Quantitative Log Evaluation of the Prairie Evaporite Formation in Saskatchewan

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ABSTRACT

The problem of solving for the fraction of sylvite, carnallite, halite and insoluble material in the Prairie Evaporite formation can be performed by a suitable interpretation program based on Gamma Ray, Sonic, Neutron and Caliper logs. Empirical relations were established between the log values and the formation parameters, the result being a set of four simultaneous equations which may be reduced to obtain the desired fractions. Tedious hand calculation can be eliminated by using computer techniques and automatic log digitizing machines. Correlation between core and log analysis is good, and the speed and efficiency of the method is valuable in initial formation studies.

INTRODUCTION

THE Prairie Evaporite formation has been the object of extensive study in the past several years (1) (2). It is the richest known potash-bearing bed in the world, and, as such, it is important that any information gathered concerning the zone be accurate and immediately useful.

Electrical and radioactivity well logs have proved to be of value for formation evaluation in the oil industry. A recent paper (3) illustrates their use for both qualitative and quantitative interpretation in evaporite sequences in various parts of North America.

This paper will outline the theory and technique used for a quantitative interpretation procedure in the potash beds of the Prairie Evaporite formation in the Province of Saskatchewan. The data are set up so that they can be handled by an electronic computer. The equations can also be computed by hand at the well site to supplement the data already available.

The computer program is presented as an Appendix. An extensive bibliography, covering potash geology, development and logging techniques, is included.

THEORY

It is well known that potassium has a radioactive isotope which emits gamma ray energy. This isotope (K_{40}) comprises a constant fraction of the total amount of potassium, so that a Gamma Ray Log, which measures the amount of natural radioactivity in a formation, frequently gives a measure of the potassium content.

Considerable work was done in 1964 to establish an empirical correlation between gamma ray activity and the K_2O content of a potash bed (3). The graph shown in *Figure 1* illustrates the results obtained in oil-base muds. As borehole conditions affect the response of gamma ray logging instruments, hole size and mud weight must be taken into account.

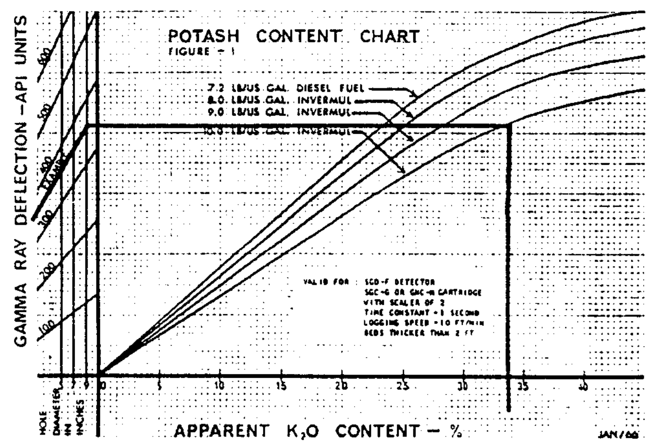

Figure 1.

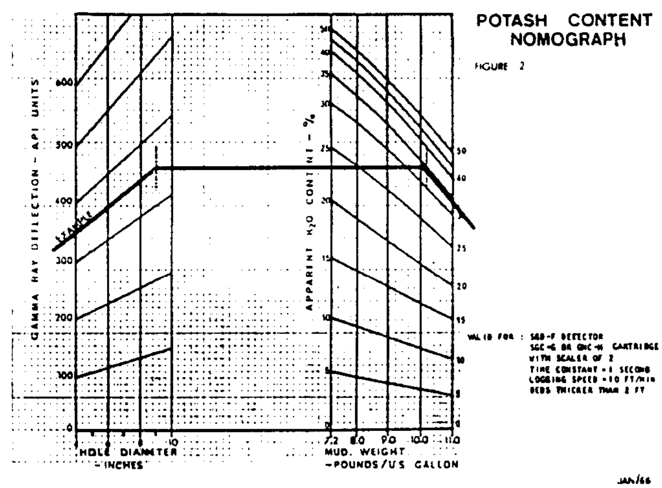

Figure 2.

Figure 2 illustrates a nomogram which facilitates conversion of gamma ray activity to apparent K_2O content. It is derived from the graph of *Figure 1* and therefore gives the same results. The result is labelled "apparent" K_2O content because the insoluble content of the formation generally is slightly radioactive and the chart thus gives an incorrect K_2O value if insolubles are present. A correction can be applied, which will be dealt with later, but it is small in many cases and will not greatly affect the total K_2O value of a zone. These results are valid only for the logging tools listed on the chart and for beds thicker than 2 feet.

**Schlumberger of Canada, Calgary, Alta.*

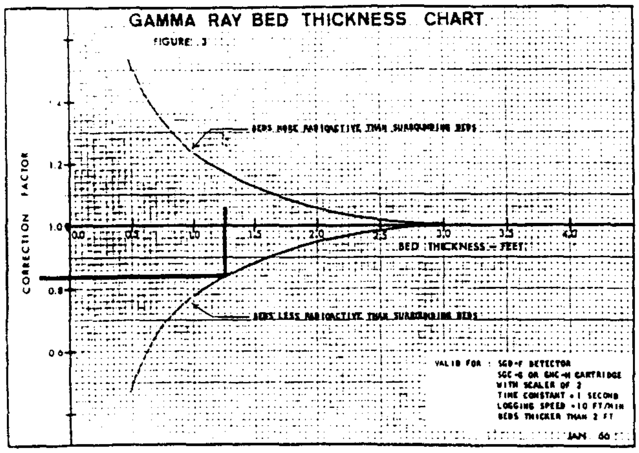

Figure 3.

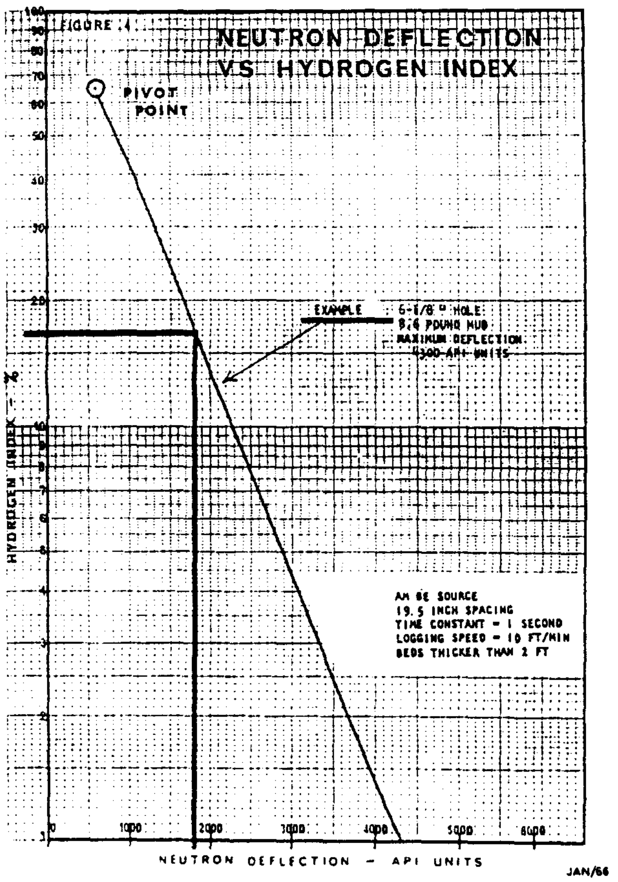

Figure 4.

TABLE I

COEFFICIENTS FOR POTASH LOG EVALUATION

Mineral	Halite	Sylvite	Carnallite	Insolubles
Symbol	w	x	y	z
Apparent K_2O Content (fractional)	0.00	0.63	0.17	0.05
Hydrogen Index (fractional)	0.00	0.00	0.65	0.30
Sonic Travel Time (microseconds per foot)	67.0	74.0	78.0	120.0

For thin beds (from ½ foot to 3 feet), a correction can be made using the empirical chart shown in *Figure 3*. The gamma ray reading in API units is multiplied by the correction factor derived from *Figure 3* to arrive at the corrected value. For beds less than 1 foot in thickness, the correction becomes quite large and is not accurate. Bed boundaries are chosen at the inflection points of the gamma ray curve and the bed thickness is that distance between any two successive inflection points.

As only those zones which are low in carnallite content are commercially attractive at present, a means of delineating these beds must be employed. The Neutron Log is an excellent carnallite logging tool, because it responds to the hydrogen content of the formation. The water of hydration associated with carnallite comprises a large part of its volume, so that a zone rich in carnallite will have a large hydrogen index. The hydrogen index of pure carnallite is 65 per cent (4). Sylvite and halite have an index equal to zero, except for a small (1 to 2 per cent) volume of included water.

Again, the insoluble content of the zone affects this log, and it should be taken into account if it is found to be very large (greater than 5 per cent).

An empirical chart similar to *Figure 4* can be made for each well to be interpreted to obtain the hydrogen index. A pivot point at 600 API units and a 65 per cent hydrogen index defines one end of the straight line (on semi log paper). The Neutron Log value (API units) in a clean salt zone and a 1 per cent hydrogen index defines the other end.

The pivot point used for this example applies only for the tool, spacing and source type noted on the chart. Different pivot points must be determined for different tools. Precise interpretation using the Neutron Log is limited to beds thicker than 2 feet.

A Sonic Log is employed as an aid to determine the insoluble content. This is a required factor if an accurate interpretation is to be made. Knowledge of the insoluble content is also necessary because excessive amounts of insolubles can make an apparently good zone commercially unattractive, as it is an expensive process to refine these impurities from the final product.

Studies on laboratory samples and field correlations (3) have given sonic travel time values in halite, sylvite, carnallite and insoluble material as 67, 74, 78 and 120 microseconds per foot respectively. This data, combined with the information which can be determined from the Gamma Ray Log and the Neutron Log, can be used to set up simultaneous equations to solve for the per cent of halite, sylvite, carnallite and insolubles (w, x, y and z respectively*) (5).

Table I shows the values used for the coefficients of the equations. These coefficients represent values of the parameters for 100 per cent pure minerals.

As it is assumed that only halite, sylvite, carnallite and some insolubles are present, their total volume must comprise the total formation volume. This is represented by equation 1.

$$w + x + y + z = 100 \quad \ldots\ldots \text{ equation 1}$$

The total apparent K_2O content of the formation, based on the Gamma Ray Log, is made up of each component fraction multiplied by its respective K_2O value. Thus:

$$0.63\,x + 0.17\,y + 0.05\,z = K_2O_{app} \ldots\ldots \text{ equation 2}$$

*Symbols defined in Appendix I.

TABLE II

EVAPORITE MINERAL PARAMETERS

Mineral	*Apparent K_2O Rating* Per cent	*Hydrogen Index* Per cent	*Apparent Density* Grams per cubic centimeter	*True Density* Grams per cubic centimeter	*Sonic Travel Time* Microseconds per foot
Anhydrite	0.0	0.0	2.98	2.96	50
Carnallite	17.0	65.0	1.57	1.61	78
Gypsum	0.0	49.0	2.35	2.32	52
Halite	0.0	0.0	2.03	2.16	67
Kainite	18.9	45.0	2.12	2.13	—
Langbeinite	22.6	0.0	2.82	2.83	52
Polyhalite	15.5	15.0	2.79	2.78	57
Sylvite	63.0	0.0	1.86	1.98	74
Insolubles	5.0	30.0	2.60	2.60	120

DEPTH	GR	NL	SL	HS	INSOL	CARN	SYLV	SALT	KOT	KOC	KOS
4000.0	22.	2300.	64.5	6.1	-9.1	16.3	-1.2	95.0	1.9	2.7	-.7
4000.5	30.	1600.	73.0	6.1	5.4	24.9	-3.9	74.1	1.7	4.2	-2.4
[redacted]											
4002.5	18.	2800.	71.5	6.1	6.5	3.3	.4	90.4	.8	.5	.2
4003.0	16.	2800.	71.5	6.1	6.5	3.3	.2	91.0	.7	.5	.1
4003.5	20.	2650.	72.0	6.1	7.3	3.9	.4	89.4	.9	.6	.2
4004.0	22.	2550.	71.5	6.1	6.1	5.4	.3	89.2	1.1	.9	.2
4004.5	26.	2450.	72.5	6.1	7.8	6.2	.4	86.6	1.3	1.0	.2
4005.0	32.	2300.	73.5	6.1	9.3	7.8	.5	83.3	1.6	1.3	.3
4005.5	40.	2350.	73.0	6.1	8.3	7.5	1.5	83.7	2.2	1.2	.9
4006.0	42.	2600.	73.0	6.1	9.0	3.4	2.7	85.9	2.3	.5	1.7
4006.5	60.	2600.	72.0	6.1	6.6	4.5	4.5	85.3	3.6	.7	2.9
4007.0	84.	2700.	71.5	6.1	5.4	4.5	7.1	84.0	5.2	.7	4.5
4007.5	60.	2800.	72.5	6.1	7.9	2.7	4.9	85.5	3.5	.4	3.1
4008.0	40.	3050.	71.0	6.1	5.4	2.3	3.1	90.3	2.3	.3	1.9
[redacted]											
4018.0	70.	3500.	70.5	6.1	4.3	.7	6.7	89.3	4.4	.1	4.2
4018.5	62.	3550.	70.5	6.1	4.4	.5	5.9	90.1	3.6	0.0	3.7
4019.0	80.	3160.	70.5	6.1	3.9	2.4	7.4	87.4	5.0	.4	4.6
4019.5	140.	3100.	70.5	6.1	2.9	3.2	13.9	80.9	9.3	.5	8.7
4020.0	176.	3100.	72.0	6.1	5.4	2.0	18.1	75.3	11.7	.3	11.4
4020.5	224.	3200.	72.5	6.1	5.8	1.3	23.0	70.6	14.7	.2	14.5

Figure 5.— Potash Log Analysis.

A similar expression for hydrogen index gives:

$0.65\ y + 0.30\ z = \phi_n$ ....equation 3

Wyllie's time average equation extended to four components gives:

$67\ w + 74\ x + 78\ y + 120\ z = 100\ \Delta t_{log}$ ....equation 4

The value for Δt_{log} is read directly from the log; the values for K_2O_{app} and ϕ_n are derived from the charts (*Figures 2, 3* and *4*).

Reducing these equations to obtain the required values — "w", "x", "y" and "z" — in terms of the derived values from the three logs gives the following:

$z = 2.07\ \Delta t_{log} - 0.23\ K_2O_{app} - 0.29\ \phi_n - 140.00$ equation 5

$y = 1.54\ \phi_n - 0.46\ z$ ....equation 6

$x = 1.59\ K_2O_{app} - 0.41\ \phi_n + 0.04\ z$ ....equation 7

$w = 1.50\ \Delta t_{log} - 1.79\ K_2O_{app} - 1.38\ \phi_n - 1.30\ z$ equation 8

As many core assays also list the K_2O values for an interval, it is often convenient to convert the mineral composition to equivalent K_2O using the following equations, wherein the subscripts used with K_2O are "t" for total, "s" for sylvite and "c" for carnallite:

$K_2O_t = K_2O_{app} - 0.05\ z$ ....equation 9

$K_2O_s = 0.63\ x$ ....equation 10

$K_2O_c = 0.17\ y$ ....equation 11

As an arithmetic check, one should compute the sum w + x + y + z, which should equal 100 per cent. Also the sum $K_2O_c + K_2O_s$ should equal K_2O_t.

A simple crosscheck of the data determined from equations 5 to 8 can be accomplished by running a Formation Density Log. The actual density reading can be compared with a computed density value, calculated from equation 12.

$100\ \rho_c = 2.03\ w + 1.86\ x + 1.57\ y + 2.60\ z$ ....equation 12

This equation is derived from the known densities of the four components: halite, sylvite, carnallite and insolubles (see Table II).

If the computed density verifies the log-recorded value, one can reasonably assume that the fractions, as calculated, are correct. A different value indicates that some other mineral is present, either in place of, or in addition to, those considered.

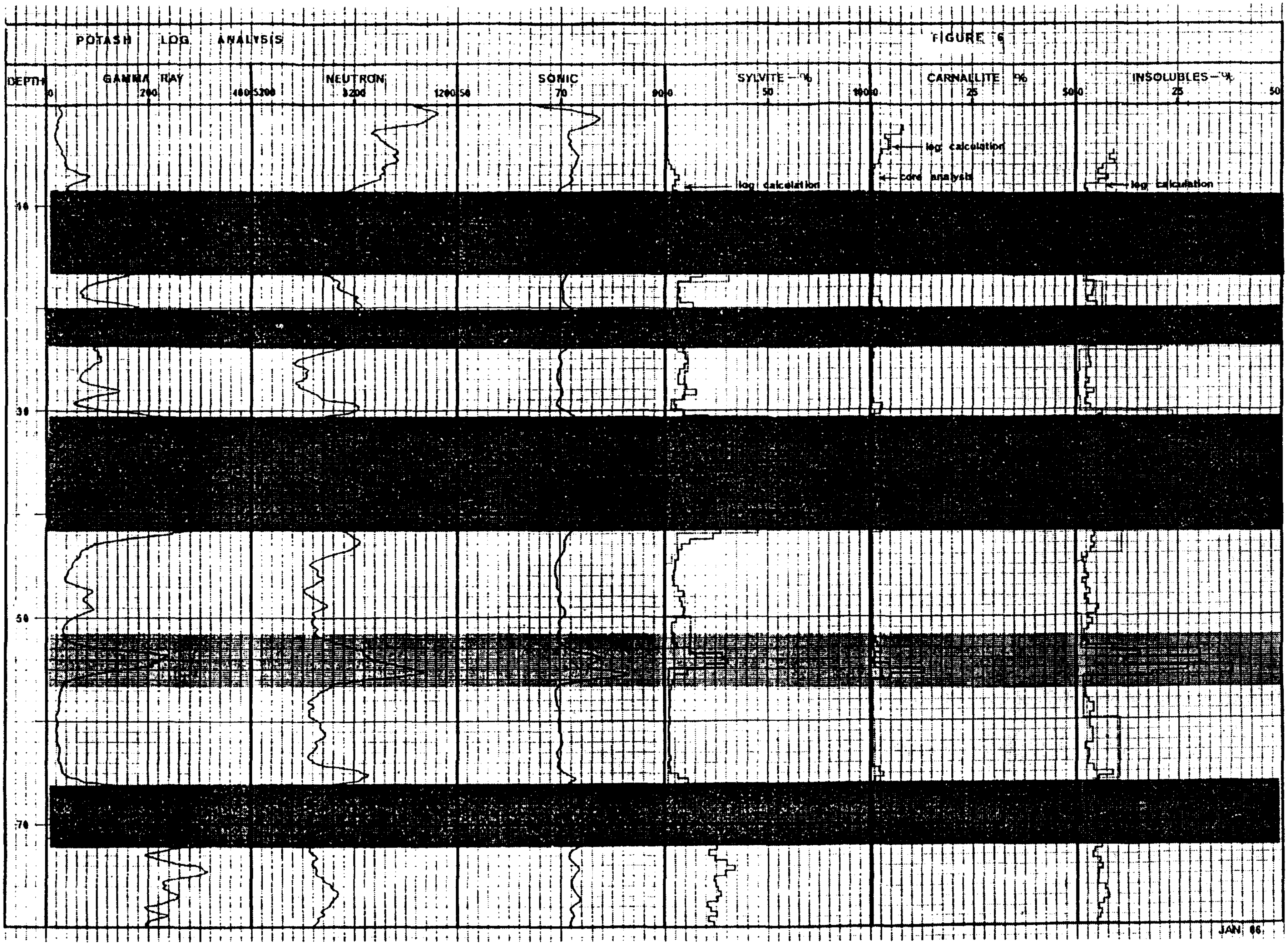
POTASH LOG ANALYSIS
FIGURE 6
DEPTH
GAMMA RAY
0
200
400
NEUTRON
5200
3200
1200
SONIC
50
70
90
SYLVITE – %
0
50
100
CARNALLITE %
0
25
50
INSOLUBLES – %
0
25
50
log calculation
core analysis
log calculation
log calculation
10
30
50
70
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Figure 6.

The four logs, Gamma Ray, Neutron, Sonic, and Density, could be used to set up equations for a five-mineral matrix, but is not often necessary, because halite, sylvite, carnallite and insolubles usually predominate over other potash minerals.

As the calculations, although simple, are quite tedious, a computer program was developed to handle this task. In order to use log values directly, the charts of *Figures 2* and *4* were reduced to tabular form, as shown in Tables III and IV. The data were normalized to 6-inch hole size with a mud weight of 7.2 pounds per U.S. gallon (diesel fuel).

Corrections for different hole sizes and mud weights were developed in equation form. Any value of hole size from 6 to 12 inches and mud weight from 7.2 to 12.0 pounds per U.S. gallon can be accounted for by using the following equations:

$$GR_c = \left\{ GR_{log} [1 + 0.05 (d - 6)] + \frac{320 (d - 6)}{GR_{log} + 100} \right\} [1 + 0.10 (m - 7.2)] \quad \text{..........equation 13}$$

$$N_c = N_{log} [1 + 0.05 (d - 6)] \quad \text{..........equation 14}$$

These are approximations only, but are sufficiently accurate for the range of values stated above. The computer program first corrects the log values, and then enters the tables, interpolating between points if necessary, to obtain K_2O_{app} and ϕ_n.

A sample of the results from an electronic computer analysis of digitized log values is shown in *Figure 5*. These same values are plotted against the core assay results in *Figure 6*. Close correlation is shown in many cases.

Those intervals in which large discrepancies occur are probably due to the different volumes of investigation of the core and the logs. The logging instruments are capable of analysing as much as 100 times the volume of a conventional 2⅛-in. core. Particular examples of such discrepancies occur at 4,014 to 4,022 feet and at 4,031 to 4,044 feet on the insoluble calculation shown in *Figure 6*.

The high insoluble content interval between 4,053 and 4,056 feet on *Figure 6* is shown quite clearly. The absolute values do not agree with the core analysis, but there is no problem concerning interpretation as this amount of insoluble material would condemn the zone even if it had contained sufficient potash to be considered a prospective commercial orebody. Bed boundaries are clearly defined and correlate exactly with the core.

Bed thickness corrections should be applied to the Gamma Ray Log readings before inserting them in the machine computation program. Thin-bed effects can be seen on the examples where rich ore intervals are less than 3 feet thick.

Some discrepancies with core analysis, caused by problems other than thin beds, can be noted in the higher grade sylvite and carnallite intervals. The Gamma Ray logging tool does not respond linearly to K_2O content, and resolution is poorer in high-K_2O-grade ores.

Due to the logarithmic response of the Neutron Log to hydrogen index, the resolution of this logging tool in the zones of high carnallite content is not as good as in the lower grade carnallite. *Figure 7* illustrates this effect. Here, a high-grade sylvite bed grades into a high-carnallite-content zone. The comparison between core analysis and log calculations is not as good as in *Figure 6*. However, no one could mistake the content of the zone. The log-derived bed boundaries agree very closely with the core analysis. Unfortunately, this bed is not thick enough to be considered commercially attractive.

The result of the bed thickness and tool resolution problems is a pessimistic sylvite and carnallite assay in thin rich zones. Fair accuracy is possible in thick, rich ores, and good accuracy is attained in low- to medium-grade beds.

The value of the Caliper Log is evident from *Figure 7*. The sylvite fraction could have been in error by as much as 14 per cent in Example 4 had the hole diameter been assumed equal to the bit size of 9 inches.

The computer program can be adapted to any computer. At present, logs must be digitized by hand. The output is in the form of punched cards which are used for off-line listing. Plotting of results from this list can be accomplished by hand; the data can also be recorded by an incremental digital plotter.

A more complex computer program has been developed to translate directly the recorded logs to a computed log. A sample of the output from such a program is illustrated in *Figure 8*. In this application, the logs are digitized, calculations are performed,

TABLE III

GAMMA RAY vs. K_2O_{app}

Gamma Ray Deflection API units	K_2O_{app} %
0	0
45	2.5
90	5.0
135	7.5
175	10.0
220	12.5
265	15.0
310	17.5
355	20.0
400	22.5
435	25.0
470	27.5
505	30.0
530	32.5
550	35.0
565	37.5
580	40.0
590	42.5
600	45.0
605	47.5
999	99.9

TABLE IV

NEUTRON vs. ϕ_n

Neutron Deflection API units	ϕ_n %
6000	0
4300	1
3600	2
3200	3
2600	5
2400	7
2200	9
2000	12
1700	16
1500	20
1300	26
1100	35
800	50
600	65
0	99

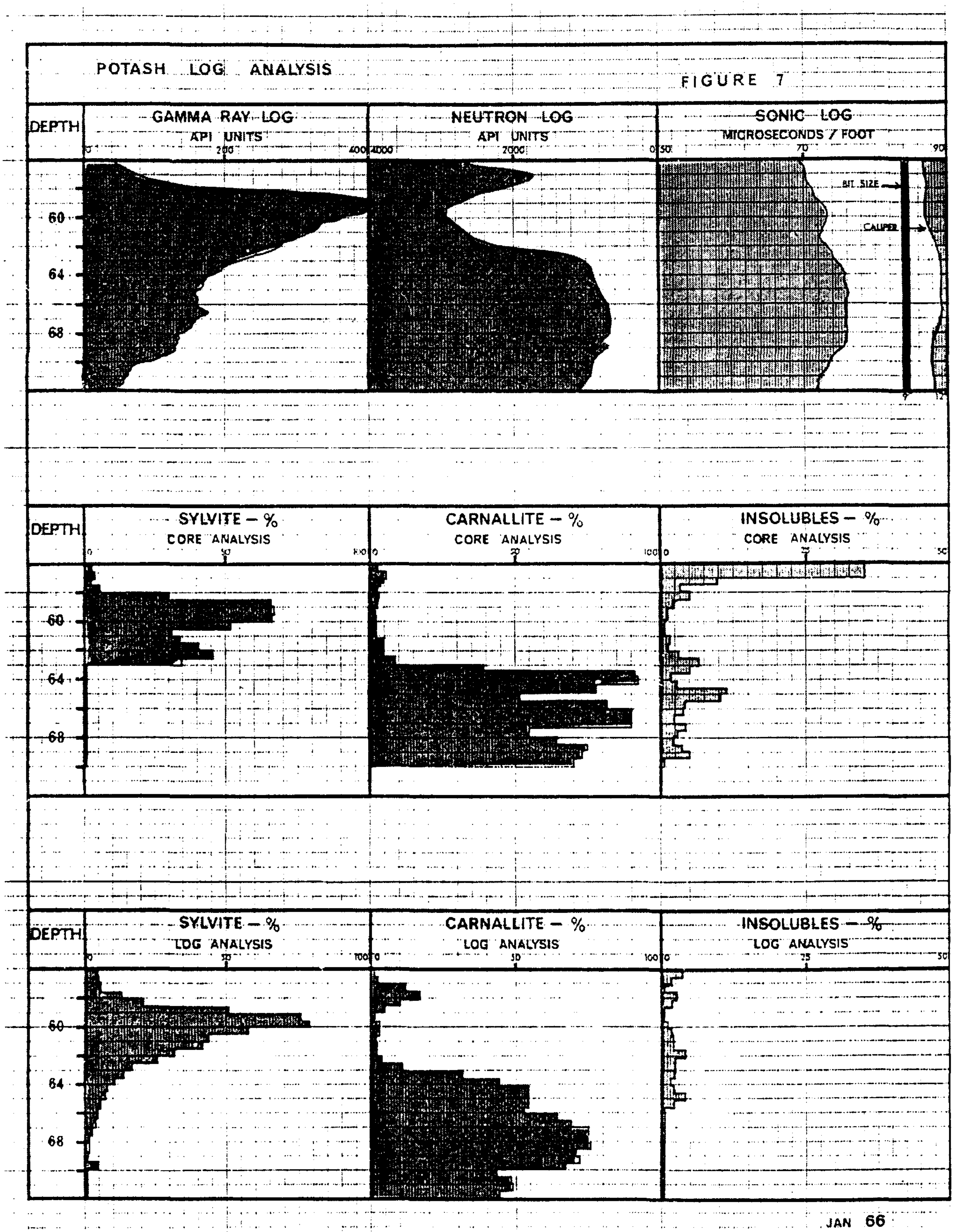
POTASH LOG ANALYSIS
FIGURE 7
DEPTH
GAMMA RAY LOG
API UNITS
NEUTRON LOG
API UNITS
SONIC LOG
MICROSECONDS / FOOT
BIT SIZE
CALIPER
60
64
68
SYLVITE — %
CORE ANALYSIS
CARNALLITE — %
CORE ANALYSIS
INSOLUBLES — %
CORE ANALYSIS
SYLVITE — %
LOG ANALYSIS
CARNALLITE — %
LOG ANALYSIS
INSOLUBLES — %
LOG ANALYSIS
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Figure 7.

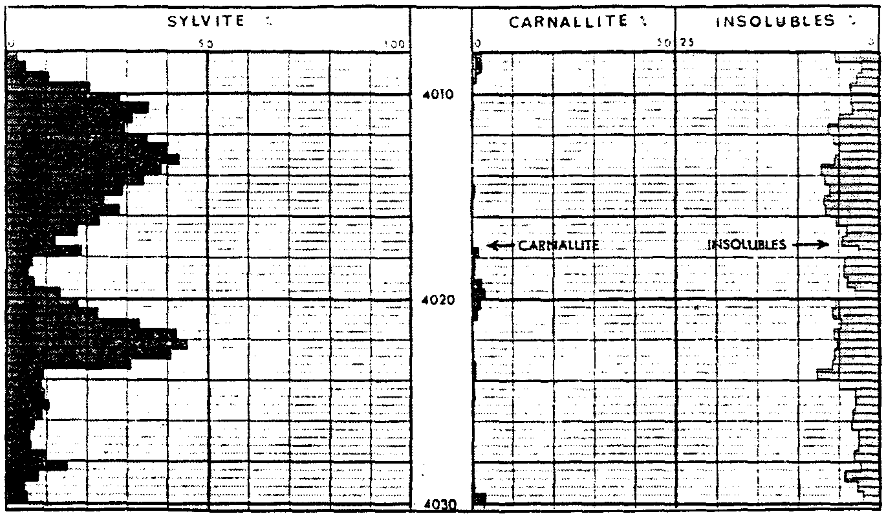

Figure 8.—Potash Log Analysis.

and the results are plotted by an incremental digital plotter in a continuous sequence, eliminating the source of error in manual digitizing and plotting.

The direct digitizing, computing and plotting technique is available as a commercial service at those centers which have the suitable hardware.

Conclusions

It has been shown that with three standard well logs it is possible to evaluate quantitatively the Prairie Evaporite potash beds. The arithmetic is simple and the presentation, as illustrated in the examples, is informative and self-explanatory. Auxiliary surveys such as the Caliper Log or the Formation Density Log, can be used to supplement and cross-check data derived from the three basic logs.

Computer techniques are admirably suited to this interpretation approach, and eliminate much tedious hand calculation. The graphical display of the calculations allows correlation, mining studies and mapping to be accomplished with ease.

Acknowledgments

The authors wish to express their appreciation to the companies whose logs were released for presentation in this paper. Access to the confidential information required to complete this study is gratefully acknowledged.

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APPENDIX I

List of Symbols

Symbol	*Definition*	*Units*
GR_{log}	Gamma Ray Log reading from log at depth D	API Units
GR_c	Gamma Ray Log reading corrected for hole size and mud weight	API Units
N_{log}	Neutron Log reading at depth D	API Units
N_c	Neutron Log reading corrected for hole size	API Units
w	Per cent of halite in formation	Per cent
x	Per cent of sylvite in formation	Per cent
y	Per cent of carnallite in formation	Per cent
z	Per cent of insolubles in formation	Per cent
K_2O_t	Total K_2O content of formation	Per cent
K_2O_s	K_2O content of formation in sylvite	Per cent
K_2O_c	K_2O content of formation in carnallite	Per cent
K_2O_{app}	Apparent K_2O content of formation from Gamma Ray Log	Per cent
ϕ_n	Hydrogen Index from Neutron log	Per cent
d	Borehole diameter from Caliper Log or from bit size	Inches
m	Mud weight	Pounds per U.S. gallon
Δt_{log}	Sonic travel time from Log	Microseconds per foot
ρ_c	Computed formation density	Grams per cubic centimeter

APPENDIX II

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