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Prediction of Flow Units of the Khuff Formation

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Abstract

Bahrain field is located in the Gulf of Sulwa between Saudi Arabia and Qatar (**Fig. 1**). The Permian Khuff in the Bahrain field has been the subject of many studies aimed at optimizing the development of its gas reserves.

The need to provide continuous profiles of permeability for all present and future Khuff wells prompted this study. As the Khuff wells are not extensively cored, it was necessary to use the openhole logs as the basis for this effort.

Permeability estimation from logs must be done in two steps. The first step is to establish a methodology for identifying the various rock fabric textures from the openhole logs. The second step is simply to generate a porosity to permeability transform for every fabric texture. The method to generate these transforms is straight forward by plotting log permeability versus porosity (log-linear regression).

Introduction

Permeability is a key parameter in reservoir characterization that governs, to a large extent, reservoir development and management. This parameter is normally measured in the laboratory on reservoir cores. Unfortunately the cored intervals represent a small fraction of the total thickness of the producing reservoirs. Thus permeability data are sparse and scattered compared to other data such as porosity and oil saturation.

The problem is compounded in carbonates as against clastic reservoirs. Carbonate reservoirs are much more complex. Porosity and permeability variations in carbonates are far more drastic than in clastics. Moreover, most of the available core analyses were performed on core plugs, which renders the results of limited value in characterizing these carbonate reservoirs.

Various methods have been proposed for deriving permeability from openhole wireline logs. Some had limited success in clastic reservoirs but none proved to be successful in carbonates. The objective of this paper is to identify the potential best flow units in the Khuff carbonates based on the interpretation of the dual laterolog, the density/neutron log and the visual examination of the cutting samples.

Cutting samples and basic openhole logs are available in almost all wells. This makes the suggested method cost effective as it requires no additional data acquisition.

Khuff Stratigraphy

The gas bearing Khuff Formation is of Permian age and consists of about 2000 feet mix of carbonate lithofacies. Khuff formation is conformably over lain by the Triassic Sudair Shale and un conformably underlain by the Devonian Sandstone of the Jauf formation (**Fig. 2**). The Khuff formation is described as a fine to coarse crystalline dolomite with a few interbeds of limestone and anhydrite. Percentage of limestone does not exceed two to three percent of the total reservoir thickness.

The formation is subdivided into four main zones, from the top, K-0, K-I, K-II and K-III. K-0 is about 300 feet thick. This interval encompasses the oomoldic porosity zone, about 20 feet thick. Generally it has high porosity and low permeability, except in areas where leaching has broken the barriers between the oomolds.

Khuff-I gross thickness ranges from 456 to 522 feet. The main porosity interval varies in thickness between 40 feet to over 150 feet. K-I porosity is mostly intercrystalline to intergranular with traces of moldic and vugular porosity developed in fine to coarse crystalline brown dolomite. There is extreme vertical variability in both porosity and permeability. For example, the porosity can change from 4 to 20% and the permeability from 3 milidarcys to 1800 milidarcys in an interval of one foot.

Khuff-II gross thickness ranges from 293 to 366 feet. The gross porosity interval varies in thickness from about 45 feet to 180 feet. Like K-I, it is predominantly intercrystalline to intergranular with some moldic, vuggy and fracture porosity in a light brown, fine to coarsely crystalline dolomite.

K-III is the lowest zone with a gross thickness of around 930 feet. K-III lacks any well developed porosity. Fractures constitute the only interconnected porosity in this zone.

Statement of the Problem

Khuff Formation has two thick, mainly interparticle porosity zones developed within it, namely K-I and K-II. Length of these porous intervals range from 40' to 180'. (**Fig. 3**) is a porosity log through a typical Khuff well.

It has been noted that, in almost all wells, the bulk of the production comes from very discrete thin zones. The problem is how to define these zones to optimize the completion of the Khuff wells. Determination of the best flow units ahead of perforation will result into the following benefits:

• Reduce the completion cost of Khuff gas wells. In the well used as an illustration (**Fig. 3**) the perforation interval could have been reduced from 137 feet to 35 feet only. This reduction translates into approximately $ 40,000 direct saving in perforation cost.

• Most importantly, the ability to categorize the porous intervals into permeability classes will lead to better well completions. The current practice of perforating the total porous interval creates a problem for the engineers to stimulate the less productive porous zones, as most of the acid is drained into the best permeable zones. Definition of these zones ahead of perforation will provide us the option to either perforate the most permeable zones or perforate the less permeable zones and keep the best behind pipe. The latter scenario would enable the engineers to better stimulate and assess the producibility of the various porosity zones that are of different permeability classes.

• The differentiation between the various porosity-permeability classes and the definition of the most permeable zones will provide an important tool to describe the Khuff reservoir permeability and to relate the same to the lithofacies variation and the diagenetic history. This, of course, is invaluable information for creating the simulation model which is used to predict reservoir performance.

Permeability as a Geologic Parameter

Permeability is classically defined as an intrinsic characteristic of rock material that determines how easily a fluid can pass through it. Oil and gas production is governed by relative permeability to one fluid when the rock is saturated with another fluid. It is to be noted that, whatever precautions are taken during the laboratory test, the measured permeability will not be totally representative of the reservoir, specially in carbonate rocks. However, cores through such reservoirs are extremely important for understanding the rock fabric textures and pore throat geometry. Such understanding is a prerequisite for estimating permeability from openhole wireline logs.

Permeability is in direct relationship with particles size making up the rock. The size of dolomite crystals is influenced by many factors. The most important are the pre-existing rock fabric, temperature and the soaking time, during which the dolomitizing fluid was in contact with the original carbonate rock.

The permeability inferred from logs can be termed absolute permeability despite the fact that all logs measurements are made under ***in-situ*** conditions. Permeability in carbonate reservoirs is closely tied to the rock fabric. The rock fabric texture of carbonate varies quite rapidly with depth. Each fabric is characterized by a different porosity permeability transform. Thus, it is almost impossible to work out a universal equation that can estimate permeability through carbonate reservoirs from wireline logs.

The process of estimating permeability from openhole logs should therefore be treated as consisting of two parts. The first part is the most difficult and represents the major part of the solution.

The first part of the solution is to develop a technique for identifying the various rock fabric textures based on their openhole logs responses. After accomplishing this step, it will be possible to categorize the various identified rock textures into permeability classes without assigning them absolute permeability values. In other words the porous intervals will be assessed as being of class A, B or C permeability fields, with A the best and C the worst permeability field.

The second part of the solution is to generate a continuous permeability curve scaled in millidarcys. This can be done by developing a transform to convert porosity to permeability for every identified rock texture. For achieving this objective, the various rock textures must be described in term of their measured permeabilities. At least one low porosity and one high porosity points are needed to establish the porosity-permeability transform for every rock texture.

When no cores are available this part of the solution can be made through correlating the identified textures to similar ones from other fields, for which porosity permeability transforms have already been established.

This paper will focus on achieving part one of the solution as it represents the most critical part. Part two will be addressed separately in a follow up paper as it requires significant computer programming.

Pore Space Classification

Pore spaces must be understood and classified in a way to ease the use of the openhole wireline logs, cutting samples and cores in describing the flow characteristics of the various porosity types in carbonate rocks. In his classification, Archie (1952) tried to relate the rock fabrics to the petrophysical properties by classifying pore spaces into two classes-matrix and visible porosity. He stated that chalky texture indicates a matrix porosity of ±15%, sucrosic texture indicates a matrix porosity of ±7% and compact texture indicates a matrix porosity of about 2%.

On the other hand, visible pore space is described according to pore size, and ranges from no visible pore space to larger than cutting size. The biggest shortcoming of Archie classification is the difficulty in relating his classification to geologic models, because the descriptions cannot be defined in depositional or diagenetic terms.

Lucia classification (1983) emphasized the petrophysical aspects of carbonate porosity. He showed that the most useful subdivision of pore types for petrophysical purposes was of pore space between grains or crystals called interparticle porosity, and all other pore spaces called vuggy porosity. Vuggy porosity was further subdivided into two groups depending on how the vugs are interconnected - separate and touching vugs. This classification is fit for the purpose of estimating permeability from wireline logs. However, the petrophysical properties of fractures are substantially different from that of vuggy porosity. Therefore, a small modification to Lucia classification is recommended to set these two pore systems apart. This modification makes porosity types of carbonate rocks fall into the following categories:
1- Interparticle (intergranular and intercrystalline). 2- Vuggy (separate and touching). 3- Fracture porosity.

Lucia (1995) subdivided non-vuggy limestone and dolomites into three texture classes. Class-1 characterizes the fabric that is made up of particles greater than 100 micrometers. Class 2 is made up of particles that range in size from 100 to 20 micrometers and Class 3 is made up of particles that are less than 20 micrometers in size. The permeability fields of the three fabric classes are drastically different. For examples a 15% porosity will have a permeability of around 3 millidarcies in a 20 micrometers interparticle fabric, 35 millidarcies in a 100 micrometers interparticle fabric and well above 1000 millidarcies in a 500 micrometers interparticle fabric. **(Fig. 4)**

Khuff Porosity Types

Khuff-0 is characterized mainly by moldic (vuggy) porosity. K-0 is almost completely dolomitized with fine crystal size (<20 micrometers). It is natural to expect that the leaching process must have aided the original low intercrystalline permeability. **(Figs 5A and 5B)** are examples of the cryptocrystalline K-0, leached and unleached. It is to be noted that the original rock texture is still preserved.

On the other hand, Khuff-I and Khuff-II main porosity zones are characterized by mostly intercrystalline porosity. Similar to K-0, the main porosity zones of K-I and K-II have been almost completely dolomitized. It is important to note that crystal size varies vertically in the same porosity zone. Crystal size varies between 10 to 500 micrometers. **(Figs. 5C and 5D)** are examples of a fine to medium crystalline porous dolomite. **(Figs. 5E and 5F)** are examples of coarsely crystalline porous dolomites. In these example, the dolomitization process has totally obscured the original fabric of the parent rock. As the crystal size increases, the precursor fabrics becomes more difficult to determine.

K-III lacks any well developed porosity zones. It produces only through fractures. **(Fig. 6)** is an example of a fractured zone that has been producing for over five years at a rate of over 50 MMCFGD.

Concept development

A thorough visual examination of cutting samples of many Khuff wells was made to understand the various fabric textures present in the Khuff Formation. The description has helped a great deal in selecting and, later, in modifying the classification of carbonate porosity types, for the purpose of determining permeability from wireline logs.

The cutting description was also the cornerstone based on which log responses were predicted for the various rock classes. This facilitated the process of selecting the openhole logs and then to derive some other curves to discriminate between the various textures.

An obvious difficulty with cutting samples is the presence of cavings. Despite this shortcoming, an experienced geologist can use these samples to generate conceptual geological models that can be related to other data, such as openhole logs.

The best flow units of well A72 were first picked from the cutting samples description. These zones were traced on the wireline logs and their log signatures were carefully studied. This has resulted in the formulation of the methodology that will be described in the following section to identify the best flow units from openhole wireline logs.

Khuff Flow Units from Wireline Logs

The irreducible water saturation is inversely related to particles size. The larger the particles the lower the irreducible water saturation, and the higher the resistivity. Resistivity will also increase with the decrease in porosity. To differentiate between the textures of coarsely crystalline porous dolomite and tight dolomite, a derived curve (RPHI) is created by multiplying the true resistivity (Rt) by twice the percent porosity.

The invasion profile is also influenced by the crystal size. In other words, all porous coarse crystal fabrics 'for example' should have more or less similar characteristics. Another derived curve SPHI is created by multiplying the separation ***between*** Rt and Rxo by twice the effective porosity. This curve helps in differentiating between the various rock classes, based on the expected similarity of the invasion profile between zones that are made up of the same rock fabric. The SPHI curve will also help in minimizing the invasion effect caused by the capillary forces in tight carbonates on the estimated permeability.

The third parameter that has a direct effect on permeability is the effective porosity. For each fabric class, the permeability is in direct relationship with the amount of porosity. It must be stressed that this relationship is true for each fabric class but not ***between*** the various fabric classes.

The three parameters are crossploted with log RPHI on the x axis, PHIEE on the y axis and log SPHI on the z axis. The 3D crossplot for Well #A72 is shown on (**Fig. 7**). It is readily noted that:

- The crossploted points fall into clear distinctive vertical bands.
- These bands are inferred to represent different rock fabrics. The particle size in these bands increases from left to right. In other words the first band from the right represent the rock fabric that is made up of the largest crystal size and should, therefore, have the best flow characteristics.
- Within each band, the porosity increases in the vertical direction and thus the zones of highest porosity should have highest permeability for that particular rock class.
- Plotting the various bands shown on the 3D crossplot on the wireline composite log in different color coding enables us to zonate the thick porous interval into thinner zones that are a function of their crystal size. (**Fig. 8**) is a color coded zonation of KII of Well A72. Blue zones have largest crystal size, orange is medium size and yellow is the finest.. It is important to note that the above described methodology will help to categorize the flow characteristics of zones having interparticle porosity. The flow characteristics of vuggy (oomoldic) porosity and fracture porosity will be addressed in a subsequent paper.

Validation

The excellent segregation of the crossploted points into clear vertical bands is considered an indication that the conceptual model used for predicting the log responses for the various rock fabric textures is correct. All the 13 wells used in the study had very similar 3D crossplots with the clear vertical bands. Each rock class or band is characterized by narrow RPHI, SPHI ranges.

The flow units of well A72 were first identified from the visual cutting samples examination as being intervals of maximum crystals size. The same intervals were identified from the 3D crossplot of well A72 as being represented by the first band from the right. This of course substantiated the conceptual model based on which the 3D crossplots were made.

(**Fig. 7**) shows the predicted best flow units alongwith those predicted from the Stonely Wave Permeability Analysis and the actual production log results. It can be easily seen that the recommended methodology indicates that there are two intervals that are predicted to dominate the flow profile. The two intervals are 9645 to 9690 feet and 9755 to 9770 feet. The PLT log has shown that the two intervals produce 85.1% of the total production.

The array sonic of A72 was processed to deduce the relative permeability from the Stonely Wave Analysis. The analysis was performed by a contractor and final results predicted the following flow intervals: 9737-9734; 9702-9700; 9246-9240; 9216-9212; 9180-9160 feet. It is clear that the flow intervals predicted from Stonely Wave Analysis were completely at variance to the actual flow zones as seen on the production log (PLT).

CONCLUSIONS

1. Porosity types should be classified according to their petrophysical characteristics to facilitate permeability estimation from logs.
2. The process of permeability estimation from logs consist of two parts, texture definition and porosity to permeability conversion for the various fabric textures.
3. Basic openhole logs can be used to identify the various dolomite textures in the Khuff Formation.
4. Every dolomite texture will have a unique transform for converting porosity into permeability.
5. Openhole logs and cutting samples contain immense geological information. They are certainly underutilized by geoscientists.

Nomenclature

Rt = Resistivity of the reservoir beyond the flushed zone

Rxo = Resistivity of the flushed zone

PHIE = Effective porosity

MMCFGD = Million cubic feet of gas per day

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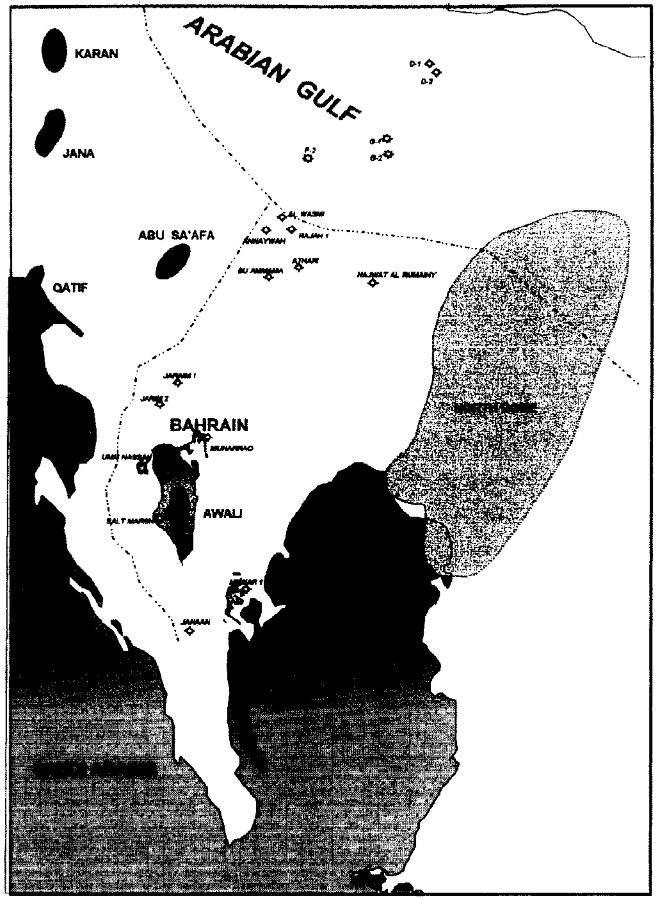
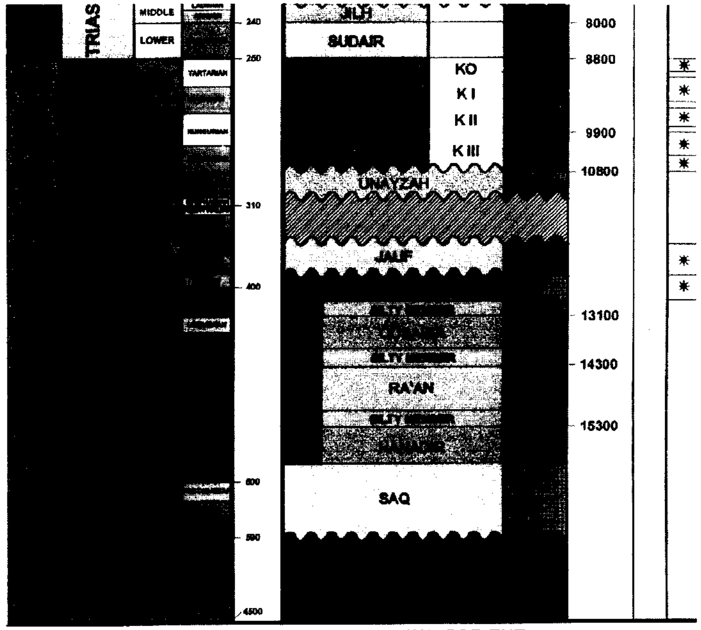
References

1. Ahmed, 4. and Crary S.F and coats G.R, May 1991, Permeability estimation: The Various Sources and their interpretation: JPT, P 578 - 586.

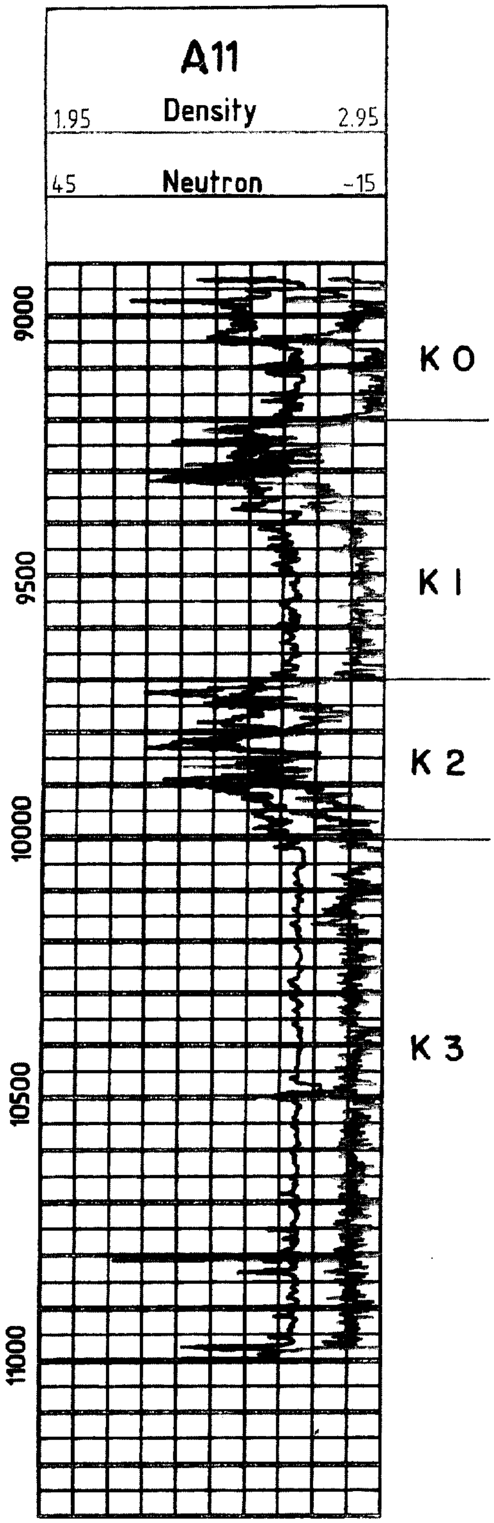
2. Archie, G.E., 1952, Classification of carbonate reservoir rocks and petrophysical consideration: AAPG Bulletin, V.36, no.2, P 278 - 298.
3. Lucia, F.J., 1983, Petrophysical parameters estimated from visual description of carbonate rocks : a field classification of carbonate pore space: Journal of Petroleum Technology, March, V.35, P 626-637.
4. Lucia, F.J., 1995, Rock - Fabric / Petrophysical classification of carbonate pore space for reservoir characterization : AAPG Bulletin, V.79, no 9 (September 1995), P.1275-1300.



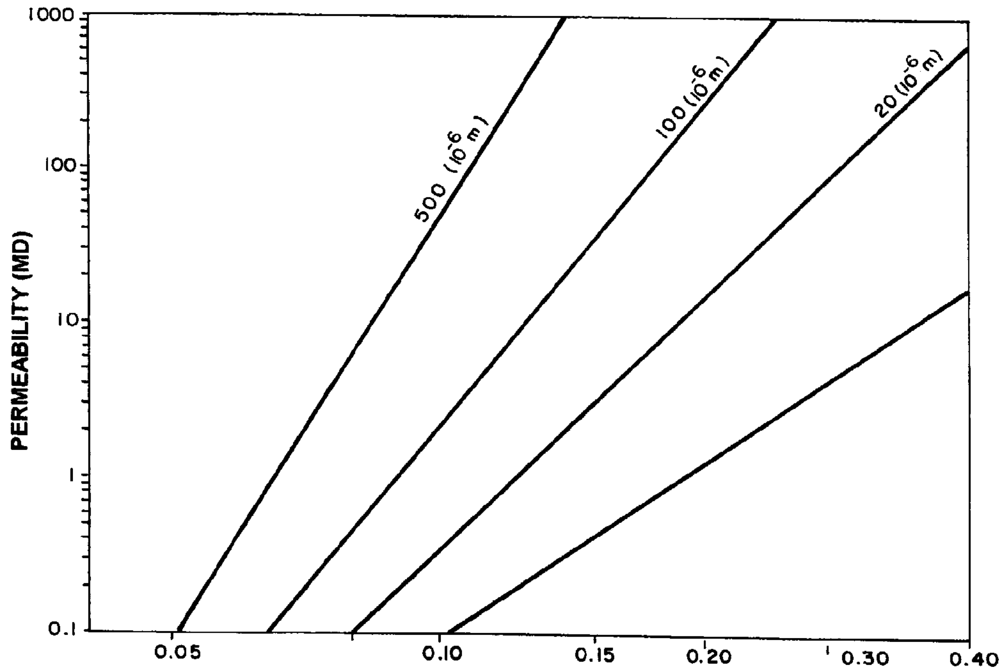
(FIG. 1) LOCATION MAP.



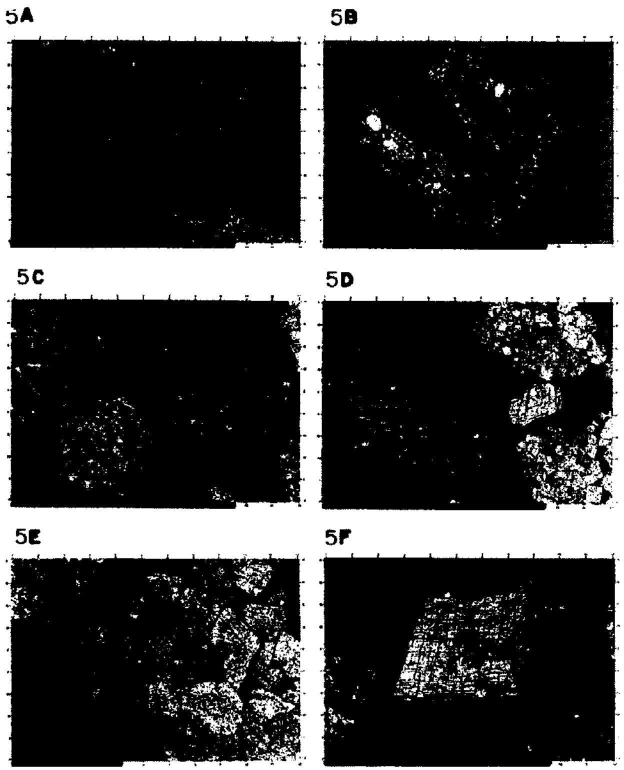
(FIG. 2) SUMMARY STRATIGRAPHIC COLUMN FOR THE PALEOZOIC SEDIMENTS OF BAHRAIN.



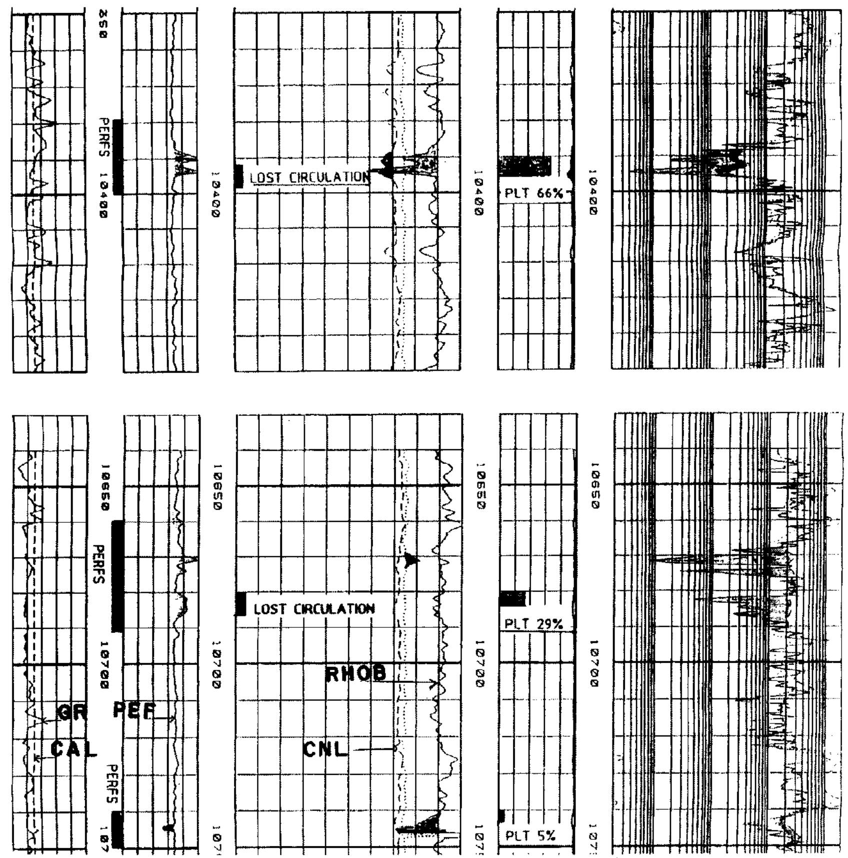
(FIG. 3) NEUTRON-DENSITY LOGS OF A TYPICAL KHUFF WELL.



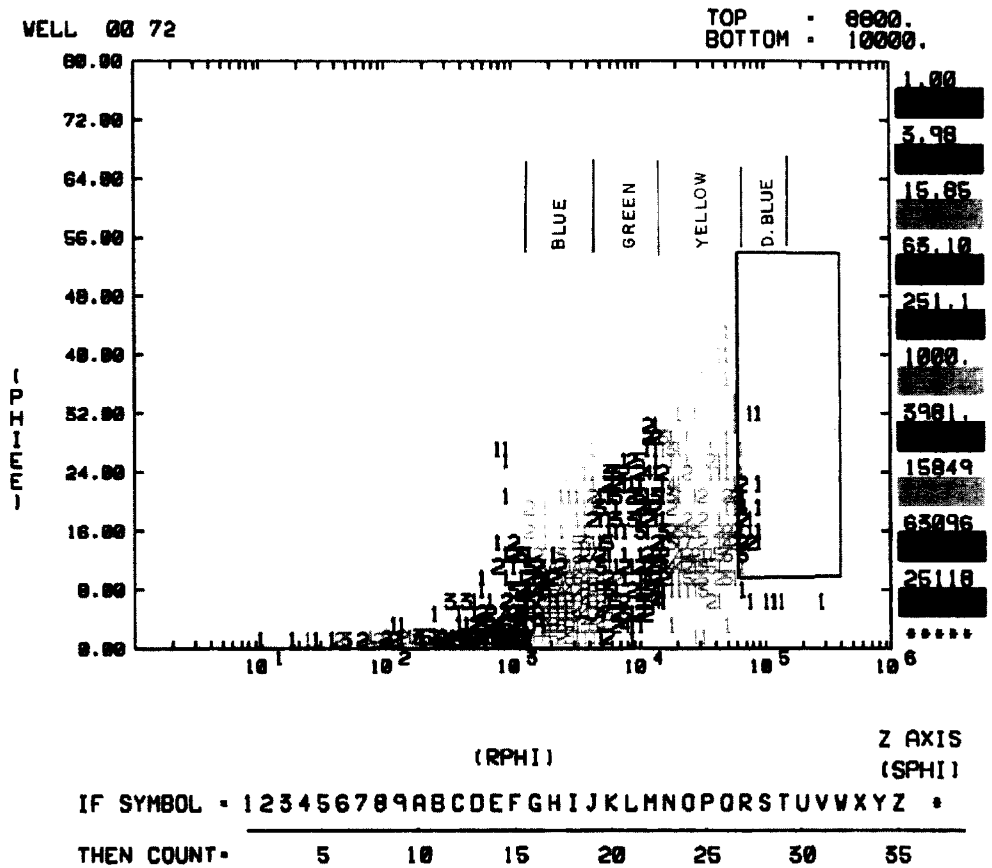
(FIG. 4) COMPOSITE POROSITY - PERMEABILITY CROSSPLOT FOR NONVUGGY LIMESTONES AND DOLOSTIONES. (MODIFIED AFTER LUCIA 1995; FIG. 12).



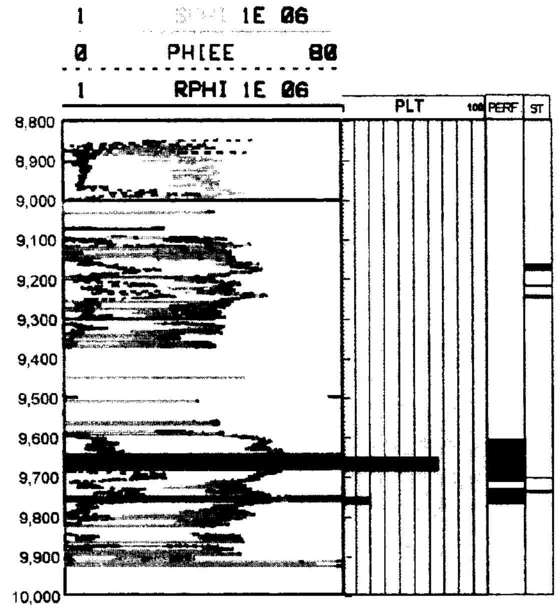
(FIG. 5) EXAMPLES OF VUGGY AND INTERPARTICLE KHUFF POROSITY TYPES.



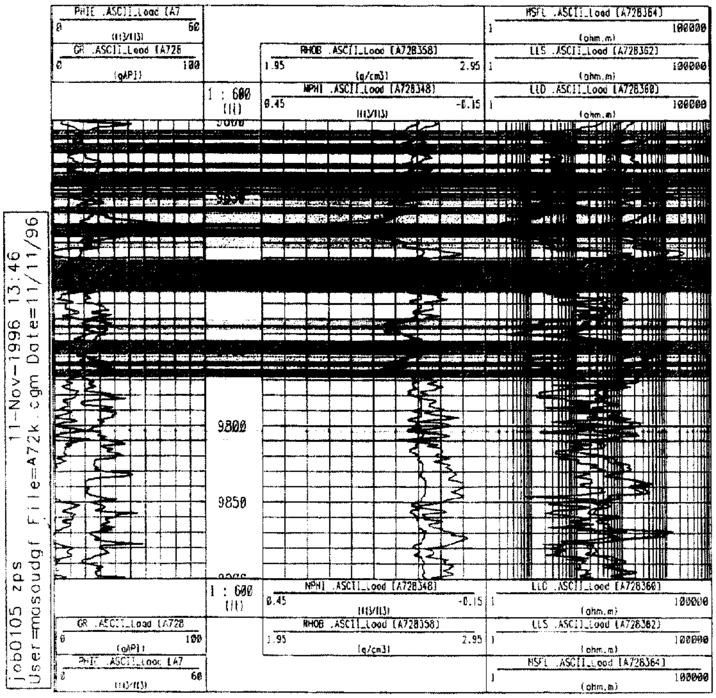
(FIG. 6) EXAMPLES OF KIII FRACTURED ZONES.



(FIG. 7) 3D CROSSPLOT FOR THE KHUFF SECTION IN WELL A72 SHOWING THE EXCELLENT DISTINCTIVE VERTICAL BANDS WHICH ARE INDICATIVE OF THE VARIOUS FABRIC TEXTURES.



(FIG. 7A) THE CROSSPLOTED CURVES WITH HIGHLIGHT OF THE POINTS ENCLOSED BY THE RECTANGLE ON (FIG. 7).



(FIG. 8) COLOR CODED ZONATION OF KII IN WELL A72.