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Evaluation of Potash Grade with Gamma-ray Logs

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Open-File Report 2007–1292

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
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Suggested citation:
Nelson, Philip H., 2007, Evaluation of potash grade with gamma-ray logs: U.S. Geological Survey Open-File Report 2007-1292, 14 p.

Abstract

Potassium is an emitter of gamma-ray radiation, consequently deposits of potash can be detected and evaluated using gamma-ray logs. A method originally designed to evaluate uranium deposits in boreholes can also be applied to potash deposits. The method equates the depth-integral of a gamma-ray log to the grade-thickness product of a potash-bearing bed or series of beds. The average grade of a bed is then determined by dividing by the overall bed thickness, which can also be obtained from the gamma-ray log. The method was tested using gamma-ray logs and potash assays from boreholes near Carlsbad, New Mexico.

Introduction

The radioactive isotope K-40 forms 0.01% by weight of natural potassium and emits a sufficient level of gamma rays to be detectable in the subsurface. Because potassium is one of only three geologically common elements that emit gamma rays, the best approach to the estimation of potash grade in boreholes is through the use of the gamma-ray log. The gamma-ray response to a "formation" comprised of pure potassium-bearing minerals was computed by Edmundson and Raymer (1979) and included in a tabulation by Hearst and others (2000), as shown in table 1:

Table 1. Gamma-ray responses to potassium-bearing minerals. From Edmundson and Raymer (1979).

Mineral	Chemical composition	K (wt percent)	API units
Sylvite	KCl	52.4	747
Carnallite	$KMgCl_3 \bullet 6H_2O$	14.1	200
Langbeinite	$K_2SO_4Mg_2(SO_4)_2$	18.8	268
Polyhalite	$K_2SO_4Mg(SO_4)(Ca(SO_4))_2 \bullet 2H_2O$	13.0	185

The measured gamma-ray flux in a potash zone varies with mineral concentration. Peak gamma-ray values in 16 potash zones in wells drilled in southeastern New Mexico range from 120 to 270 API units (Lewis, 2006).

The estimation of radioactive concentration from gamma-ray logs was of great interest in the assessment of uranium reserves and a technical procedure for doing so was developed in the late 1950s in work sponsored by the Atomic Energy Commission. Borehole calibration facilities containing known concentrations of potassium, uranium, and thorium were established at various sites in the western United States (Steele and George, 1986). The procedure for estimating the grade of radioactive material is directly applicable to potash, as described below.

Method of Obtaining the Grade-Thickness Product from Gamma-Ray Logs

Gamma-rays emitted by a thin bed of radioactive material penetrate adjacent beds as well as the radioactive bed itself. Consequently, a logging tool measuring gamma-ray activity in a borehole penetrating a sequence of thin radioactive beds will measure not only the radiation of the nearest bed but also that of adjacent beds. These “tails” of radiation pose a problem in estimating the amount of radioactive material in a bed, because radiation encountered in a borehole will be the sum of radiation emitted by the radioactive material at that depth plus the sum of the “tails” from all adjacent beds. As a consequence, a plot of gamma-ray activity γ (measured in a borehole) versus the concentration of in situ radioactivity (measured as grade G from core material) can exhibit considerable scatter, reducing the utility of the form $G = m\gamma + b$, where m and b are empirical constants. (The determination of true grade from a simple linear relation is valid only if the gamma-ray detector is positioned in the center of a thick bed with uniform radioactivity, where “thick” means greater than 3 ft (Scott, 1963).)

Scott and others (1961) showed experimentally and theoretically that the grade-thickness product of a radioactive bed is proportional to the area under the gamma-ray curve,

$$GT = KA \qquad (1)$$

where:

G is the grade or average concentration of a radioactive element by weight in a bed (weight percent U_3O_8 in the original experimental work),

T is the thickness (feet) of the bed,

K is the proportionality factor (weight percent U_3O_8 / γ-ray response unit), and

A is the integral of the γ-ray response with respect to depth (the area under the γ-ray curve) and is referred to here as the "gamma-ray-thickness".

In practice, A is evaluated by summing the γ-ray response with respect to depth (Fink, 1978),

$$A = \Sigma\, w_i\, \gamma_i \qquad \text{for } i = 1,\ldots N \qquad (2)$$

where w_i is the thickness of the ith interval and γ_i is its gamma-ray response. The sum extends over an interval sufficient to capture the response of the logging tool to the bed (or the sum can be truncated near the bed boundaries and a "tail factor" can be applied (Scott and others, 1961)). If the γ-ray response is digitized at regular intervals w, then

$$A = w\, \Sigma\, \gamma_i \qquad \text{for } i = 1,\ldots N \qquad (3)$$

A common value for w is 0.5 ft. In oil and gas well logging, γ-ray response is measured in "API units", a unit established in a calibration facility in Houston, Texas, in which case the units of A are API-feet. If a logging tool is not calibrated in API units, the response is generally in counts per second (cps), and the units of A are cps-feet.

Scott and others (1961) noted that "although the method has been applied specifically to uranium deposits, the principles upon which it is based are generally applicable to deposits of other elements which either emit gamma rays or are quantitatively related to gamma-ray emitters." There is a caveat to this statement, however. Uranium-rich beds produce high count rates, so the background count rate is negligible. In potash-rich beds, count rates are lower and the background may not be negligible. To remove background, the value of γ_i in equations 2 and 3 should be determined after subtracting out the gamma-ray baseline, which typically ranges from 10 to 20 API units.

A Test of the Grade-Thickness Method for Potash

To test the grade-thickness approach, I used two data sets from the Carlsbad, New Mexico area supplied by Jim Lewis, Chief Geologist of Intrepid Mining, LLC. The first data set includes a total of 72 depth intervals in 7 wells, within which there were 16 potash zones with K_2O analyses and accompanying gamma-ray values. Data from six contiguous depth intervals in one zone from well AEC-008 are given in Table 2 to illustrate the nature of the data set.

Table 2. K_2O analyses and gamma-ray values in potash zone 10C in well AEC008.

Top (depth in feet)	Base (depth in feet)	Thickness (feet)	K_2O Grade (wt %)	Grade-thickness (wt %-ft)	Gamma-ray (API)	Gamma-ray-thickness (API-ft)	Correction factor	Corrected Gamma-ray (API)	Corrected Gamma-ray-thickness (API-ft)
1,589.1	1,589.7	0.6	4.26	2.56	119	71.4	1.12	133	80.0
1,589.7	1,591.7	2.0	17.68	35.36	151	302.0	1.12	169	338.2
1,591.7	1,592.2	0.5	16.18	8.09	183	91.5	1.12	205	102.5
1,592.2	1,594.5	2.3	21.23	48.83	196	450.8	1.12	220	504.9
1,594.5	1,594.7	0.2	12.87	2.57	94	18.8	1.12	105	21.1
1,594.7	1,595.5	0.8	4.59	3.67	57	45.6	1.12	64	51.1
Sum				101.08		980.1			1097.7

Figure 1 shows the gamma-ray response plotted against K_2O grade; the plot contains 72 points from the first data set, including the six points from well AEC-008 listed in table 2. The plot (fig. 1) shows a general increase in gamma-ray responses as K_2O grade increases, although as the K_2O grade decreases to zero, the gamma-ray response does not drop to zero, but instead ranges from 20 to around 100. This plot (fig. 1) indicates that an attempt to estimate grade in thin intervals from a simple relation $G = k\gamma$ will result in overestimates of grade at low count rates.

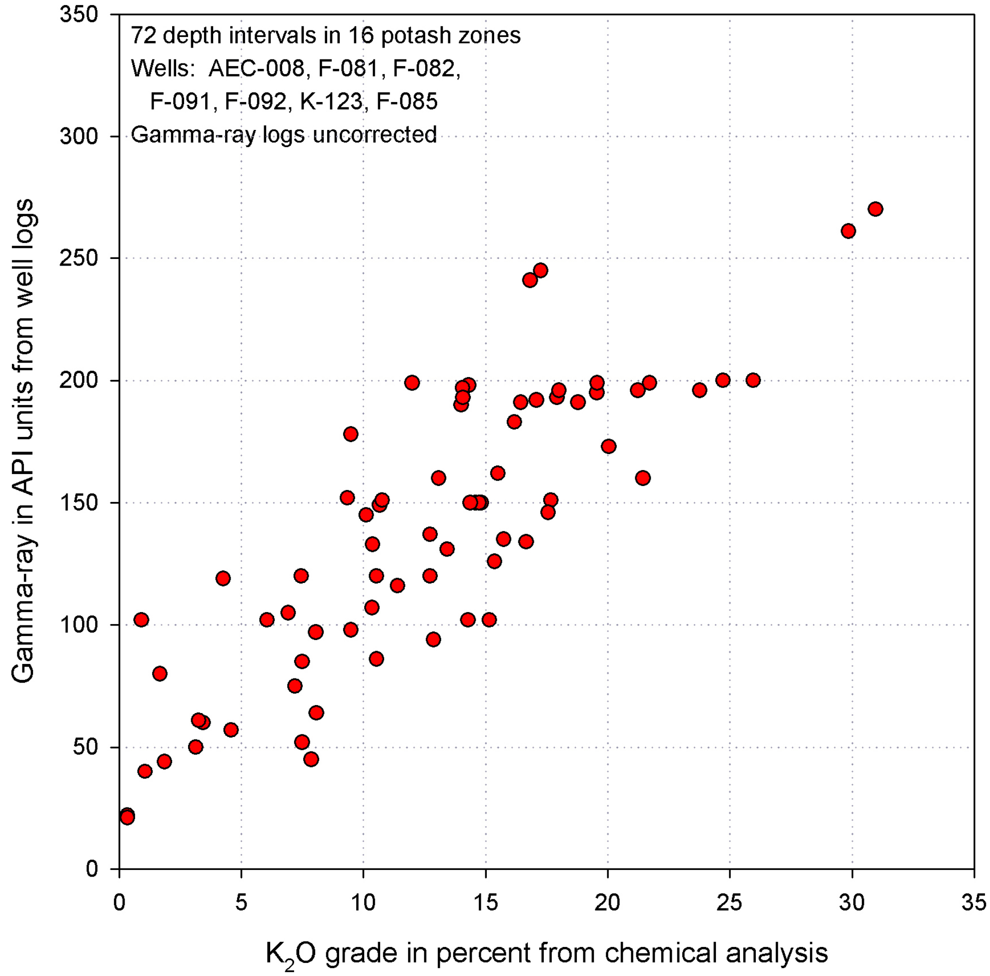

Figure 1. Plot of gamma-ray responses versus K_2O grade in potash zones in 7 wells near Carlsbad, New Mexico (data set 1).

Potash analyses were done over varying thickness intervals, so to determine the gamma-ray-thickness sum *A*, equation 2 was applied to these data instead of equation 3. For zone 10C in the AEC-008 well, the K_2O grade-thickness, obtained by summing the product of the thickness and K_2O grade in table 2, is 101.1 weight percent-ft, and the value of *A* for the uncorrected gamma-ray log is 980.1 API-ft. This value of *A* and the values of *A* for 15 other potash zones are plotted against the K_2O grade-thickness in figure 2. The gamma-ray thickness product *A* increases as the K_2O grade-thickness increases, although with some scatter along the trend. The gamma-ray-thickness response appears to approach zero as the K_2O grade-thickness approaches zero.

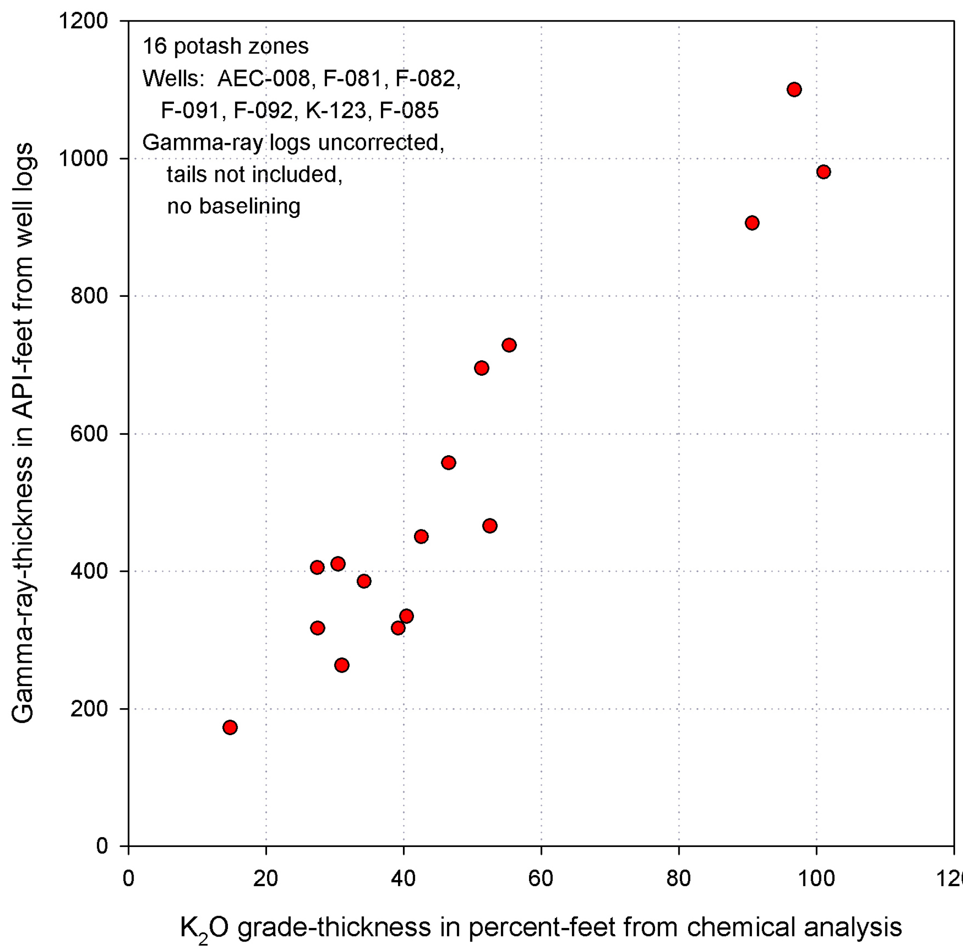

Figure 2. Plot of gamma-ray-thickness versus K_2O grade-thickness in potash zones in 7 wells near Carlsbad, New Mexico (data set 1).

The second data set used in this study incorporates gamma-ray logs and K_2O analyses from the P-series of wells, in which the gamma-ray log was recorded in cps rather than API units. This data set includes 100 depth intervals in 29 potash zones in 11 wells. A plot of all 100 pairs of gamma-ray values and K_2O analyses (fig. 3) shows a general increase of gamma-ray response as K_2O grade increases, with more scatter than exhibited in figure 1. When the grade-thickness computation is done, the scatter is greatly reduced and the resulting data points from the 29 zones show better correlation between gamma-ray-thickness and K_2O grade-thickness (fig. 4).

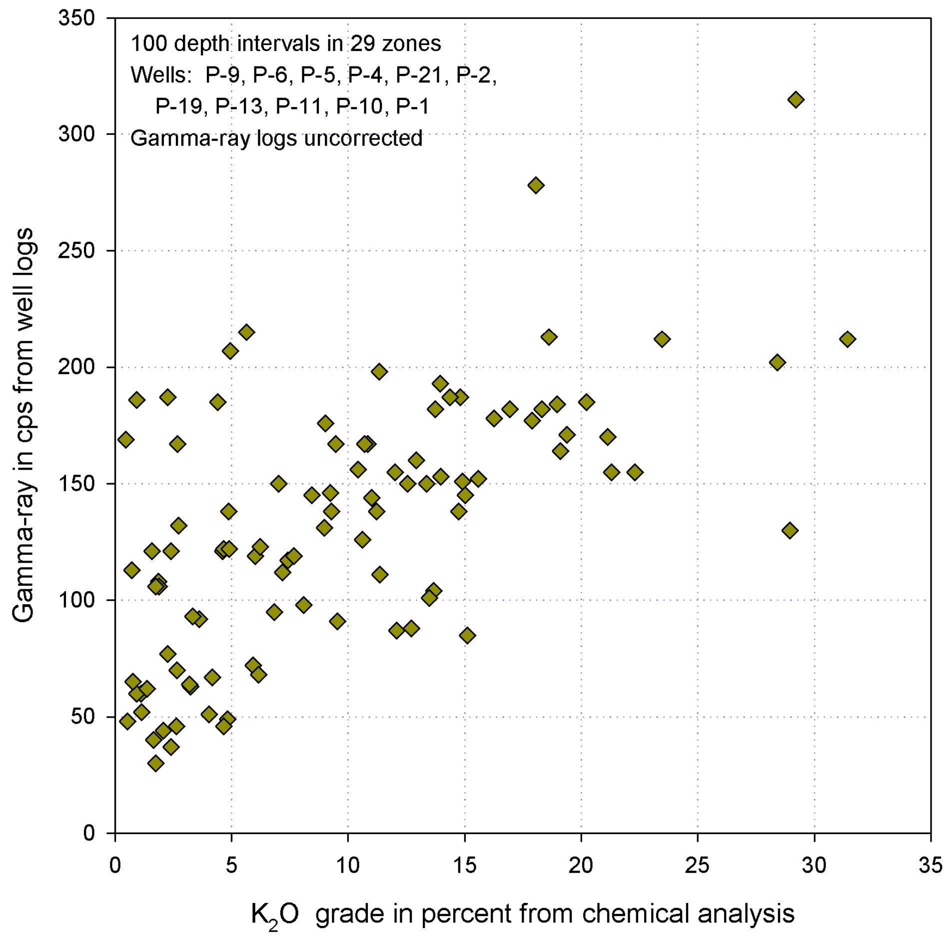

Figure 3. Plot of gamma-ray responses versus K_2O grade in potash zones in 11 wells near Carlsbad, New Mexico (data set 2).

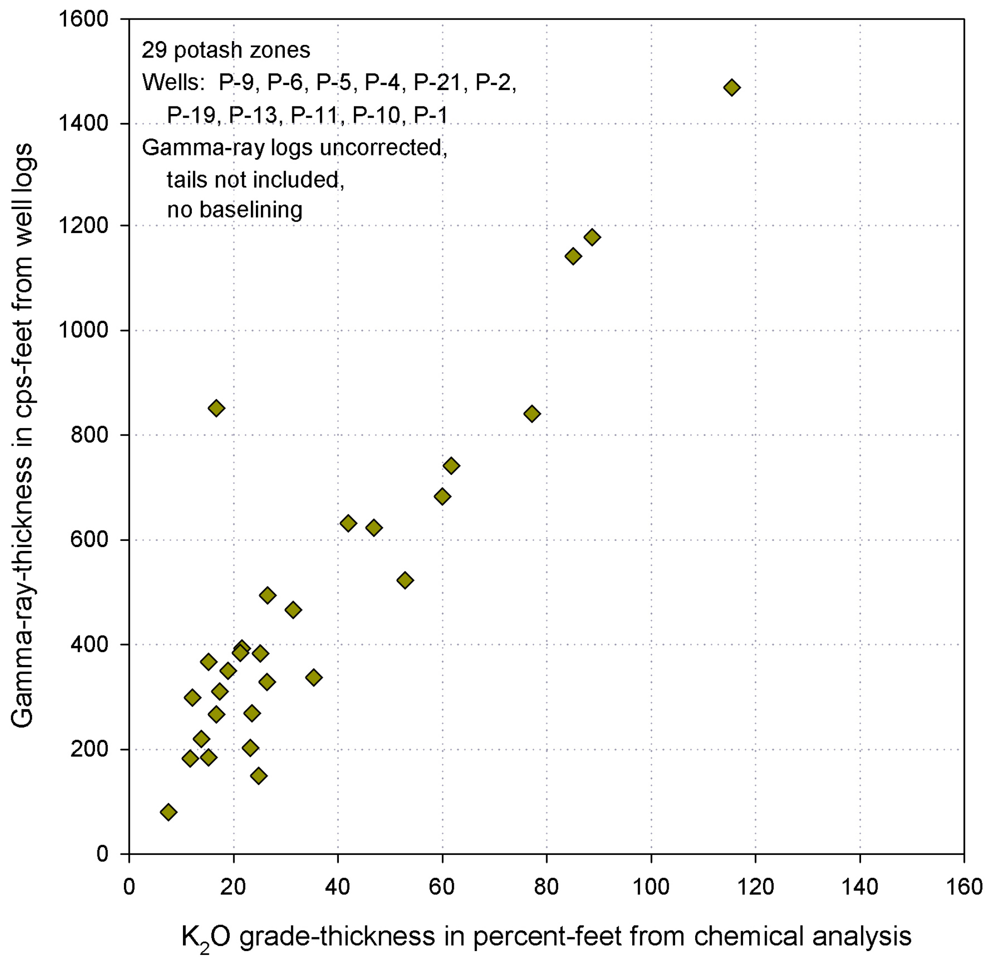

Figure 4. Plot of gamma-ray-thickness versus K_2O grade-thickness in potash zones in 11 wells near Carlsbad, New Mexico (data set 2).

One might wonder why the slopes differ between figures 1 and 2, inasmuch as the data in figure 2, displaying the grade-thickness and gamma-ray-thickness averages, are closely related to the data of figure 1, displaying the individual measurements. (Note that both figs. 1 and 2 have ratios of 10:1 for the y-axis:x-axis.) The same question applies to figures 3 and 4. Inspection of table 2 supplies an explanation for this dilemma. At the upper edge of zone 10C, K_2O is 4.26%, a factor of 4 less than the 17.68% value of the underlying layer, yet the gamma-ray value only dropped from 151 to 119 API units, because gamma-rays have propagated upwards as well as laterally and because gamma-ray detectors have a finite length. As a result, unexpectedly high gamma-ray values are recorded within layers having low values of K_2O. This effect accounts for the high gamma-ray values at low K_2O values in figures 1 and 3. The opposite effect occurs at high values of K_2O, where the contribution of adjacent layers with lesser potash content can produce lower gamma-ray response. By taking the effect of adjacent layers into account, the grade-thickness computation provides a more robust estimate of K_2O content than do estimates on a foot-by-foot basis.

These two examples illustrated in figs. 1-2 and 3-4 represent a preliminary demonstration of the grade-thickness calculation for potash rather than a complete one, because the tails of the gamma-ray log above and below the ore zones were ignored and because the gamma-ray baseline value should be removed before computing the sum. The calculations should be repeated with digitization of the gamma-ray log on equal (half-foot) increments, with inclusion of the tails, and with removal of the gamma-ray baseline. With these steps, the scatter in figures 2 and 4 should be further reduced and the *K*-factor can be determined.

Determination of Average Grade

Once the grade-thickness is determined for a single potash zone, the average grade for that zone is determined simply by dividing by the zone thickness. The thickness is the distance between the elevations at which the gamma-ray response declines to one-half its maximum value.

Sources of Error in Using the Grade-Thickness Computation

Errors in using the grade-thickness computational method, such as those listed below, deserve consideration. However, the method does eliminate some sources of error that would be encountered in using a method based upon least-squares analysis.

1. Depth misalignment. Logging depths differ from driller's depths, so the depth mismatch must be resolved when comparing chemical analysis to well log data. Consideration of the chemical data for an entire bed along with the total gamma-ray anomaly, as is done with the grade-thickness method, reduces the error in depth matching.

2. Excessive logging speed. Too fast a logging speed reduces the count rate and thereby reduces the grade-thickness estimate.

3. Gamma-ray attenuation caused by cement, casing, mud weight. The correction factors for the gamma-ray logs (1.12, table 2) were obtained in a manner described by Lewis (2006). The value of *A* for the corrected gamma-ray log is 980.1*1.12 = 1097.7 API-ft for well AEC-008. When the values of *A* for all wells were plotted in a manner identical to that of figure 1, the scatter worsened (not shown), indicating that correcting the data for borehole conditions can create more problems than it solves.

4. Washouts. Extreme washouts of potash zones are expected to reduce the gamma-ray count, and therefore reduce the grade-thickness estimate. This problem is alleviated by use of the grade-thickness method if only a portion of the potash zone is washed out.

5. Thin beds. Beds having less than a minimum thickness will produce a gamma-ray signature that is determined by the detector size and logging speed, although the gamma-ray-thickness *A* of the gamma-ray response is not altered (Woodhouse, 1994). Because only the maximum thickness, T_{max}, can be determined for a thin bed, the estimate of average grade, $G_{est} = (GT)/T_{max}$, will therefore be a minimum estimate.

6. Use of drilling muds containing potassium. Potassium-based muds will raise the overall count rate and increase the gamma-ray baseline level. Accounting for the baseline in the grade-thickness method removes this source of error.

7. Errors in calibration of gamma-ray logs If an offset has been introduced, then the grade-thickness method will not be affected. However, if the API value is off by a constant multiplicative factor, then the grade-thickness evaluation will be proportionately in error.

8. Presence of uranium and thorium. Both uranium and thorium emit gamma-rays and if present would raise the count rate of a total-count gamma-ray tool. The levels of uranium and thorium in potash zones can be established from core or by logging some test wells with spectral gamma-ray logging tools.

Summary

The grade-thickness method is recommended as the best procedure for calculating potash grade from well logs. Overall accuracy cannot be assessed until calculations more thorough than used in this review are carried out.

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