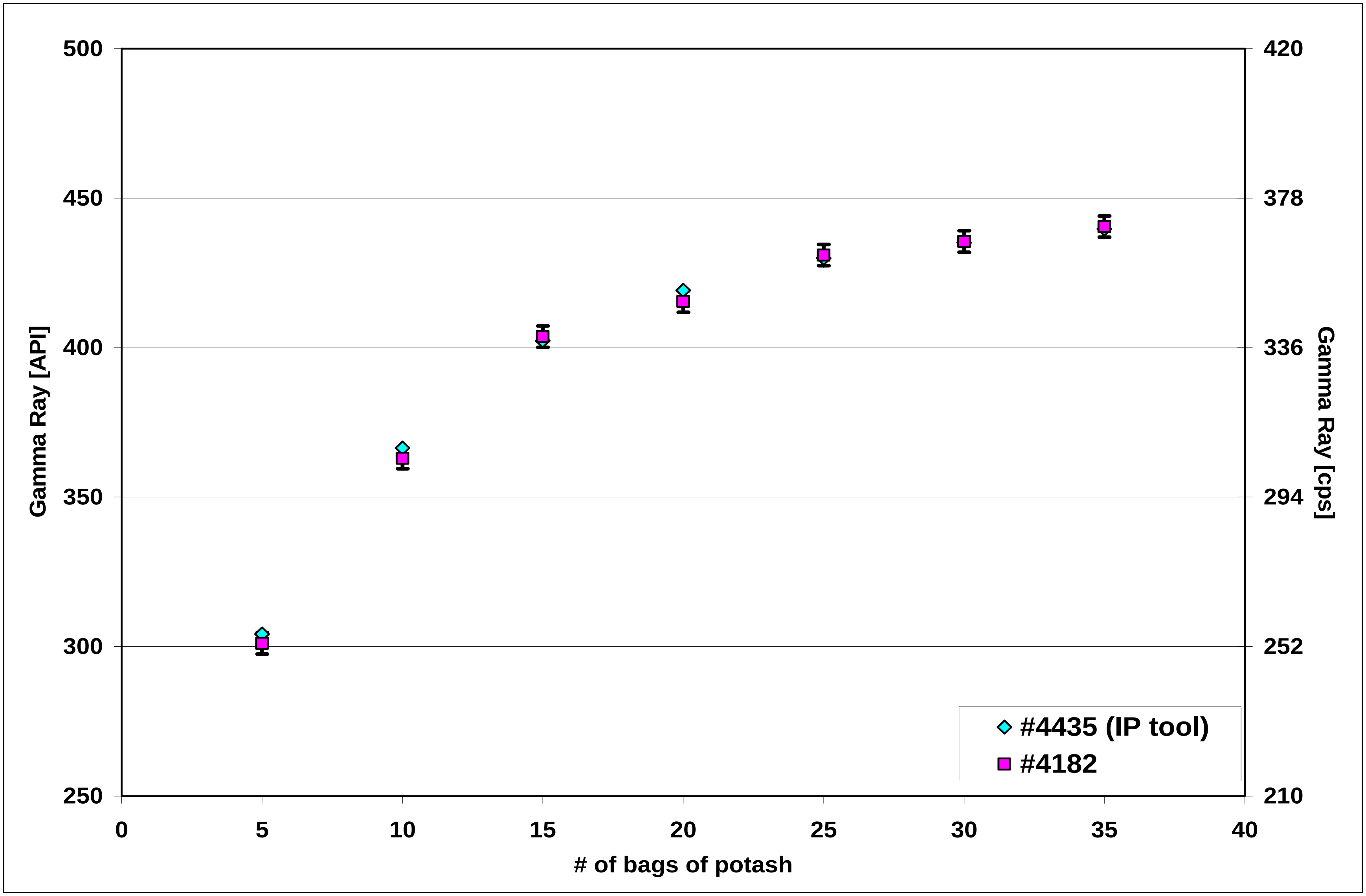
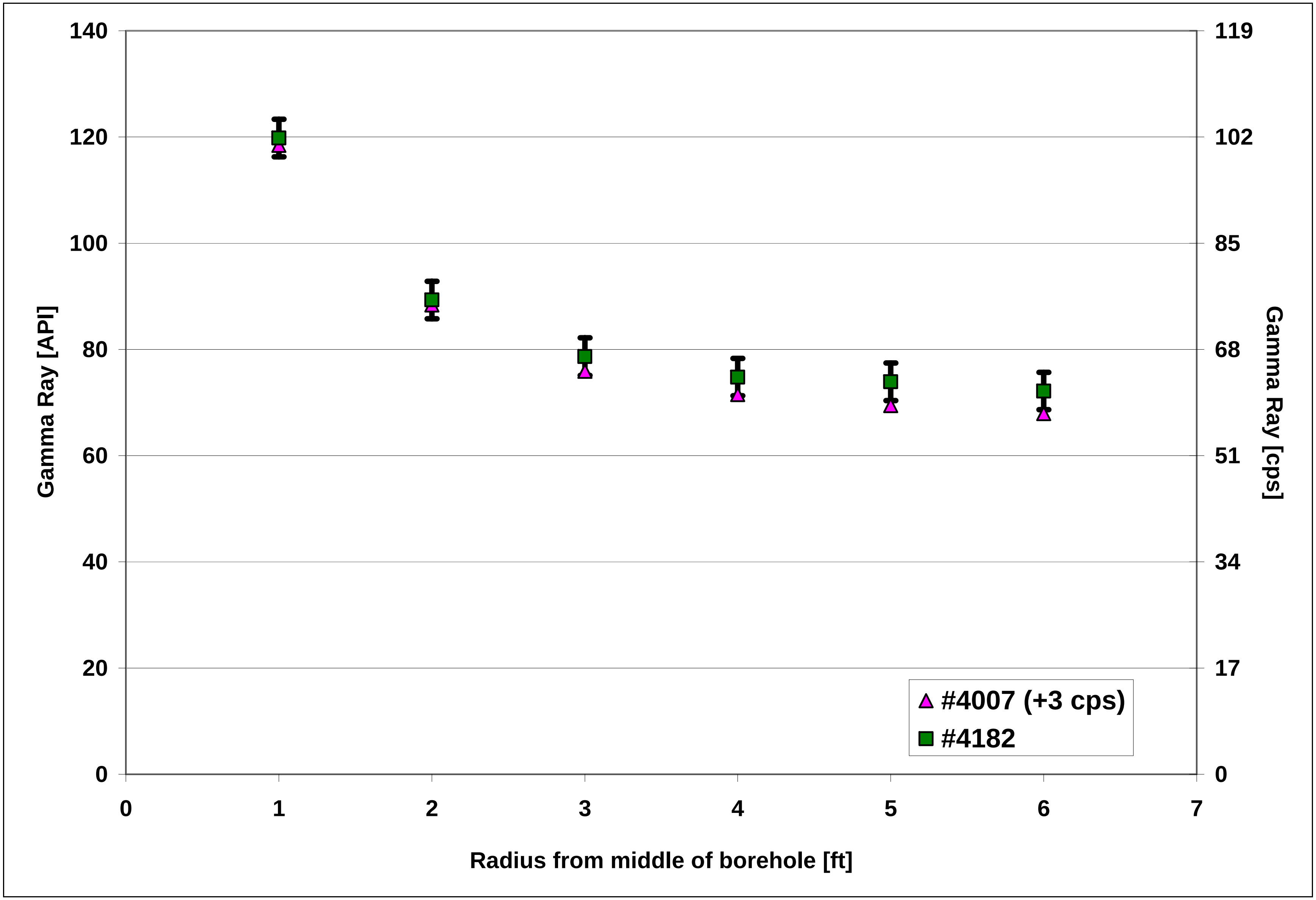


Figure #13A: Variation between different logging tools - “Bag test” with sylvite directly around bucket



#13B: Variation between different logging tools - 6 bags of KCl vs. radius from tool. (Tool #4007 was normalized by +3 cps)

Table #1: Table of radial ring dimensions

Substance Filling Inner Ring	**Inner Radius**	**Outer Radius**	**Mid Radius**
Air	2.875’	3.13’	3’
Air	2.5’	2.80’	2.65’
Air and NaCl	2’	2.36’	2.19’
Air and NaCl	1.5’	1.95’	1.74’
Air and NaCl	1’	1.60’	1.33’
Sylvite directly around borehole	0.1875’	1.26’	0.90’

Table #2: Table of Published Gamma Ray Specifications

	Mt. Sopris Instruments	Schlumberger	Halliburton	Baker	Weatherford	Wahl Tool Model
Measurement Range	0-100,000 CPS gamma	N/A	N/A	N/A	0 - no practical limit	theoretical response
Depth of Investigation	4.5 in (50%); 12 in (90%) in 2.16 g/c3 salt	9 ~ 15 in.	4 in (50%); 11 in (90%)	12" for 8" hole with 20% φ	N/A	4 in (50%) and 10 in (90%) in 2.20 g/c3 formation
Vertical Resolution	19 in in salt	24 in.	18 in	N/A	N/A	~30-35 cm
Precision / Resolution	0.02% of full scale	N/A	At 30 ft/min ±5% or ±5 API, whichever is greater At 60 ft/min ±7% or ±7 API, whichever is greater	N/A	0.7 API	N/A
Accuracy	±1% of full scale	±7 GAPI at 1800 ft/hr	±5 API	±2.6 p.u. in shale	N/A	N/A

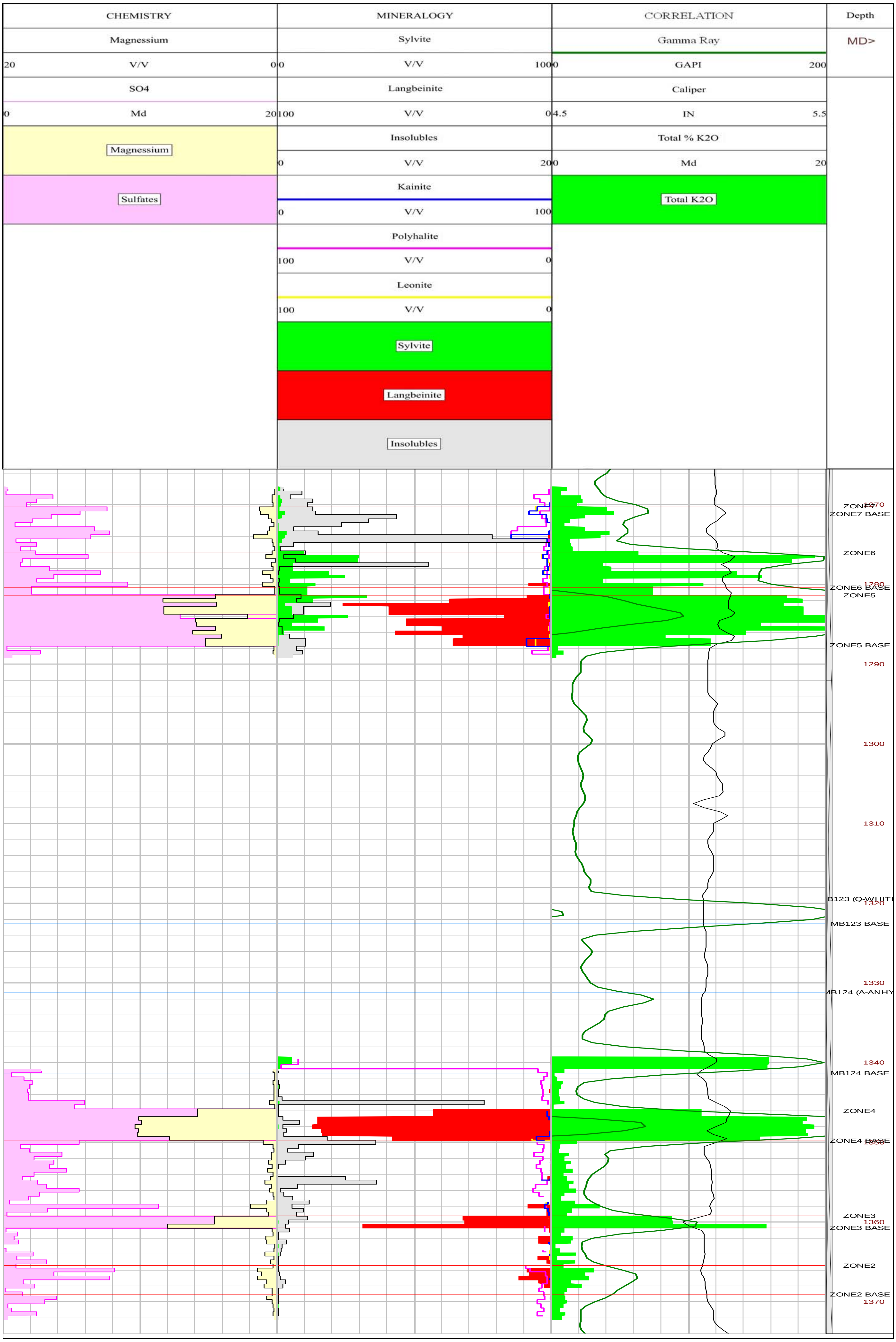


Figure 14: Example log of Gamma Ray Response in API to mineral assay data