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Salty Matters

John Warren - Saturday March 31, 2018

Well (wireline) log interpretation of evaporites: An overview

Introduction

Often, when I run an evaporite training program for a client in the hydrocarbon or the potash industries, I am asked to add a short training module on the identification of evaporites in a set of conventional wireline log outputs. This blog is an overview of what I discuss in such a module. But every evaporite basin has its own set of mineralogies and problems and a generalised discussion, as in this blog, must be refined to meet the needs of the drilling or mining program in a particular evaporite basin.

Significant thickness units of evaporites are rarely cored in oil and gas drilling, unless in error, while when drilling rock chips of the more soluble salt minerals are quickly dissolved in most drill muds; so only a small portion of any subsurface evaporite bed can be studied directly. The situation is somewhat different in Salt and potash mining where cores are commonly collected ahead of the mine face to ascertain ore extent and thickness. Increasingly core calibrated well logs are replacing the need for extensive coring when ascertaining and predicting ore quality.

Many evaporite properties can be ascertained by examining a suite of conventional wireline logs. Many evaporite beds contain only one or two dominant saline minerals, they lack free pore fluids and have negligible porosity. This dramatically simplifies log interpretation and enhances the reliability of inferences with respect mineralogy. Thick clean evaporites will show the same characteristic set of log responses, not only locally but according to some authors worldwide (e.g., Serra, 1984, p. 173; Warren, 2006, Chapter 10). The most commonly available logs for the study of evaporites are the logs measuring hole diameter, electrical properties, bulk density, neutron porosity logs, sonic logs and, if significant levels of potash salts are present, both gamma and multispectral gamma logs.

Evaporites as seen in well logs

Well-logs are a continuous recording of a geophysical paragf meter along a borehole, where the value of the measurement is continuously plotted against depth in the borehole. Currently, the well logging industry is transitioning from wireline or cable-based well logging tools (Figure 1) to the increasing use of well-log tools designed for use in directional drilling. Wireline or cable tools can only be utilised in vertical to steeply inclined wells. The same set of conventional well log measurements are now increasingly collected using MWD (measurement while drilling) and LWD (logging while drilling) tools. With MWD/LWD, measurements are made by a suite of well-logging tools that reside immediately behind the advancing drill-bit. Part of the data collected by these tools is sent to the surface in real time (MWD) by mud pulsing or some other method of telemetry. The remaining portion of the collected data (LWD) is stored on a hard disk and recovered typically when a worn drill-bit is pulled to the surface to be replaced.

Although there are numerous well-logging tools and measurements that can be used in the study of evaporites, this section deals with only a few of the more conventional logging methods. Rider (1996) is an excellent overview from a geological, not petrophysical, perspective of the general principles of well-log interpretation. For a more comprehensive discussion of the geological applications of well-logs, there are many logging-company manuals, as well as excellent books and articles such as Kruger (2014), Crain (2010), Ellis and Singer (2007), Nelson (2007), Rider (1996), Nurmi (1978), and Alger and Crain (1966), Crain and Anderson (1966).

Electrical properties

Electrical resistivity, the reciprocal of electrical conductivity, is the degree with which a formation opposes the flow of electrical current. Onshore, a log of the spontaneous potential of a formation is run at the same time as a resistivity log. In reality, the measured resistivity is dependent on the combined resistivity of both the rock matrix and any contained fluids. Most solid rock materials are insulators, while their enclosed fluids are conductors. Hydrocarbons are the exception to fluid conductivity; they are infinitely resistive, and this is the basis for the quick look-identification of hydrocarbons and the use of Archies Law to determine water saturation levels in potential hydrocarbon reservoirs. In terms of evaporite identification, most evaporite units contain little if any pores or free water and so have very high resistivities compared to other more porous units (Table 1).

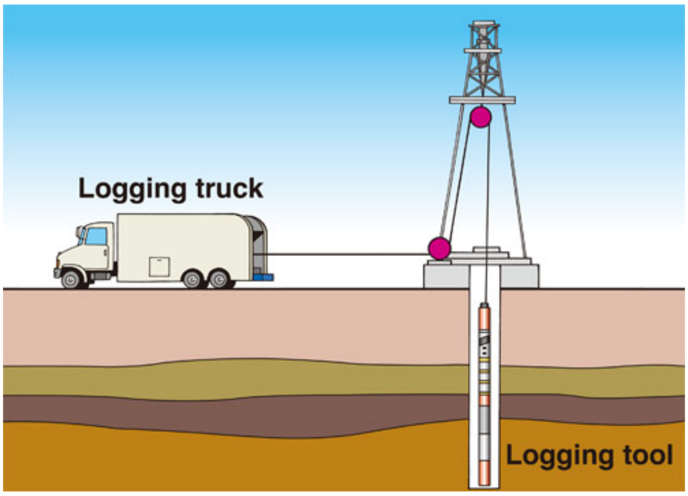


Figure 1. Basic set-up for wireline logging

		Composition	SG (gm/cc)	RHOB (gm/cc)	DT (μs/ft)	NPHI (lst ø equiv.)	GR (api)	Pe (barn/elect)	Resistivity (ohm.m)
Non-radiogenic	Anhydrite	$CaSO_4$	2.960	2.977	50	(-2)	0	5.05	10^4-10^{14}
	Gypsum	$CaSO_4.2H_2O$	2.320	2.351	52.5	49	0	3.99	1000
	Halite	NaCl	2.165	2.032	67	(-3)	0	4.65	>10^4-10^{10}
	Kieserite	$MgSO_4.H_2O$	2.57	2.59	na	43	0	1.8	
	Bischofite	$MgCl_2.6H_2O$	1.56	1.54	100	60+	0	2.6	
	Tachyhydrite	$CaMg_2Cl_6.12H_2O$	1.67	1.72	92	50+	0	3.82	
	Epsomite	$MgSO_4.7H_2O$	1.68	1.71	na	60+	0	1.2	
	Trona	$NaCO_3.NaHCO_3.2H_2O$	2.120	2.08	65	35	0	0.71	
	Sulphur	S_2	2.070	2.030	122	-3	0	5.40	
Radiogenic	Carnallite	$KCl.MgCl_2.6H_2O$	1.610	1.570	78	65	≈220	4.09	
	Sylvite	$KCl.MgCl_2.6H_2O$	1.984	1.863	74	(-3)	≈500	8.51	10^{14}-10^{15}
	Kainite	$MgSO_4.KCl.3H_2O$	2.130	2.120	na	45	≈245	3.50	
	Langbeinite	$K_2SO_4.2MgSO_4$	2.830	2.820	52	(-2)	≈290	3.56	
	Polyhalite	$K_2SO_4.MgSO_4.2CaSO_4.2H_2O$	2.030	2.790	57.5	15	180	4.32	
Sedimentary minerals									
Calcite		$CaCO_3$	2.710	2.71	49.7	0	0	5.08	
Dolomite		$CaMg(CO_3)_2$	2.870	2.88	43.5	4	0	3.14	
Quartz		SiO_2	2.654	2.64	52.9	-2	0	1.8	
Opal (3.5%H_2O)		$SiO_2.(H_2O)_{0.1209}$	2.15	2.13	58.0	2	0	1.8	
Barite		$BaSO_4$	4.5	4.09	na	-2	0	267	
Celesitite		$SrSO_4$	3.95	3.79	na	-1	0	55	
Sedimentary rocks									
Limestone (Ø=10%)			2.540	2.540	62	10	5 to 10	4.5	80-6000
Dolomite (Ø=10%)			2.680	2.683	58	13.5	10 to 20	3.09	8-6000
Sandstone (clean to dirty sst)			2.489	2.485	65.3	3	10 to 30	1.7-2.7	low-mod.
Shales			2.2 to 2.75		70 to 150	25-60	80-150	3.0-5.0	variable
Water at 32°C									
Fresh			1.000		200	100			
Saline 100,000 ppm NaCl			1.067		189	100			
Hypersaline 200,000 ppm NaCl			1.114		176	100			

Table 1. Typical well-log and physical properties of evaporite salts and associated sediments and brines. Compiled by the author from a variety of sources.

When the evaporite unit is relatively pure and monomineralogic, it creates a distinctive blocky log shape, whereas when it entrains beds of thin more porous lithologies (mudstones, shale, sands, limestone, dolomite) or perhaps contains brine-filled cavities and vugs, a muh spikier log is seen across a saline interval. The actual wireline log signature depends on the content of brine, sand, clay, bitumen and other variables. Within a local area in a basin, an elevated resistivity signature, although it does not allow a first indication of the presence of evaporite salts, can subsequently confirm it. When bitumens and salts are present in the same interval (as in salt-encased EoCambrian carbonate-slither reservoirs in the South Oman Salt Basin), the co-occurrence of halite cement, anhydrite cement and bitumen complicates a reliable interpretation of movable hydrocarbons.

Total & Spectral gamma-ray logs

The gamma-ray or gamma log is a record of the formation's radioactivity. The radiation emanates from uranium, thorium and potassium which occur naturally in the formation. A simple gamma-ray log measures the radioactivity of the three radiogenic elements (U, K, Th) combined, while the spectral gamma log shows the amount of each radiogenic element contributing to a formation's radioactivity.

As a first indicator of lithology in non-evaporitic intervals, the gamma log is extremely useful in suggesting where shale may be expected in a formation; worldwide, elevated gamma readings in a sandstone-mudstone succession are typically used to indicate shaliness of the formation (V_{clay}). Clays can contain high levels of potassium-containing minerals, thorium (another radiogenic mineral) tends to be fixed in shales (c.f. sands), and that clays typically “fix” marine uranium into the sediment in three main ways i) chemical precipitation in acid (pH 2.5 - 4.0) or reducing environments, ii) adsorption by organic matter in the clays, iii) adsorption by phosphates in the clays. Uranium can also be mobilised and “re-fixed in the subsurface across redox interfaces. High gamma readings can also be due to the elevated potassium content in glauconite-rich sands, or the secondary movement of uranium to form “hot” cement and fissure fills in a number of Middle East reservoirs.

More importantly for our purposes, high gamma signatures can be associated with those evaporites which contain high proportions of the potassium salts such as sylvite, carnallite, and polyhalite (Table 1; Figure 2). In the potash-entraining salts, there is between 10% and 50% potassium by weight. When it is considered that the average shale contains only 2.7% potassium, the very strong radioactivity indicative of the potassium salts in an evaporite suite is understandable and means potash beds can be distinguished from the somewhat-elevate uranium-derived kicks of marine shale and the low radiogenic content of any adjacent halite, anhydrite or carbonate beds.

In contrast to halite units containing potassium salts, the more common evaporites, such as halite and anhydrite, give very low readings on the gamma log scale (Figure 2). Once an initial tie-back to core-determined assay values is done, it is possible to reliably estimate the percentage of K_2O from the gamma response. As a general "rule of thumb," Edwards et al. (1967) showed that for a 6.25-inch, liquid-filled hole there was a correlation of 12.6 API units per 1% K_2O.

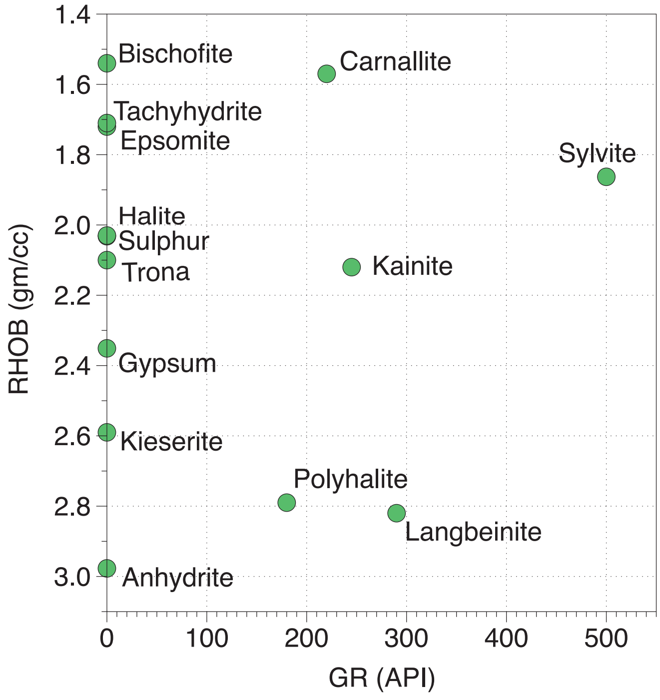


Figure 2. Gamma GR versus RHOB (density). The gamma values clearly differentiate non-potash (non-radiogenic) from potash salts (radiogenic), while the characteristic bulk densities can define and separate most near mono-mineralic evaporite salt beds.

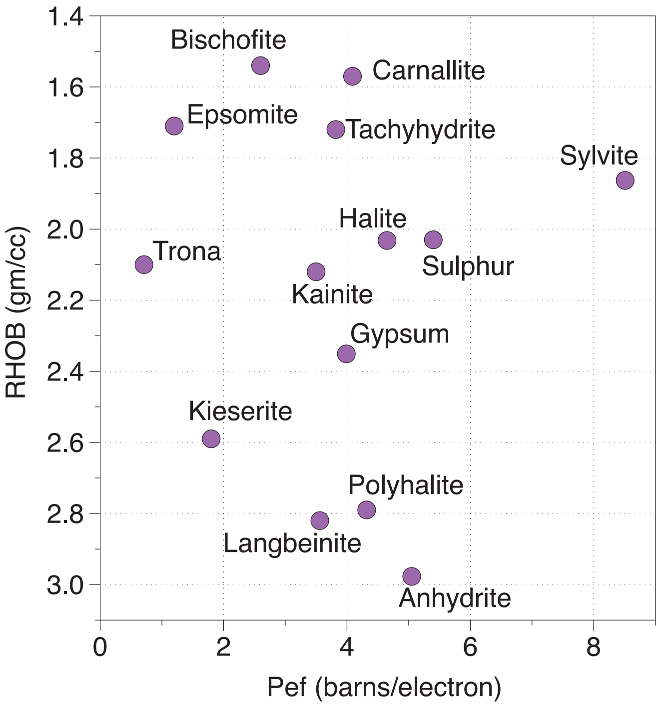


Figure 3. Density versus Pef crossplot

Bulk Density Log

The bulk density or density log is related to the electron density of a formation and is the near-numerical equivalent of the formation's specific gravity (gm/cc); that is it is considered to measure variations in the average total density of the formation. A tool-measured value includes the density of the solid rock matrix and the density of fluids enclosed in the pores. The bulk density log is a measure of the degree of scattering

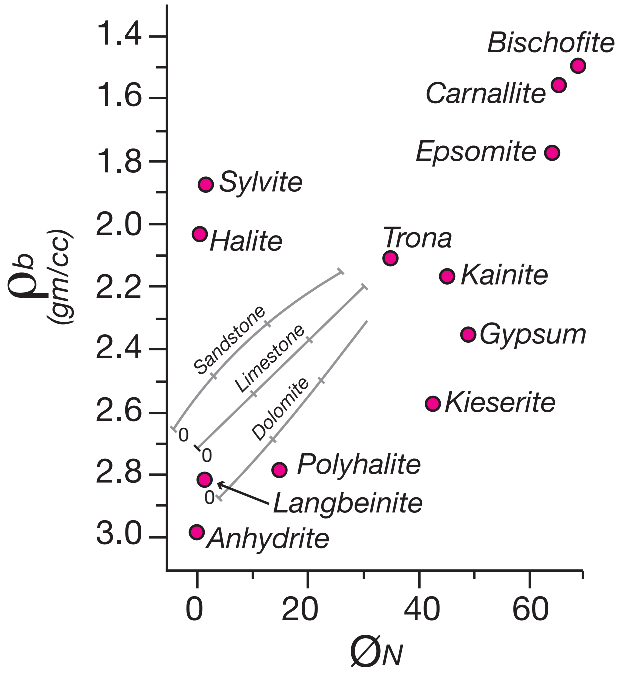


Figure 4. Crossplot of neutron (NPHI Ø) versus density (RHOB gm/cc) for a variety of evaporite salts. Also shown are the typical field lines for most sandstones, limestones and dolomites with variable porosities.

or attenuation of gamma rays by electrons in the formation (Compton scattering). The electron density of a formation (electrons/cc) is closely related to the common density (gm/cc) and is typically used as a direct indicator of common density. Unfortunately, some minerals, including halite and sylvite, have electron densities that are not directly proportional to their specific gravities. Such minerals require the use of apparent bulk density for interpretation. Fortunately, many of the evaporite minerals have sufficient differences in bulk density to be recognised especiallry when crossplotred against Pef or NPHI (neutron) values (Figure 3, 4 and 5).

Many evaporite units are relatively pure and often mono- or bi-mineralic. Because of this, their lithological composition can be suspected, if not positively identified from the density log. However, when impure, the densities will fluctuate. Fortunately, most relatively pure evaporites thicker than a metre tend to give intervals of constant density with only minor variation. When this occurs, densities near the expected value in a clean evaporite unit can be easily identified and correlated to mineralogy using the bulk density log.

Neutron Logs

The neutron porosity index or neutron log provides a continuous record of a formation's reaction to fast neutron bombardment. It is primarily a measurement of the hydrogen concentration in the formation, whether from the water of hydration, as in the case of hydrated salts such as gypsum and carnallite, or from water or oil in the more commonly understood non-evaporite situation. Quantitatively, the neutron log is used to measure porosity (in limestone-equivalent porosity units), qualitatively, it is a good discriminator between oil and gas in intervals without hydrated salts or other minerals. Geologically, it can be used to identify gross lithology, and so define evaporites (negative porosity values), hydrated minerals, and volcanic rocks and zeolites. A crossplot of formation bulk density versus neutron-log measurement is an extremely valuable tool for identifying various subsurface evaporite lithologies (Figure 2).

For example, in thick evaporite successions, a neutron log can distinguish between various evaporite salts on the basis of water of crystallisation (Rider, 1996). Gypsum is the most common of the evaporites containing water of crystallisation. However, carnallite, polyhalite, and kainite also contain the water radical (Table 1). In a neutron-density (NPHI-RHOB) crossplot, all these hydrated salts have high neutron-log values and characteristic tightly-clustered apparent bulk densities, which separates them from other anhydrous evaporites such as salt or anhydrite, which contain no water and hence have NPHI values near zero (Figure 4).

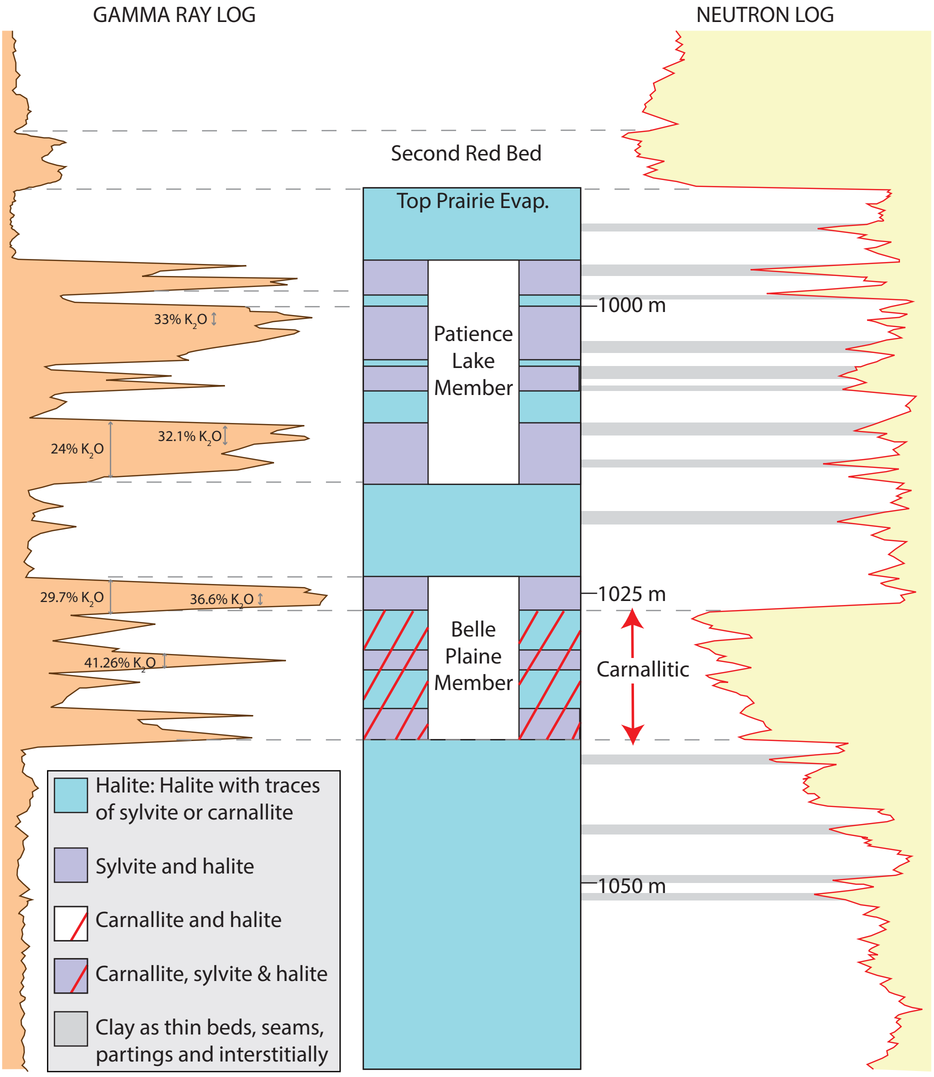


Figure 5. Typical wireline characteristics, thicknesses and inferred ore grades of the potash members in the Upper Prairie Evaporite (after Fuzesy, 1982).

Sonic or Acoustic Logs

The sonic or acoustic log shows a formation's interval transit time, designated Δt, measured in microseconds/ft or microseconds/m (Δt is the reciprocal of sonic velocity * 1000). It is a measure of a formation's capacity to transmit sound waves. Geologically this capacity typically varies with lithology and rock texture, notably porosity. Once again, because most subsurface evaporites have extremely low porosities and are often relatively pure, the sonic log can be used to reliably identify evaporites, once an initial identification has been made by some other means (Table 1). The seeming precision of the figures given in Table 1 are illusory as the actual transit times in thick evaporites can be strongly influenced by compositional variation, temperature and confining pressure.

Rock salt is formed mainly composed of the mineral halite and is a lithology whose density is effectively constant with depth (Warren, 2016; Chapter 1). Since density is probably the most critical factor in determining acoustic velocity, the Δtma of a thick halite unit tends to be relatively constant over a wide depth range. For pure halite, the interval transit time is 68 μsec/ft (14,625 ft/sec). However, many halite units contain varying levels of impurities, usually anhydrite, either as interbeds or disseminated throughout the sequence. Anhydrite has an interval transit time of 50 μsec/ft (20,000 ft/sec). The velocity variations in a binary system of halite and anhydrite are related linearly (either by weight or volume) to the densities of the various mixtures of the end member values allowing semiquantitative determinations of the purity of the units. Sonic logs are widely used in the oil industry for correlation and the construction of synthetic seismograms. When considering representative velocities in interpreting seismic lines, it must be remembered that the presence of bedded anhydrite and carbonate units within the total rock salt interval can have an appreciable effect on the average seismic velocity through a salt interval.

Basic identification conventional wireline log outputs

The gamma log ()aka as the lithology log) measures the natural or spontaneous radioactivity of a formation. In a sand-shale basin, the measured gamma values are used to infer clay contet. In an evaporite basin, the gamma log (especially the spectral gamma log) is a reliable indication of the presence or absence of potash salts.

In a classic quick-look analysis of any potential hydrocarbon reservoir, the sonic, density and neutron logs are used both individually and in combination to estimate the porosity of likely reservoir strata. These three logs are referred to as the “porosity logs”. Although they are typically used to indirectly infer porosity, they actually reflect variations in rock properties related to the passage of sound, induced gamma radiation and high energy neutron bombardment. The fact there is negligible porosity in most subsurface evaporites means the “porosity logs” in combination with each other, or with a spectral gamma log, can be used to identify evaporite mineralogies.

With conventional wireline log suites in bedded and halokinetic sequences worldwide I use following quick-look procedure to identify various major anhydrite, halite and potash units (refer to Table 1 and figure 5):

1) Tentatively define evaporite intervals as zones dominated by lowest gamma-ray values (some carbonates also show very low, but typically slightly higher gamma values). Remember potash beds encased in halite, or less often anhydrite, will have high gamma values.

2) Confirm pure anhydrite intervals (thicker than a metre -tool resolution dependent) using

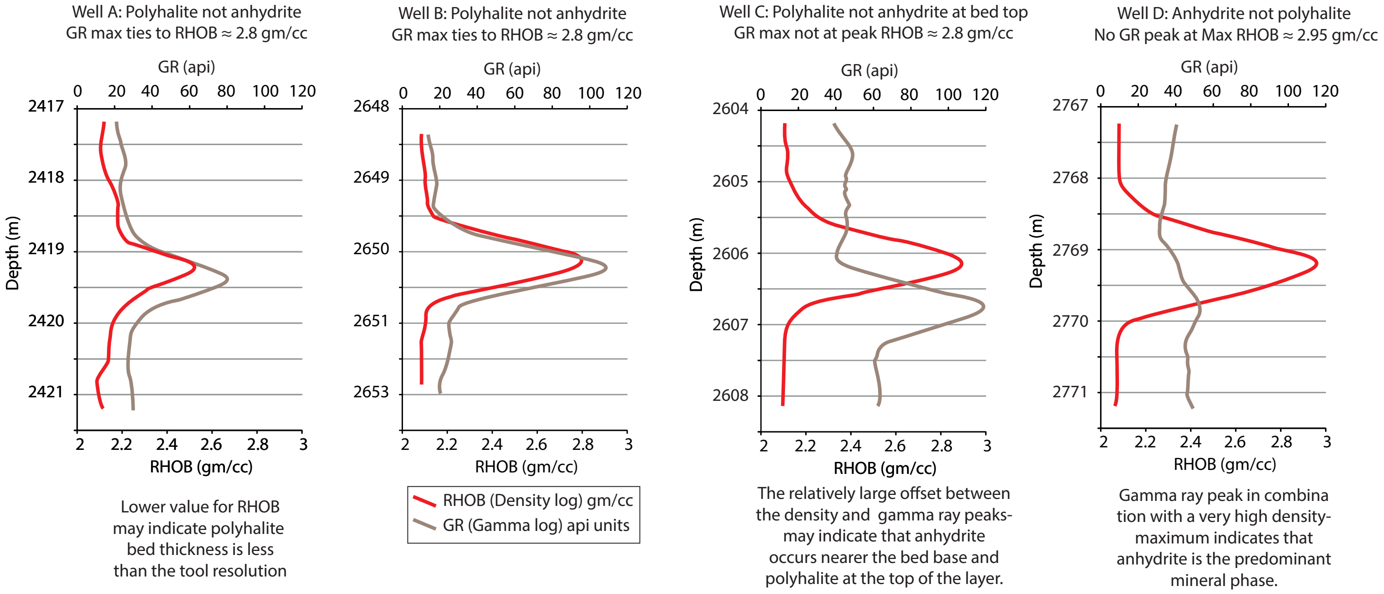
a) Sonic - Δt ≈ 50 microseconds

b) Bulk Density - Log value of 2.98 gm/cc. Anhydrite densities in log curve greater than 2.95 typically indicate anhydrite (but be aware of possible metal sulphides (pyrite, galena) and barite cement in some evaporite masses, especially in the caprock to halokinetic structures. NPHI porosities of anhydrite tend to hover at zero or on the negative side (in standard limestone porosity units)

3) Confirm pure halite intervals (thicker than a metre) using a combination of density and NPHI (neutron) logs. Halite-dominated zones show a consistent combination of bulk densities around 2.1 gm/cc, negative NPHI porosities and sonic (delta T) values around 64 - 70 μs/ft.

4) Use the caliper - a curve tracking the nominal bit size to confirm anhydrite versus halite (±potash salts). A caliper value much larger than bit-size indicates borehole washout, it is probably due to the intersection of salt, not the less-soluble anhydrite. Anhydrite beds tend to show an "in-gauge" caliper profiles and also tend to be slower-drilled units compared to halite (penetration data can be seen in a mudlog or well completion report). However, carbonate intrasalt beds can also show slow drill penetration rates and an "in-gauge" profile

5) Use the resistivity log - Salt like anhydrite has high resistance to current flow (Table 1), but, due to wash-out, salt units often shows lower apparent resistivity values, especially in the microresistivity and shallow reading curve outputs.



Well A: Polyhalite not anhydrite
GR max ties to RHOB ≈ 2.8 gm/cc

Well B: Polyhalite not anhydrite
GR max ties to RHOB ≈ 2.8 gm/cc

Well C: Polyhalite not anhydrite at bed top
GR max not at peak RHOB ≈ 2.8 gm/cc

Well D: Anhydrite not polyhalite
No GR peak at Max RHOB ≈ 2.95 gm/cc

Lower value for RHOB may indicate polyhalite bed thickness is less than the tool resolution

The relatively large offset between the density and gamma ray peaks-may indicate that anhydrite occurs nearer the bed base and polyhalite at the top of the layer.

Gamma ray peak in combina tion with a very high density-maximum indicates that anhydrite is the predominant mineral phase.

Figure 6. Typical density and gamma ray log signatures that can be related to spatial changes in polyhalite/anhydrite mineralogy within the Z2sl2 unit in the Zechstein of NW Europe (After Biehl et al. 2015). . Well D shows a signature that is typical for the Groningen High, Germany. Typical log values for the Z2 halite are density around 2.1 g/cm^3 and a natural radioactivity <20 API units.

6) If there are high gamma (K-rich) intervals within thick halite beds or high-density values (>2.8gm/cc) adjacent to anhydrite consider these intervals to be possible zones with elevated levels of salts such as sylvite, carnallite or polyhalite.

7) Zones of very-low apparent bulk densities (<1.4 gm/cc) and low gamma values within a thick halite may indicate beds dominated by a non-potash evaporite minerals such as bischofite.

8) An overlaid combination of a density and a gamma log in the same track can also useful in separating what are often two co-associated high density subsurface sulphate salts, namely anhydrite and polyhalite (Figure 6). Polyhalite is a potash salt with elevated density (2.8 gm/cc) and elevated gamma values. Anhydrite has an even higher density but lacks potash and hence exhibits relatively low Gr values. This diffence in potash response in what are both characteristically high-density minerals allows for their differentiation.

9) A lack of porosity and the near linear response of the spectral gamma log to mineral proportions means GR outputs when tied to assay values can be reliably used to infer K_2O ore grades (Figure 7).

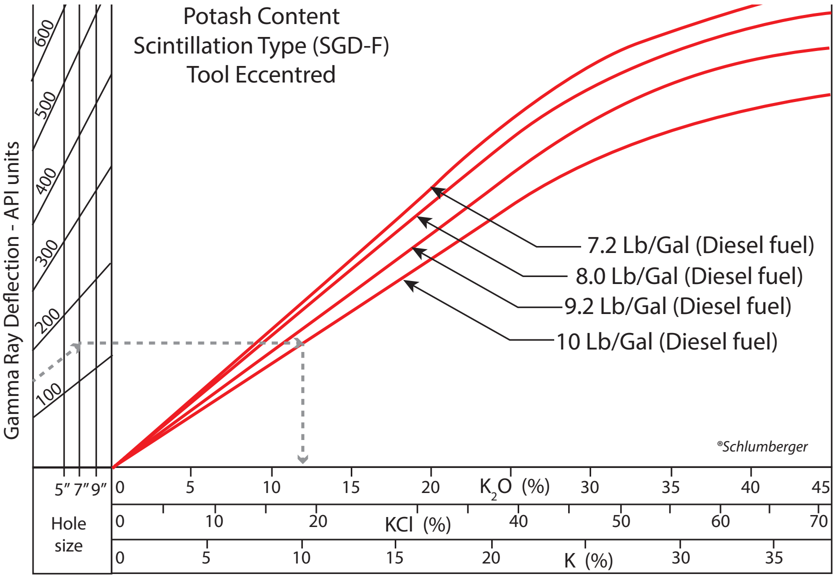


Figure 7. Conversion chart for approximate K_2O calculations using a total GR log run through an interval of potash salts (Schlumberger). The chart shows a worked example: 150 API in a 7-inch borehole with 10 lb/gallon diesel fuel-based drilling mud is the equivalent of ≈ 12% K_2O. This chart follows the approximating rule of thumb mentioned in the text, so that each increase of 15 API units is equivalent to an increase in ore grade of around 1% K_2O.

In summary, most nonporous, thick relatively monomineralic evaporite units are readily identified using wireline logs, and often the proportions of minerals can be reliably determined using relevant crossplots. However, any mineralogical interpretation based on a well log outputs is just that, an interpretation, and whenever possible should be checked against rock evidence such as chips or core. When confirming a log suite interpretation of an evaporite interval, you should keep in mind that chips composed of the more soluble evaporite minerals are often completely dissolved in the drilling mud before they reach the shale shaker. In this case, the wireline logs can give a better indication of actual mineralogy than the mud chips.

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