BAKER HUGHES

Baker Atlas

SOUTH FLORIDA WATER MANAGEMENT DISTRICT

PERMEABILITY PROFILE GENERATION "METHODOLOGIES"

METHODOLOGIES FOR PERMEABILITY PROFILE GENERATION

Three different permeability profiles are generated for the South Florida water wells. These profiles and methodologies to derive them are discussed below:

MPERM is an output of the NMR log processing. MPERM is computed by using the "Bound Water Model" with literature based 92 milliseconds $T_{2cutoff}$ time for the BVI (bulk volume irreducible) determination. The equation for this profile is given below:

$$k, md = \left(\frac{MPHE}{C}\right)^m \left(\frac{MBVM}{MBVI}\right)^n$$

Where:
MPHE : effective porosity from NMR log
MBVM : movable portion of the effective pore volume
MBVI : immovable portion of the effective pore volume
C, m, n : coefficient and exponents (derived via optimized solution / calibration of the equation for known MPHE, MBVM, MBVI and core permeability values)

Partial calibration was done due to lack of the capillary pressure data at the time of processing. $T_{2cutoff}$ time is taken as constant -92 milliseconds- throughout the interval. An optimum set of C, m and n values is obtained for an acceptable match between MPERM and core permeability values by solving the permeability equation for C, m and n with known values of MPHE, MBVI and MBVM. This approach is prone to error for the formations as complex as the one that is cut by the subject wells. $T_{2cutoff}$ time for a mixed lithology at very shallow depths with lesser compaction may vary drastically. However, an acceptable match between the core-based permeability and porosity is attained via manipulating the C, m and n coefficient and the exponents of the equation.

Alternative permeability profile **-RK-** is derived as a byproduct of the capillary pressure conversion of the NMR log data. This conversion generates the MBVI profile without requiring priori knowledge of the $T_{2cutoff}$ time, hence, it does have the advantage over the traditional methods of computing MBVI when the actual $T_{2cutoff}$ time varies drastically. The permeability profile (RK) is computed based on Bound Water Model equation with RBVI generated from Pc-conversion. This unique technique is developed by Baker Atlas Geoscience Development and fundamentally relies on the following theoretical foundation:

Capillary pressure conversion of NMR data:

NMR T_2 decay in porous media is commonly interpreted in terms of pore size distribution (where pore size distribution is used synonymously with pore-body size) because the T_2 relaxation time is proportional to the ratio of the pore volume to pore surface area and inversely proportional to surface relaxivity. This relationship is valid when the pores are water wet, there is no diffusive coupling, the T_2 distribution is not shifted by the presence of hydrocarbons, and the T_2 of the bulk fluid is large enough to drop the term ($1/T_{2b}$) from the equation. The governing equation for the T_2 decay phenomena and capillary pressure can be written in their simple forms as follows:

$$\frac{1}{T_2} = \frac{1}{T_{2b}} + \rho_2 \frac{S}{V}$$

$$P_c = \frac{2\sigma \cos(\theta)}{r_{pt}}$$

where:
T_2 = Observed relaxation time
T_{2b} = Relaxation time of bulk fluid
ρ_2 = Surface relaxivity
S = Surface area of pore
V = Volume of pore body
Pc = Capillary pressure
r_{pt} = Pore throat size
Φ = Contact angle
σ = Interfacial tension

T_{2b} is a relatively large number and the $1/T_{2b}$ term may be dropped from the equation simplifying the T_2 decay equation:

$$\frac{1}{T_2} \cong \rho_2 \frac{S}{V}$$

Assuming a geometrically definable shape for capillaries (spherical or tube like), the surface to volume ratio can be written in terms of pore size.

$$\frac{S}{V} = \frac{F_s}{r_b}$$

where:
F_s : The shape factor, 3 for round pores and
2 for cylindrical tubes

By assuming a relation between pore-body and pore-throat size and by replacing the r_{pt} in the capillary pressure equation with the corresponding T_2 term, the following equation is obtained:

$$\frac{1}{P_c} = \frac{\rho_2}{2\sigma\cos(\theta)} \frac{r_{pt}}{r_b} F_s T_2$$

If we rearrange the above equation and regroup the surface relaxivity and pore throat to pore body ratio variance into a variable called C,

$$C = \frac{\rho_2}{2\sigma\cos(\theta)} \frac{r_{pt}}{r_b} F_s$$

where:
r_b = pore body size

The original equation can be rewritten as follows:

$$\left(\frac{1}{P_c}\right) = CT_2$$

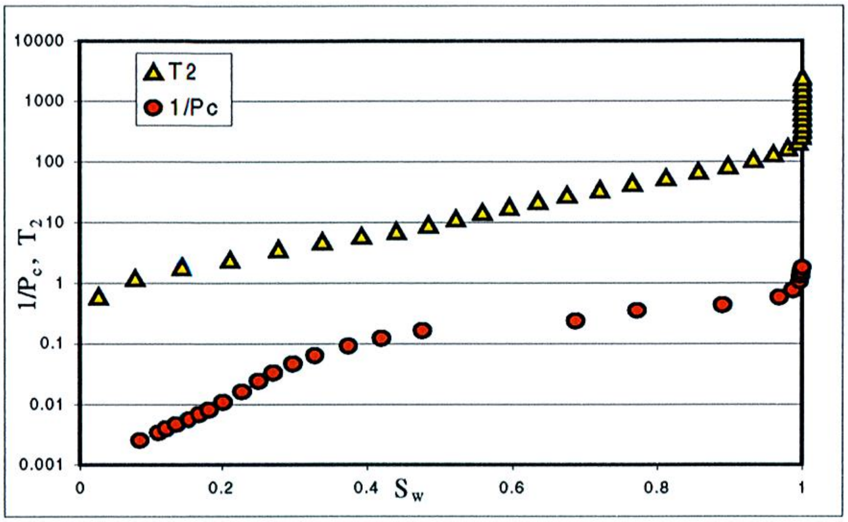
By taking the logarithms of both sides of the equation, we obtain:

$$Log\left(\frac{1}{P_c}\right) = Log(C) + Log(T_2)$$

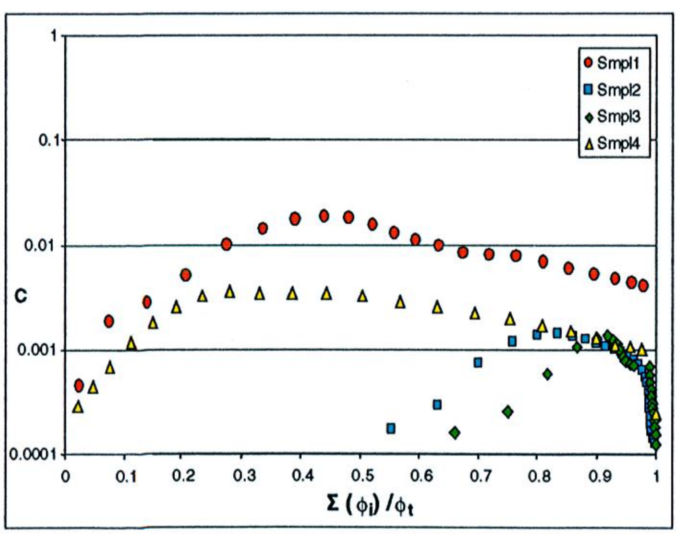
The C factor can be computed for each level when the T_2 distribution and the corresponding P_c curve are available from laboratory tests.

$$Log(C) = Log\left(\frac{1}{P_c}\right) - Log(T_2)$$

The above function calculates the minimum distance between each data point of the curves of $1/P_c$ versus S_w and T_2 versus S_w. A sample of these curves are given below:



The C factor that minimizes the distance between the two curves ($1/P_c$ and T_2) is a product of the pore-throat to pore-body ratio and the surface relaxivity to interfacial tension ratio. If interfacial tension and the contact angle being reasonably constant in a given interval, the C factor simply reflects the changes in pore throat size and the surface relaxivity. The following plot depicts the change in C values with respect to different $\sum\phi_i/\phi_t$ values for different samples:



The C-factor is calculated for each core sample when core is available and a correlation of C versus effective porosity is determined. Baker Atlas has derived a model for computing C-factor on the fly based on an extensive database of sandstone and carbonate core samples. The C-factor profile for this study is obtained by referring to the Baker Atlas model because of lack of core-NMR and core capillary pressure data at the time of the interpretation.

The equation for C, as given below, helps us understand the relationship between T_2 and P_c and the saturation change of the wetting phase.

$$C = \frac{\rho_2}{2\sigma\cos(\theta)} \frac{r_{pt}}{r_b} F_s$$

The variation in C with wetting phase saturation for an assumed pore size and T_2 distribution (wetting phase saturation $\alpha\ r_{pt}\ \alpha\ r_p\ \alpha\ T_2$) indicates either:

- the ratio of the pore body to pore throat size is varying with pore size;
- shape factor varies with pore size
- the surface relaxivity is pore size dependent, or
- possibly all of the above

Without additional data (e.g., Image analysis, NMR diffusion measurements, ...), it is not possible to identify the dominant effect. Nevertheless, the term C suffices for calculating the synthetic capillary pressure from the NMR data.

A model equation is used to extrapolate the NMR-derived capillary pressure curves for the subject wells to very large capillary pressure levels to obtain the theoretical S_{wirr}. The same model also provides the threshold pressure as S_w approaches 100% by a parameter estimation technique. The form of the model equation is as follows:

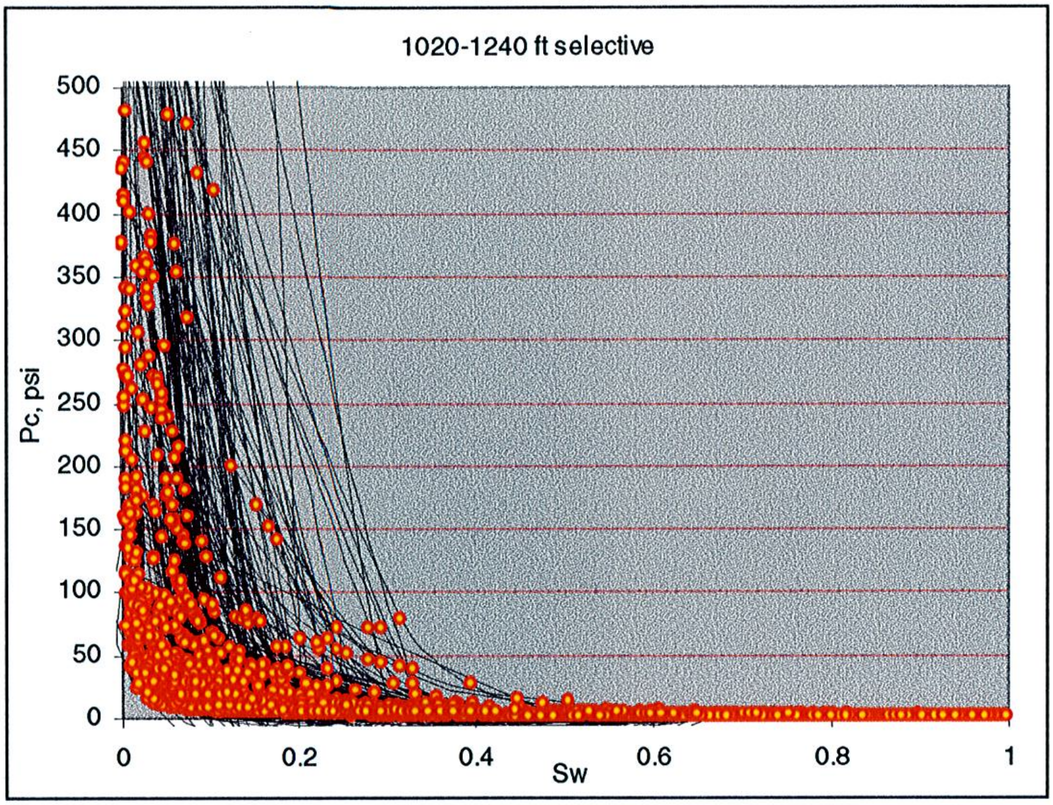
$$S_w \ = \ S_{wirr} + (1 - S_{wirr})\frac{P_d}{P_c} + (1 - S_{wirr})\frac{P_d}{P_c} Ln(\frac{P_c}{P_d})$$

where:
S_w = Water phase saturation
S_{wirr} = Irreducible water saturation
P_d = Threshold (entry) pressure
P_c = Capillary pressure

The above equation satisfies the limiting conditions of the capillary pressure saturation behavior: S_w approaches S_{wirr} when P_c approaches infinity and P_c approaches a finite number (P_d) when S_w approaches 100 %.

By processing the Pc versus S_w data with the above model equation and non-linear regression analysis, S_{wirr} and P_d values are estimated for each level spacing of the nmr log data. This provides us with a RBVI (MBVI) profile for each well independent of $T_{2cutoff}$. It is obvious that the applicability of the methodology is constrained by the validity of the NMR data; therefore, we used the technique for the intervals with valid NMR log data where there was no borehole enlargement.

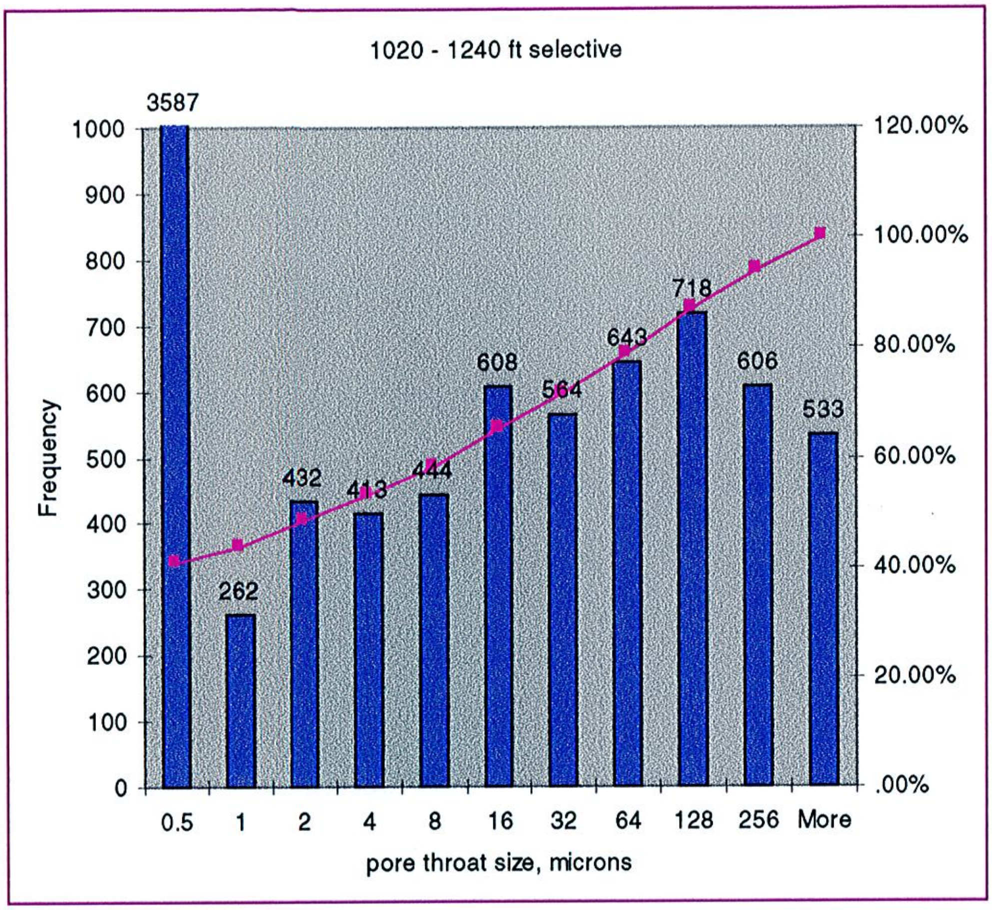
Capillary pressure data for a selected interval from 1020 ft to 1240 ft is plotted below as an example of output of this conversion. Data reduction is done for presentation purposes. The scope of this project is to provide MBVI and permeability profiles rather than capillary pressure data; hence the following chart is for presenting the output of the algorithm and the technique for this study.



Having capillary pressure information of porous media provides us an avenue to make a reasonable estimate of pore-throat size distribution by simply solving the capillary pressure equation for r_{pt}:

$$r_{pt} = \frac{2\sigma\cos(\theta)}{P_c}$$

A sample histogram is plotted in the following page for the selected interval showing the pore-throat size distribution. The lack of oil in the pore space for this case makes this representation more realistic since the hydrocarbon-induced shift of the T_2 spectra is not an issue for this specific case.



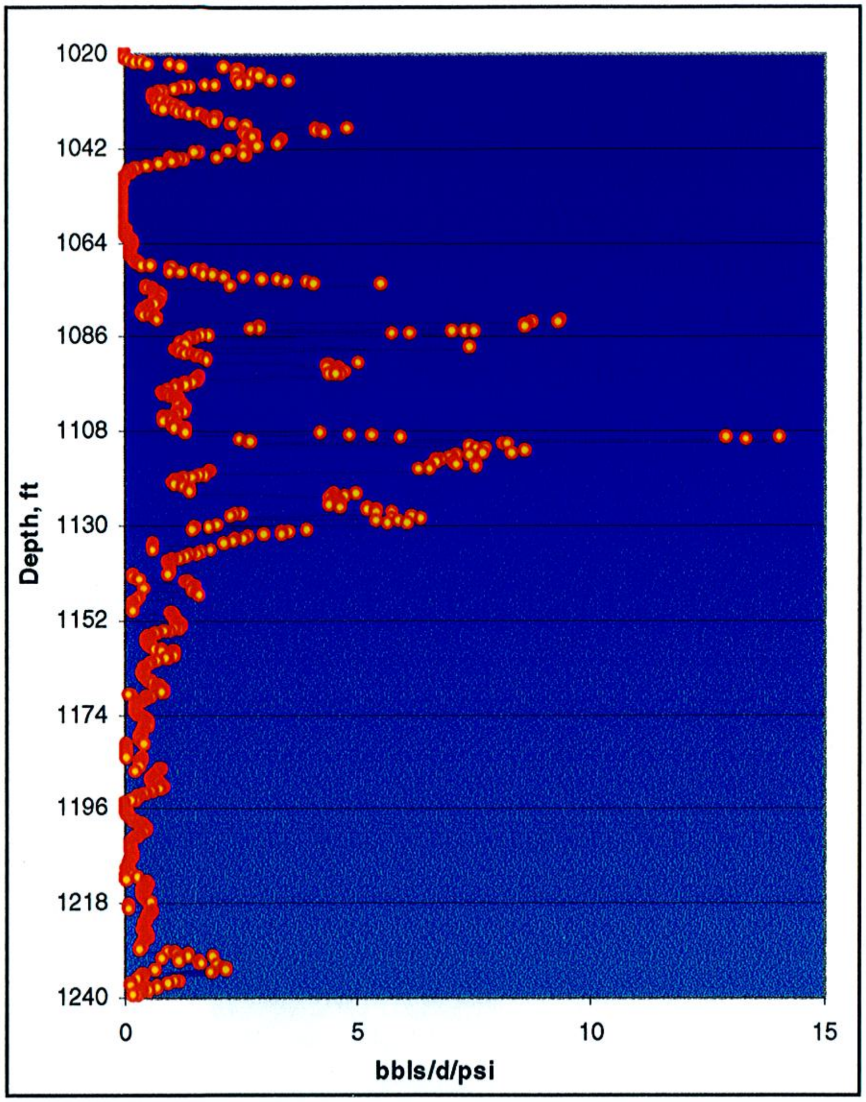
PRODUCTIVITY INDEX ESTIMATIONS:

Productivity index estimation per level spacing is also derived and displayed in the following page for the selected interval as a sample output of this methodology. The equation used for the calculation of productivity index is as follows:

$$PI, bbls/d/psi \approx 9.3 \cdot 10^{-4} \frac{k \cdot h}{\mu_w \cdot B_w}$$

Where:

K : permeability, md
H : net pay exposed in wellbore, ft
μ_w : water viscosity, cp
B_w : water formation volume factor, rbbls/stbbls



The above plot is level by level display of the PI (productivity index), and it should be summed up for selected interval to determine the bbls of water/interval/psi/day.

CORRECTED PERMEABILITY PROFILE FOR THE WASHOUT SECTIONS:

The lower portion of the NMR log data for PBF-10, starting from 1470 ft to 2050 ft, was rendered useless by the enlarged borehole. Washout caused the hole enlargement to a degree that the sensitive volume of the NMR measurement remained in the bore hole rather than the formation. This yielded borehole fluid signal instead of the anticipated signal from the fluids that fill the formation pore space. Hence, an algorithm to generate a corrected permeability profile is designed by using the open hole logs with deeper depth of investigation in conjunction with the Pc-based MBVI

The evaluation of LAB-TW produced a correlation table for approximating the Pc-based RBVI as follows:

	RBVI	CNC	CNCF	PORA	ZDEN	ZDNC	KTH	K	TH	THAPI	GR
RBVI	1										
CNC	-0.6158	1									
CNCF	0.4232	0.11736	1								
PORA	-0.4506	0.13868	-0.6377	1							
ZDEN	-0.1940	-0.04353	-0.3972	0.15346	1						
ZDNC	-0.1942	-0.04294	-0.3966	0.15344	0.99997	1					
KTH	0.7426	-0.68499	0.3254	-0.66992	-0.11729	-0.1172	1				
K	0.5653	-0.34089	0.1054	-0.01258	-0.26480	-0.2646	0.33332	1			
TH	0.6105	-0.55983	0.3707	-0.77874	-0.04549	-0.0455	0.94821	0.06156	1		
THAPI	0.6298	-0.61375	0.3351	-0.73233	-0.05234	-0.0523	0.96439	0.07756	0.99310	1	
GR	-0.2883	-0.11655	-0.6425	0.44939	0.71017	0.7103	-0.16701	-0.41981	-0.11465	-0.0810	1

This table is for the interval of 1390-1440 ft of LAB-TW where the NMR log output is acceptable. KTH curve is accepted as the correlating dependent variable for RBVI estimations for the sections where NMR log data are useless due to washouts.

Correlating model equations for FRBVI, FBVM and FPERM are determined to be in the forms of:

$$FRBVI = 0.704 + 0.078 \cdot KTH \cdot Ln(KTH)$$

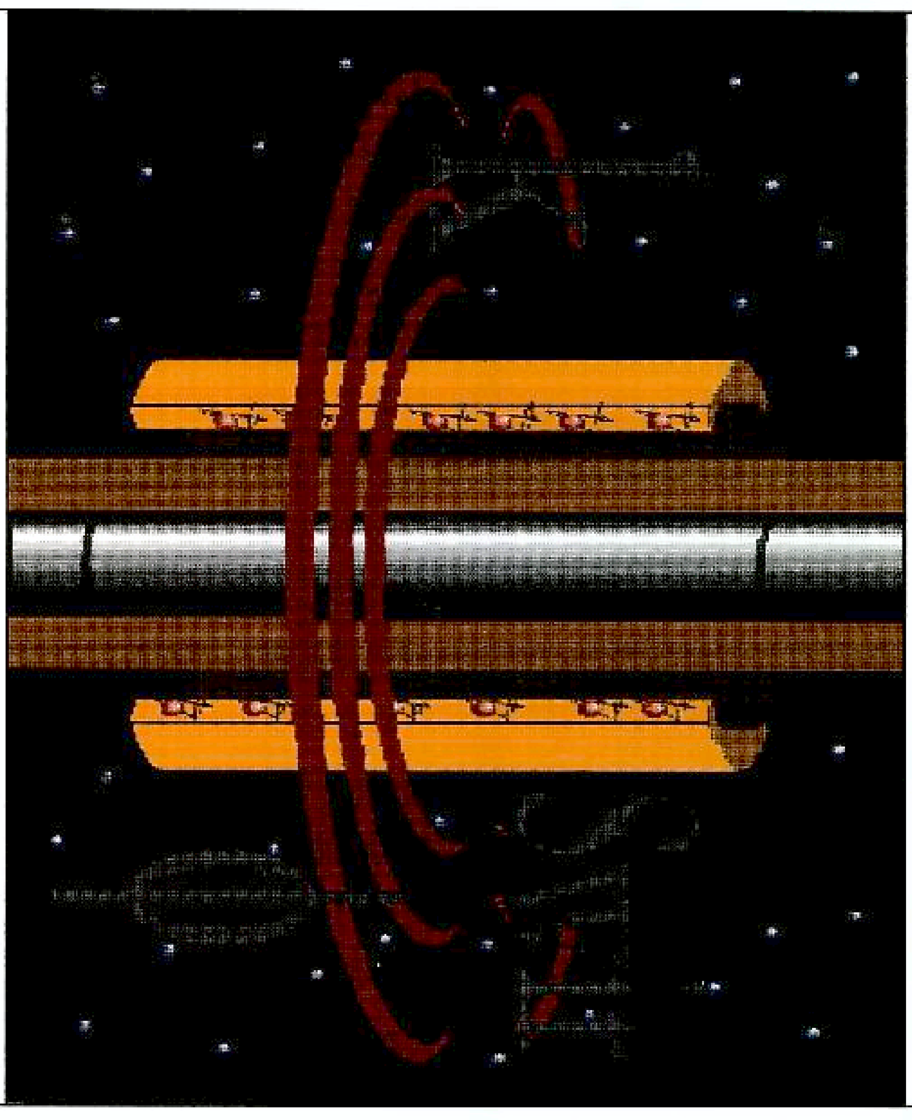
$$FBVM = PORZC - FRBVI$$

$$FPERM = \left(\frac{PORZC}{18}\right)^{3.25} \left(\frac{FBVM}{FRBVI}\right)^{2}$$

Where:

FRBVI = Bulk volume irreducible from the correlation for washout sections
FBVM = Bulk volume movable for the washout sections
KTH = Potassium, Thorium content
PORZC = Corrected density porosity

Fperm curve available for the washed out sections of PBF-10, LAB-TW, IWSD-PW, complete coverage of I75-PW, and L2-PW where there is no NMR log data.

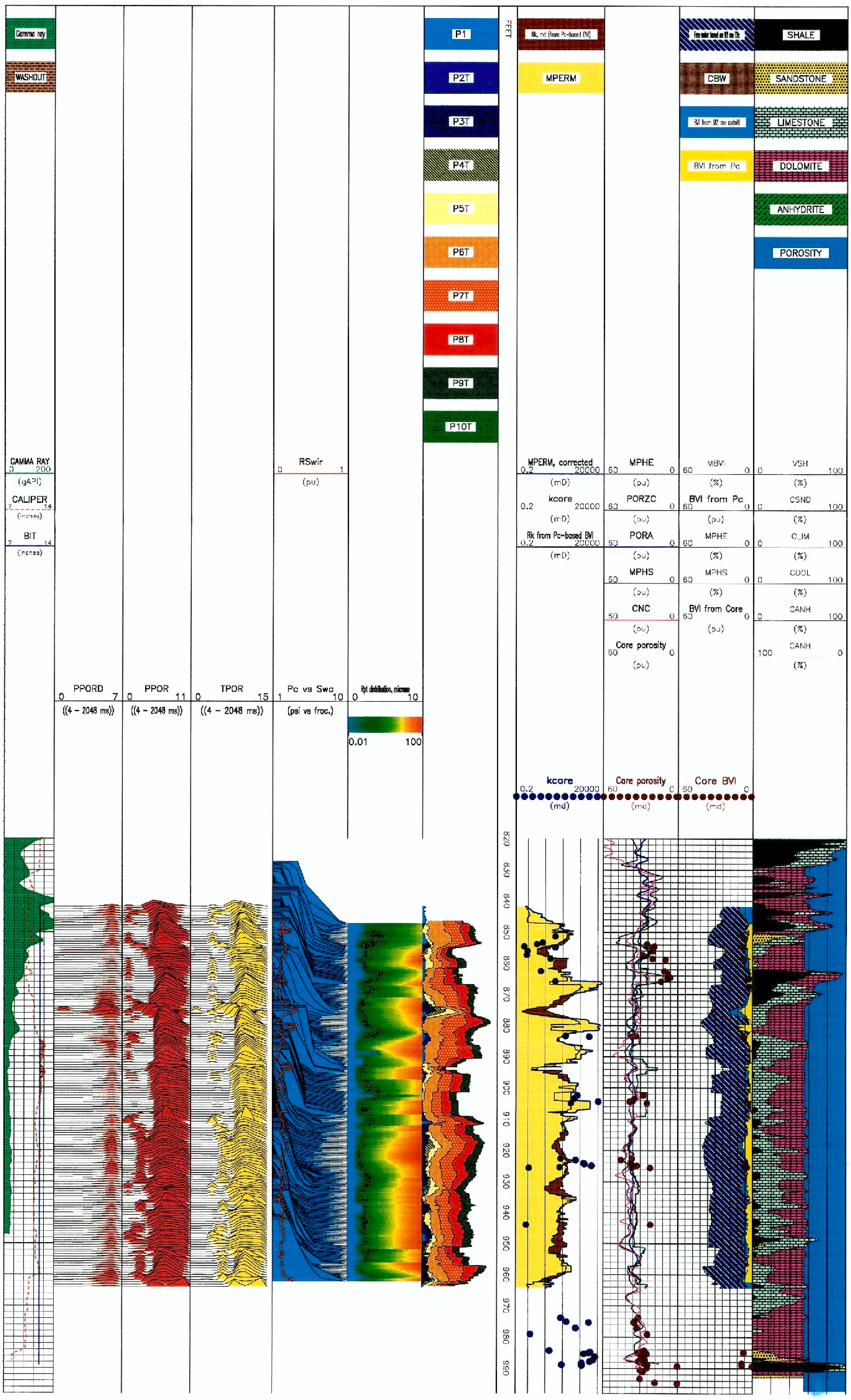


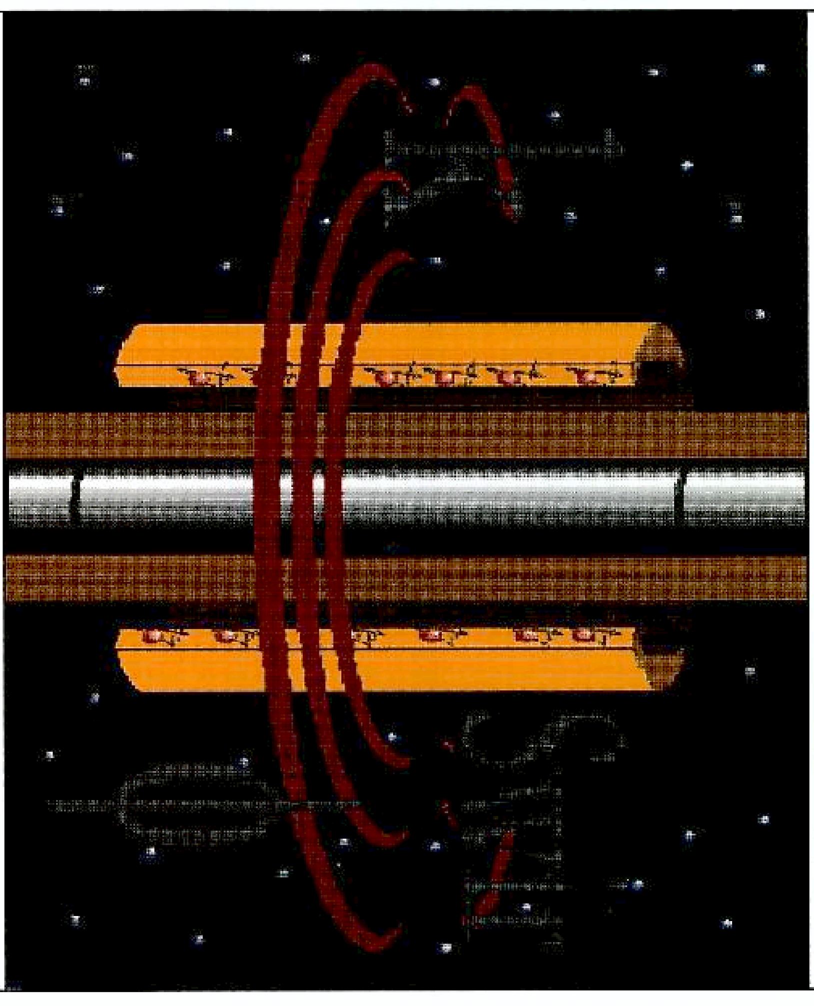
Baker Atlas
GEOScience
BAKER HUGHES

COMPANY	SOUTH FLORIDA WATER MANAGEMENT DISTRICT
WELL	BICY-PW
FIELD	BIG CYPRESS PRESERVE
COUNTY	COLLIER STATE FLORIDA
LOCATION:	SEC 34 TWP 52S RGE 30E
ELEVATIONS:	KB 10 FT DF 9.5 FT GL 5 FT
DATE	15-FEB-2000 ECC 121.00

IN MAKING INTERPRETATIONS OF LOGS OUR EMPLOYEES WILL GIVE CUSTOMER THE BENEFIT OF THEIR BEST JUDGEMENT. BUT SINCE ALL INTERPRETATIONS ARE OPINIONS BASED ON INFERENCES FROM ELECTRICAL OR OTHER MEASUREMENTS, WE CANNOT, AND WE DO NOT GUARANTEE THE ACCURACY OR CORRECTNESS OF ANY INTERPRETATION. WE SHALL NOT BE LIABLE OR RESPONSIBLE FOR ANY LOSS, COST, DAMAGES, OR EXPENSES WHATSOEVER INCURRED OR SUSTAINED BY THE CUSTOMER RESULTING FROM ANY INTERPRETATION MADE BY ANY OF OUR EMPLOYEES.

REMARKS





BAKER HUGHES

Baker Atlas
GEOScience

COMPANY	SOUTH FLORIDA WATER MANAGEMENT DISTRICT
WELL	LAB-PW
FIELD	CALOOSAHATCHEE RIVER
COUNTY	HENDRY STATE FLORIDA
LOCATION:	
	SEC 12 TWP 43S RGE 28E
ELEVATIONS:	KB 25 FT DF 24 FT GL 15 FT
DATE	15-FEB-2000 ECC 131.00

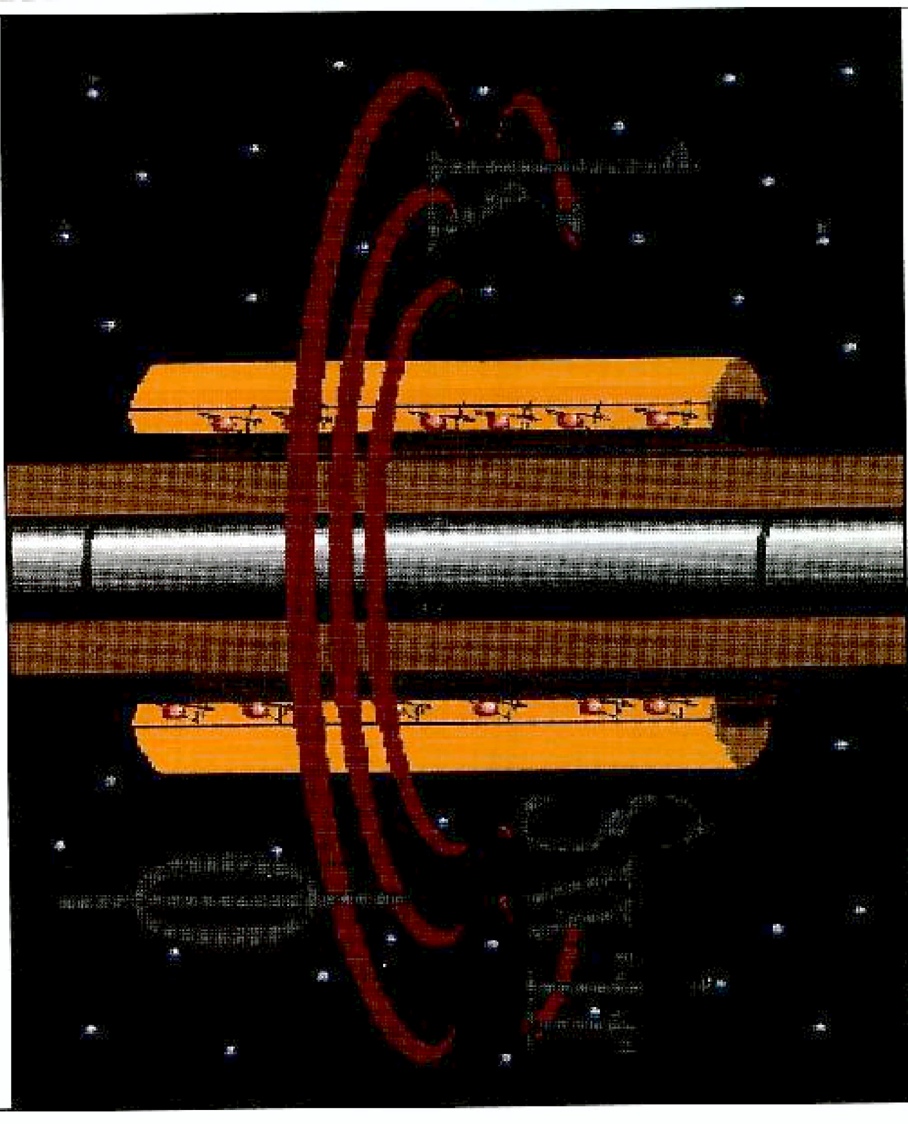
IN MAKING INTERPRETATIONS OF LOGS OUR EMPLOYEES WILL GIVE CUSTOMER THE BENEFIT OF THEIR BEST JUDGEMENT. BUT SINCE ALL INTERPRETATIONS ARE OPINIONS BASED ON INFERENCES FROM ELECTRICAL OR OTHER MEASUREMENTS, WE CANNOT, AND WE DO NOT GUARANTEE THE ACCURACY OR CORRECTNESS OF ANY INTERPRETATION. WE SHALL NOT BE LIABLE OR RESPONSIBLE FOR ANY LOSS, COST, DAMAGES, OR EXPENSES WHATSOEVER INCURRED OR SUSTAINED BY THE CUSTOMER RESULTING FROM ANY INTERPRETATION MADE BY ANY OF OUR EMPLOYEES.

REMARKS

BAKER HUGHES

Baker Atlas

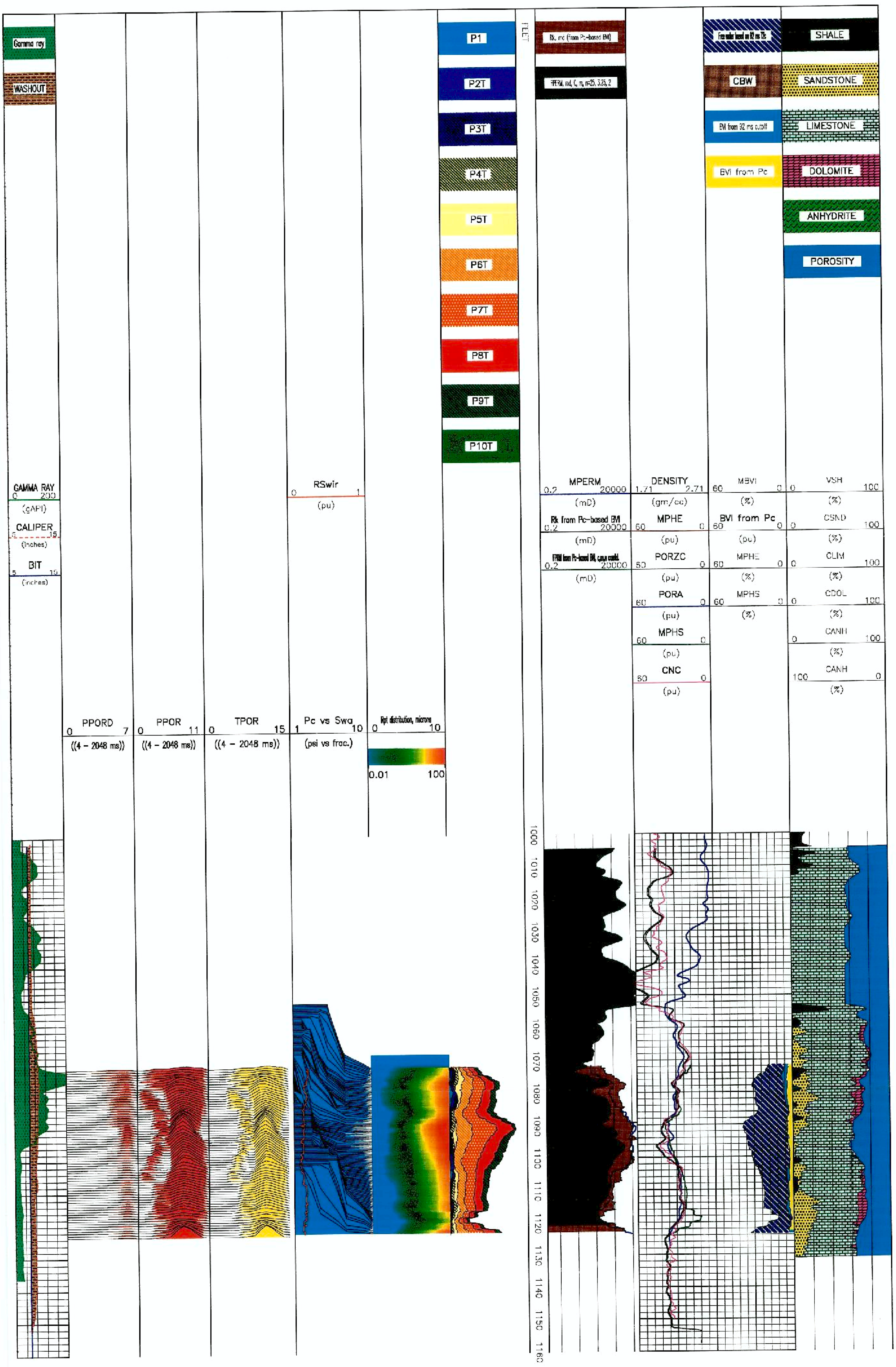
GEOScience



COMPANY	SOUTH FLORIDA WATER MANAGEMENT DISTRICT
WELL	IWSD-PW
FIELD	IMMOKALEE
COUNTY	COLLIER STATE FLORIDA
LOCATION:	SEC 4 TWP 47S RGE 29E
ELEVATIONS:	KB 41 FT DF 40 FT GL 31 FT
DATE	15-FEB-2000 ECC

IN MAKING INTERPRETATIONS OF LOGS OUR EMPLOYEES WILL GIVE CUSTOMER THE BENEFIT OF THEIR BEST JUDGEMENT. BUT SINCE ALL INTERPRETATIONS ARE OPINIONS BASED ON INFERENCES FROM ELECTRICAL OR OTHER MEASUREMENTS, WE CANNOT, AND WE DO NOT GUARANTEE THE ACCURACY OR CORRECTNESS OF ANY INTERPRETATION. WE SHALL NOT BE LIABLE OR RESPONSIBLE FOR ANY LOSS, COST, DAMAGES, OR EXPENSES WHATSOEVER INCURRED OR SUSTAINED BY THE CUSTOMER RESULTING FROM ANY INTERPRETATION MADE BY ANY OF OUR EMPLOYEES.

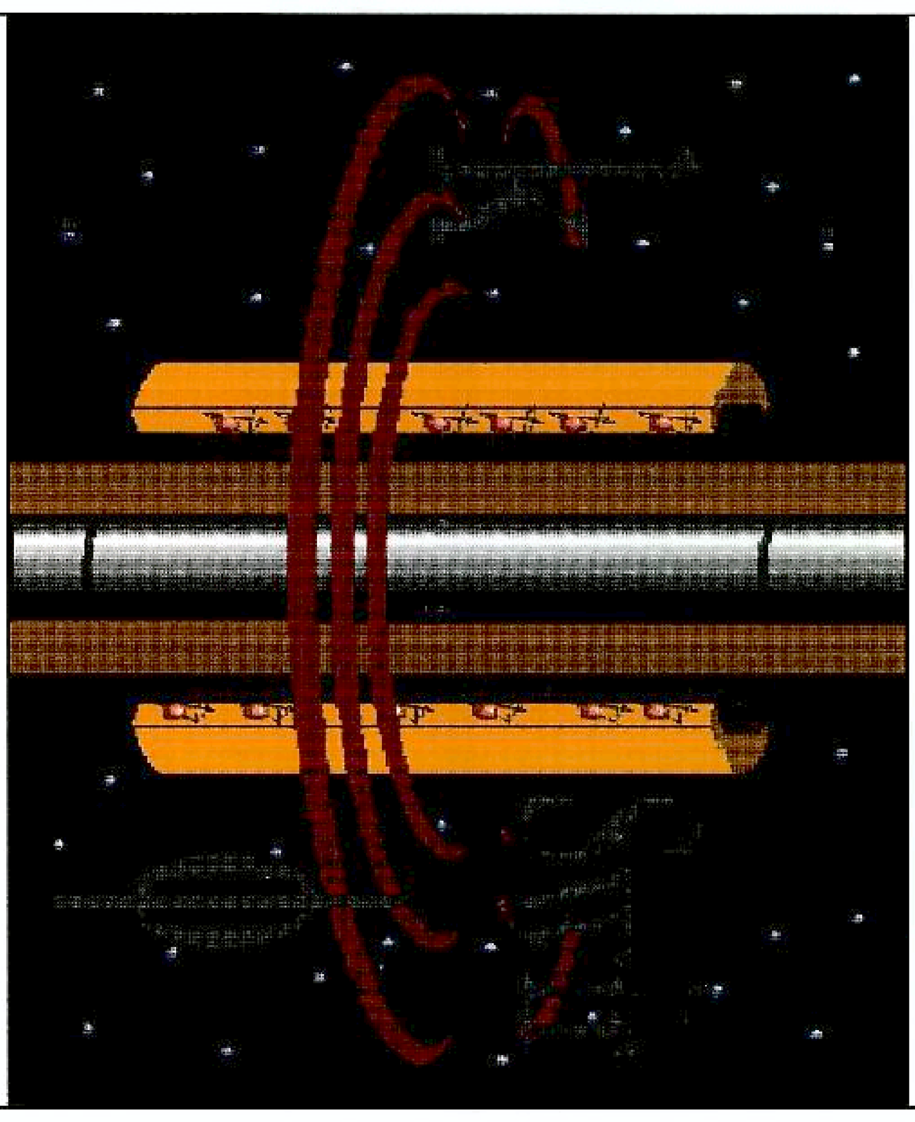
REMARKS



BAKER HUGHES

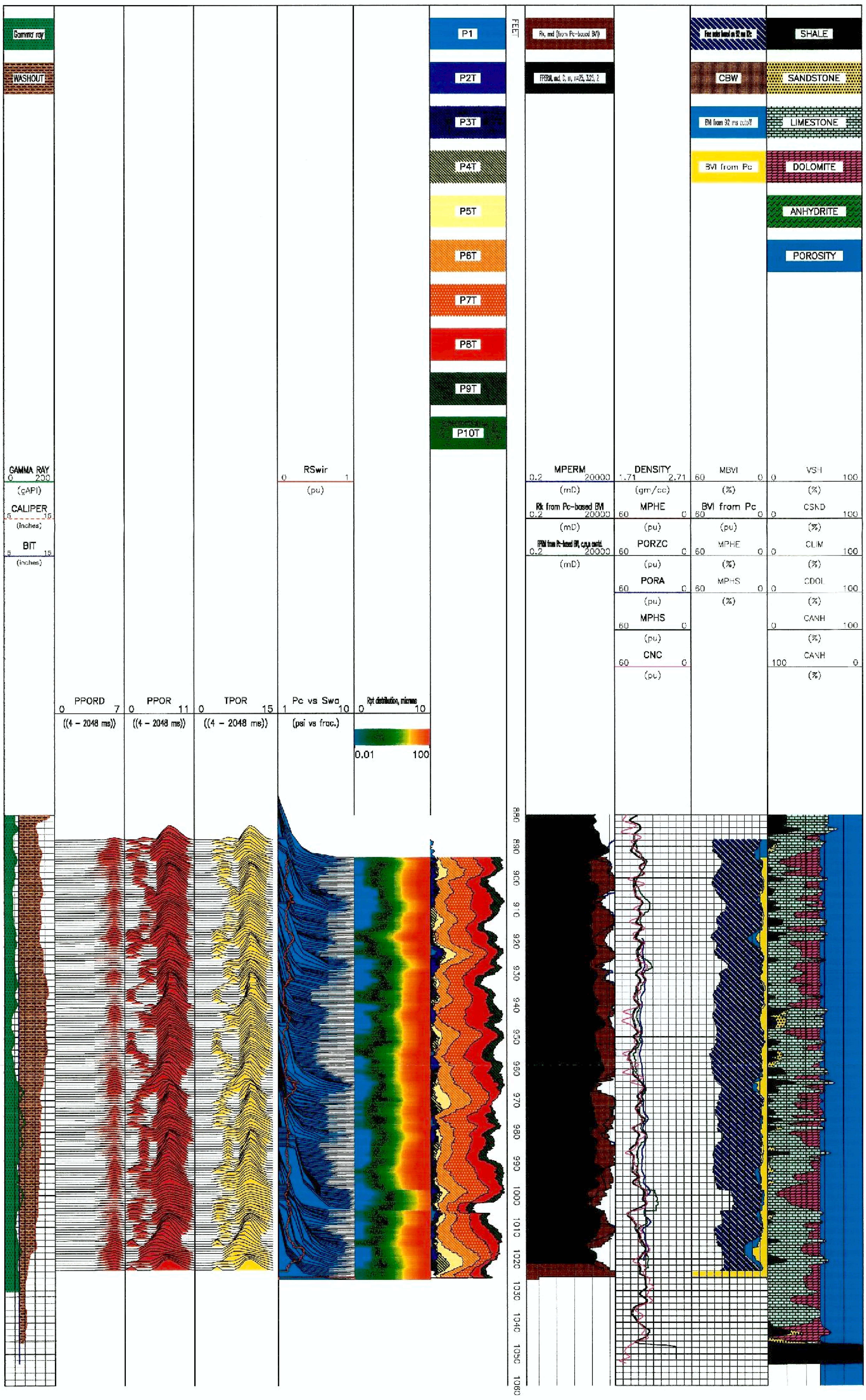
Baker Atlas

GEOScience



COMPANY	SOUTH FLORIDA WATER MANAGEMENT DISTRICT
WELL	I75-PW
FIELD	I75 CANAL
COUNTY	COLLIER STATE FLORIDA
LOCATION:	SEC 29 TWP 49S RGE 26E
ELEVATIONS:	KB 20 FT DF 19.5 FT GL 10 FT
DATE	15-FEB-2000 ECC 133.00

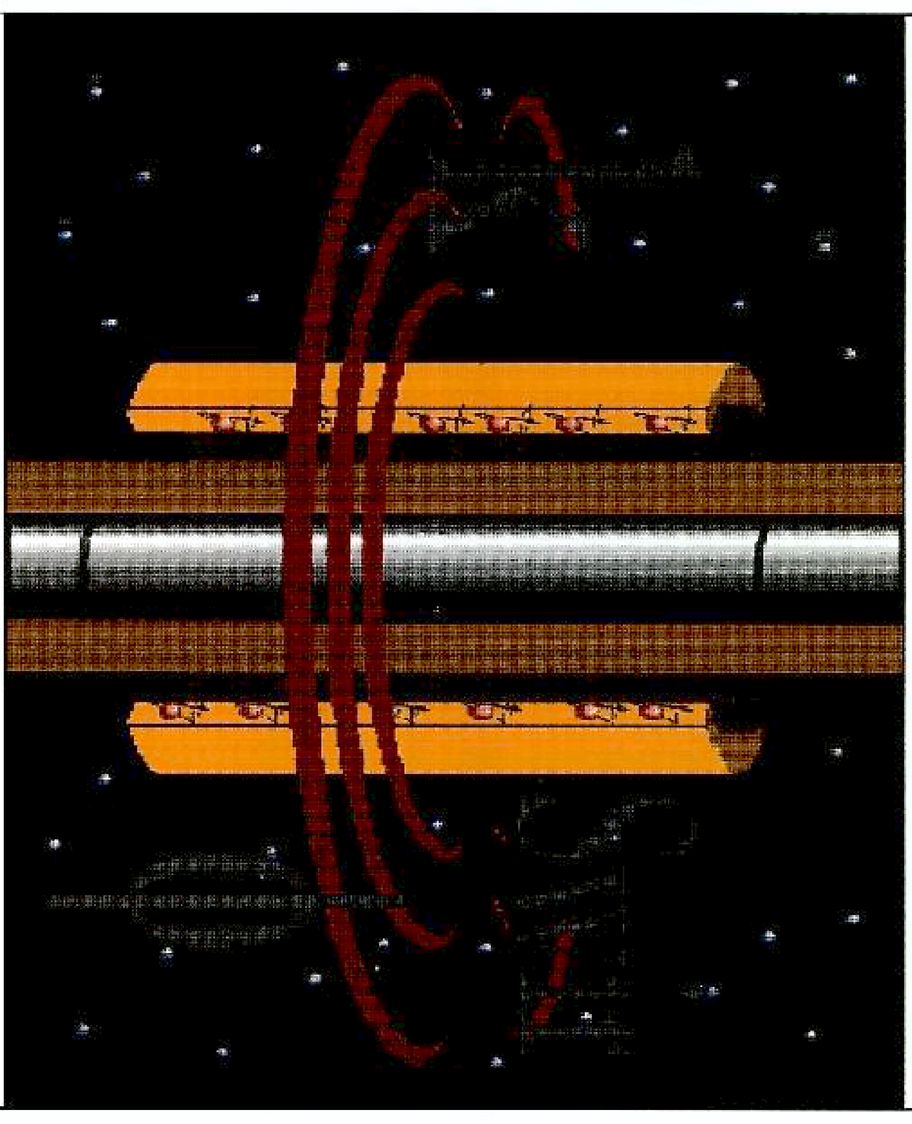
REMARKS



BAKER HUGHES

Baker Atlas

GEOScience



COMPANY SOUTH FLORIDA WATER MANAGEMENT DISTRICT

WELL L2-PW1

FIELD L2-CANAL

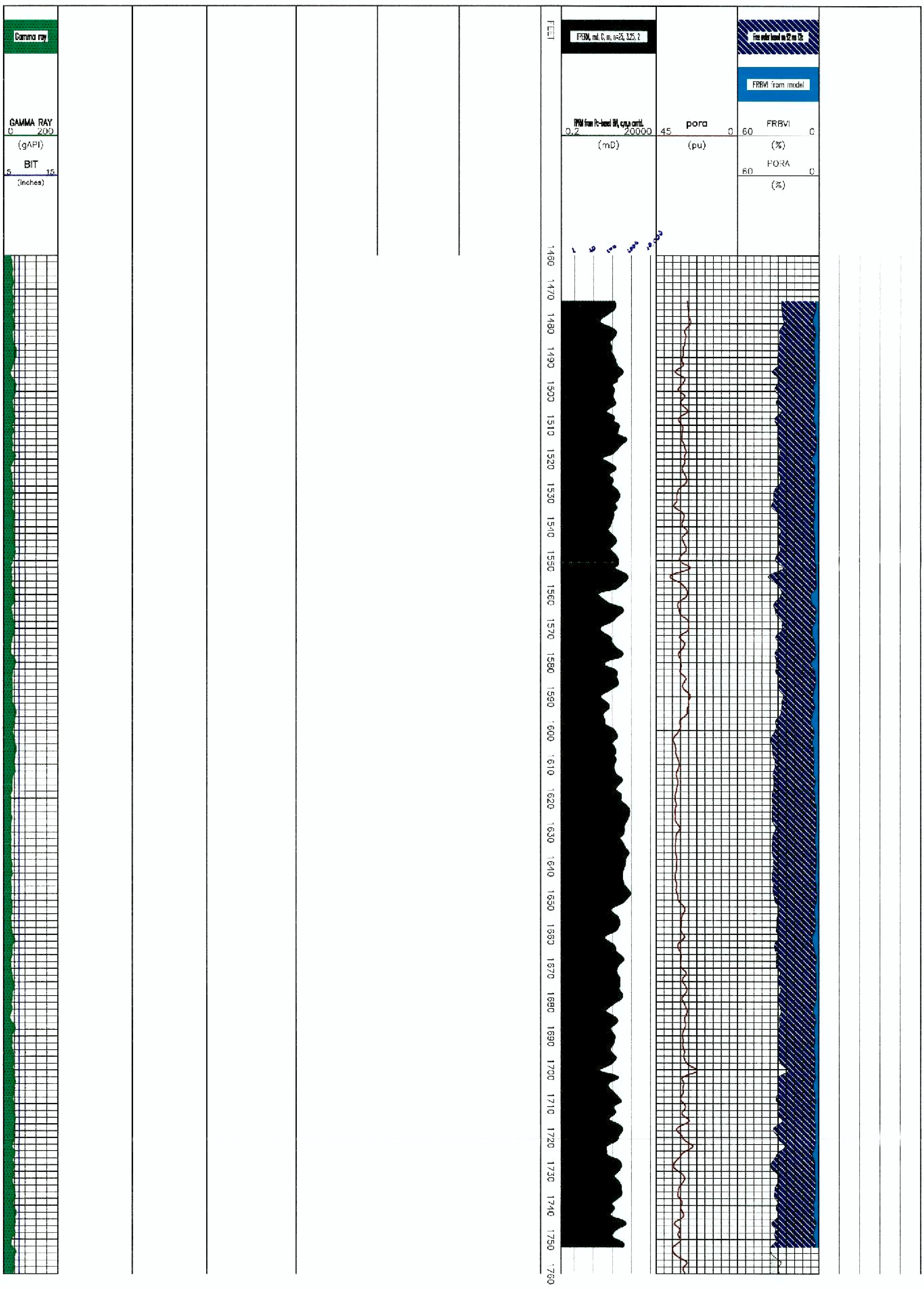
COUNTY HENDRY STATE FLORIDA

LOCATION: SEC 4 TWP 45S RGE 34E

ELEVATIONS: KB 24.5 FT DF 24 FT GL 17 FT

DATE 15-FEB-2000 ECC 132.00

REMARKS



COMPANY SOUTH FLORIDA WATER MANAGEMENT DISTRICT

WELL PBF #10

FIELD HILLSBORO

COUNTY PALM BEACH STATE FLORIDA

LOCATION:

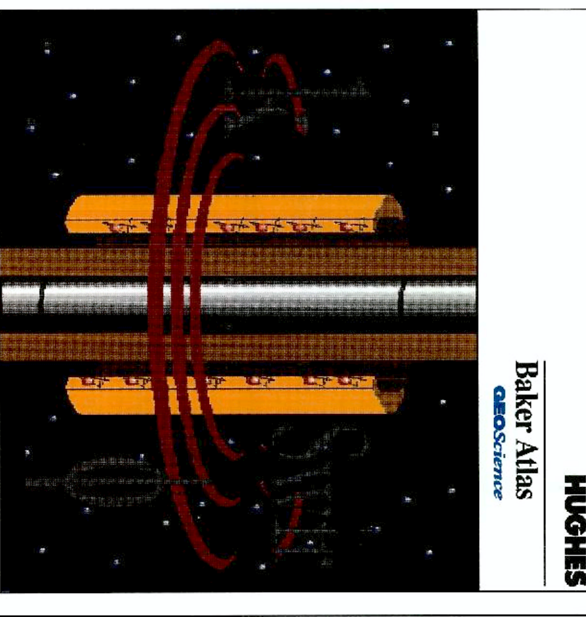
NW/4 OF:

SEC 19, TWP 47S, RGE 41 E

ELEVATIONS:

KB 19.5 FT DF 18.5 FT GL 10 FT

DATE 15-FEB-2000 ECC 8566.03



BAKER HUGHES

Baker Atlas

GEOScience

REMARKS