PROCEEDINGS, Twelfth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 20-22, 1987
SGP-TR-109

FRACTURE DETECTION IN GEOTHERMAL WELLS DRILLED IN VOLCANIC ROCKS

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ABSTRACT

The Phlegrean Fields, close to Naples, are the site of important geothermal activity. The formations are volcanic and mostly tuffites. They are originally very tight but the geothermal alteration locally produces fractures with large increase in permeability. The lack of geological markers makes well-to-well correlation quite difficult. Thus the local detection of fractured zones in each well is very important for the evaluation of its potential.

The Mofete 8 D well is a typical example. A rather complete logging program was run for fracture detection. Standard methods turned out to be disappointing. However several non-standard detectors were found to be very consistent and, later on, in excellent agreement with the analysis of cuttings. They are derived from the Dual Laterolog, the SP, the Temperature log and, most particularly, the Acoustic Waveforms from the Long Spacing Sonic.

The Dual Laterolog and the Temperature Log indicate invasion by fresh and cold mud filtrate; the SP behaves as in a typical Sand-Shale sequence. Sonic Waveforms were first analyzed by a purely empirical method derived from consistent log patterns.

A practical algorithm compares the total energy measured in each of the two fixed time windows located the one before, the other after the fluid arrivals. The altered zones (i.e. fractured and permeable) are clearly shown by a complete reversal of the relative energy of these two windows.

A more scientific method was then applied to the Waveforms; it is based on both logging experiments and physical considerations. The energy carried by the tube wave is separated by a frequency discrimination: it correlates very well with formation alteration, thus also with the other indicators including the empirical Waveform method. It should have two advantages:

- It should permit at least a semi quantitative permeability evaluation
- It seems to be promising in other formations: non-volcanic geothermal wells and even hydrocarbon-bearing rocks.

INTRODUCTION

The Phlegrean Fields are a quaternary volcanic complex located in Southern Italy, west of Naples. This area has been known for geothermal activity even before the Roman Empire. From 1939 to 1953 SAFEN* carried out an exploration program particularly in the Mofete area, a very interesting zone for geothermal application. In 1978 AGIP, in a Joint venture with ENEL** resumed geothermal exploration by drilling new and deeper wells. The results indicated the presence of a water-dominated field with three main reservoirs (2). A very low permeability of the volcanic rocks is the main problem: the potential of this geothermal field is directly dependent on the presence of active fractures. Thus their detection usually by means of wireline logging is a key to the evaluation of the reservoir. The Mofete 8 D well was drilled in 1982 to explore a strongly altered and fractured area.

GEOLOGICAL SETTING

The Phlegrean Fields volcanic complex is located in the Upper Pliocene Graben structure of the Campanian plain (fig.1). It is on the margin of the Appennine mountains and was probably developped after the opening of the Tyrrhenian basin. The Phlegrean Fields are a sequence of dominantly pyroclastic eruptive centers in a regional caldera approximately 13 Km in diameter and created by paroxistic eruption of the Campanian Ignimbrite about 35,000 years ago (8). Very recently (June 1982 to December 1984),

the Phlegrean Fields were submitted to a tectonic uplift of about 1.8 m and to intense seismicity (1); this indicates permanent underground activity due to magmatic and phreato-magmatic phenomena.
Four main stages of volcanic activity can be recognized in this area (8):

1 - a pre-caldera, mostly submarine, activity culminating with the eruption of the Campanian Ignimbrite (50000 to 35000 years ago)
2 - a post-caldera, mostly submarine, activity (35000 to 10500 years ago)
3 - an early subaerial activity (10500 to 8000 years ago)
4 - a late subaerial activity (-4500 years to present); the latest recorded activity was the Monte Nuovo eruption, 1538 AD.

The subsurface, as recognized by the wells already drilled, consists in volcanic and volcano-sedimentary rocks. The lithologic sequence, with corresponding thickness from top to bottom is the following:

1 - Yellow Tuffs: 180 m to 590 m
2 - Tuffites and interbedded subaerial tuff: 500 m to 800 m
3 - Trachytic latitic lava domes: 250 m to 500 m
4 - Volcano sedimentary complex: 500 m to 600 m
5 - Thermometamorphic rocks may be intersected at the bottom of the deeper wells.

Unfortunately there are no clear marker beds; therefore correlation between wells is extremely difficult.
Alteration minerals present in these rocks are typical of a high temperature geothermal environment (9), (4). The mineralogy of the wells drilled in the Mofete area permits to distinguish four main zones: a-argillic, b-illite-chlorite, c-calc-aluminum silicate and d-thermometamorphic zone.
The well Mofete 8 D is 907 m deep and reaches only the first two formations (2 and 8, fig.2); from the point of view of alteration minerals, only the first three types (a, b and c, fig.3) are represented.

STRATIGRAPHIC AND HYDROTHERMAL CHARACTERISTICS OF MOFETE 8 D

All rocks crossed by the well are of volcanic origin and mainly pyroclastic. The lithological sequence is as follows:

1 - 60 m to 280 m: Yellow tuffs and chaotic tuffs dating from the latest part of post-caldera activity and the last two periods (1 and 9: subaerial activity)
2 - 280 m to 890 m: chaotic tuffites with lime-argillic matrix and thin layers of interbedded subaerial tuffs; these are products of caldera filling
3 - 890 to 907 m: Trachytic lava flow of original (non altered) mineralogy.

The alteration is mainly due to the solution and deposition of new minerals caused by circulation of hydrothermal fluids. The formation of these hydrothermal minerals is controlled by: temperature, permeability, fluid composition and texture. Permeability is an essential factor since most mineralogical changes are not isochemical: in order to start an exchange of constituents there must be open fluid channels in the rock; further alteration often enlarges them, thus increases permeability. From the point of view of this hydrothermal minerals, several zones can be defined:

1 - an argillic zone characterized by the presence of montmorillonite, zeolites and smectites in general. This zone should end at 100 m
2 - an illite-chlorite zone where, in addition to these two dominant minerals, sericite is also found. On the contrary, the percentage of smectites and zeolites is much lower. This zone ends at about 500 m.
3 - at this depth a calc-aluminum combination appears. It is produced by precipitation of silica-quartz, adularia, epidote and pyrite. This mineralogical association is particularly abundant in the lower part of this well. In the calc-aluminum zone one can observe remarkable variations in the abundance of hydrothermal minerals: this is due to the presence of active fractures allowing easy flow of geothermal fluids.
Three main zones of strong alteration are evident in this zone: around 700 m, from 780 m to 840 m and from 870 m to 890 m.

LOGGING PROGRAM

The target of the well was to intersect, at shallow depth, a zone of expected high secondary permeability due to fracture.
In this part of geothermal reservoir, the fracturing is generally provided by a fault system which can be located by surface evidences and geophysical surveys. The fault system was supposed to be in connection with the most

superficial acquifer tapped by other wells drilled in the Mofete Field (2). The formation temperature was supposed to be of the order of 230 - 250° C, and the formation water salinity of the order of 35,000 ppm (NaCl) at reservoir conditions.
After completion and testing (fig.3), the well was considered productive in the interval here analysed.
Under those conditions a rather complete set of logs was run (fig.3), including a Natural Gamma Ray Spectometry Survey, and an HDT service, to improve the usual log interpretation both for lithology and fracture detection.
As it has been reported in many geothermal field studies (7), Density and Neutron logs are not only affected by porosity changes, but also by the presence of hydrothermal alteration products.
Unfortunately, due to the hostile conditions of the wells drilled in the Mofete Field, such as temperature and hole rugosity, tools which carry a radioactive source were deleted from the logging program after few experiences.
So there is no information from such a combination of logs to define porosity and hydrothermal alteration minerals distribution.

COMMENTS ON LOGS AND THEIR RELATIONSHIP WITH HYDROTHERMAL ALTERATION MINERALS

Usually the GR is a very important log to define lithology in these volcano-sedimentary sequences (5), but in case of the Mofete 8 well, the extreme homogeneity of the drilled terrains (fig.3), the interpretation of the Natural Gamma Ray Spectometry Survey does not add information compared to the standard GR log (fig.5).
A FIL (Fracture Identification Log) program, run on the HDT data, was considered not very useful to define the main fractured zones, because only scattered anomalies, probably due to different discontinuities mainly due to the hole rugosity, were detected.
At this stage a qualitative analysis of different patterns on the Acoustic Waveform recording from the SLS, gave rise to a less conventional approach for fracture detection. The information derived from this new kind of approach was of course compared with more conventional fracture detection techniques based on logs such as Dual Laterolog, SP and Temperature.
The peculiar patterns recognized on the Acoustic Waveform recording in different zones are clearly shown in fig.4 where, according to the transit time of different kind of waves, compressional and shear amplitudes are sometimes very well defined when mud and tube-wave are strongly attenuated, but in other zones the exactly inverse phenomenon is present.
Those patterns were, as a first step, correlated to a different behaviour of the DT curve, which shows a slight decrease in readings probably related to a lower porosity in a fairly homogeneous lithology (tuffs and tuffites rarely interbedded with trachilatitic lava flows) as in fig.4.
A detailed mineralogical analysis of cuttings, collected with a sample rate of 5 m per sample, in the interval from 650 to 907 m, was carried out to delineate the distribution of the most important hydrothermal alteration minerals.
This distribution seems to be strongly related to the different behaviour of different kind of waves as described before.
It is possible to differentiate three zones with different distribution of minerals within the interval of interest from top (663 m) to bottom (907 m) as shown in fig.4 and subsequents.
It is necessary to explain that the discrepancy in depth between the boundaries defined by means of logs and those defined by the analysis of the cuttings is largely due to the very poor vertical resolution of the latter.
It has been reported (5) that in such lithologies, if a cutting sampling rate of 5 m per cutting is used, this discrepancy could be more than 10 m.
The first zone (A zone), is characterised by the presence of a variable but important volume of hydrothermal alteration minerals, which are mainly constituted by calcite, phyllosilicates (such as illite-sericite and chlorite), albite and adularia and as index mineralogical phase, calc-aluminum silicates (such as epidote).
Silica is fairly diffused and mainly distributed in veins.
Those minerals are diffused both in veins and in microfractures, as well as in the "matrix" itself.
From the petrographycal analysis in the A zone the microfractures seem to be widely diffused.
These zones are distributed in the interval of interest, but the amount of such hydrothermal alteration products is very important (up to 50% of the total volume) between 790 m and 800 m and 870 m to 890 m.
A second type of zone (B zone), is characterised both by the presence of

abundant argillaceous minerals and silica, and by a significant reduction of fracturing.
These zones are well defined in the following interval: 715-740m, 830-850 m, 890-900 m.
The third type of zone (C zone) is constituted by unaltered and unfractured lava beds, between 900 and 907 m.
It has been widely documented that the presence of hydrothermal alteration minerals in this reservoir is due to the possibility of geothermal fluids to move within the formations mainly through microfractures and, only in the second place, through primary permeable levels (3).
The SP log behaves like in a shaly-sand sequence, showing permeability in a wide extension of the analysed interval.
A broad positive deflection, present between 838-858 m and 887 m to bottom, shows that the permeability is strongly reduced here; those zones broadly correspond to zones classified as B as far as the hydrothermal alteration is concerned (fig.5).
To make this relationship more evident, an empirical treshold was set on the SP curve and a different shading was applied for positive or negative excursions (fig.5).
By the use of a technique based on a calculation of the second derivative of the SP curve it is possible to define the boundary between levels of different concavities and, according to the value and sign of the second derivative, zones with different permeability (fig.5) (10).
The separation between resistivity curves from a Dual Laterolog is related to the invasion of the formation by fresh mud filtrate. This invasion is mainly due to the presence of microfractures. This high porosity formations (up to 40%) have very low initial permeability (from 0 to few tens of MD).
Knowing the average salinity of the formation water, which is of the order of 35,000 ppm (NaCl), and the mud filtrate salinity, which is something like 5,000 ppm (NaCl), the zones, showing a separation between LLD and LLS readings with LLS resistivity higher than LLD one, are supposed to be invaded and thus permeable.
Where the resistivity readings of the two different devices are practically of the same value, the formation is free of invasion and those zones are to be considered as impermeable.
The zones where the invasion is present are generally in correlation with the zones classified as type A, those where the invasion is not present are broadly related with the zones classified as B or C (fig.4 and 5).
Two different temperature profiles recorded at different times indicate a broad invasion by cold mud, and particularly in two wide zones between 760-840 m and 860-890 m the separation is rather high, showing an increase in permeability. These two zones broadly correspond again to the zones classified as A.

TIME DOMAIN WAVEFORM ANALYSIS

To make evident with a more quantitative approach the different behaviour of the Acoustic Waves in zones characterised by a different distribution of hydrothermal alteration minerals, an empirical time window technique was applied.
The recording with a spacing (between transmitter and receiver) of 10' was selected.
Two different time windows of different lenght were selected in a fixed position in time in such a way that the first one includes only formation waves (compressional and shear together) and the second one fluid and borehole controlled waves.
The length of the second window is twice the length of the first.
A display of the amplitude integration measured in the two different windows is shown in fig.6.
These values are very high, as far as the first window is considered, in case of the A zone, and very low in case of B and C zones.
A complete reversal is observed for the curve representing the energy measured by the second window i.e. corresponding to mud and tube wave.
It has been suggested that a drastic tube wave amplitude reduction is a diagnostic feature in vicinity of fractured zones (6), such as in the A zones, where the amplitude integration reaches the lower values.
On the contrary a strong build up in amplitude of the tube waves should be related to the less fractured zones like the B and C zones are.
The propagation modes seem to contain also information about the interaction between the borehole fluid and the borehole elasticity which may be related to the formation permeability.
The complete reverse behaviour of the "formational waves" (as compressional and shear waves can be considered) adds new information about the rigidity of the formation itself. It seems reasonable to think that the hydrothermally altered formations are more rigid than the other ones, either because they were so before alteration, or because

the thermal and chemical processes helped to make them more rigid, thus its elasticity is reduced. On the contrary a rock, which is unfractured and contains authigenic clay minerals and silica seems to become more plastic and more attenuative to compressional and shear waves.
The higher activity of the integrated amplitude curve measured in the first window seems to be related to a locally non homogeneous distribution of the hydrothermal alteration minerals and thus a local change in permeability.
To summarize the information given by each single curve, a ratio between the two curves was calculated and displayed in fig.6 in a logarithmic scale.
A qualitative permeability related information is readily available when a treshold is applied.
The lower values compared to the treshold level are shown in black and these values are related to higher permeability levels as in A zones.
The higher values compared to the treshold level are left in white and are related to less permeable levels like in B and C zones.
Fig.6 displays the results of the interpretation carried out as discussed before. It is surprising that practically all the logs, if used like a permeability indicator, are in good agreement to discriminate zones of different distribution of hydrothermal alteration mineral and different elasticity of the formation.
Only the second derivative of a temperature profile (also tried to improve the sensibility of this permeability related indicator), does not seem a satisfactory medium to discriminate the main invaded zones but local changes in the formation behaviour may affect the variability of the curve.

FREQUENCY DOMAIN WAVEFORM ANALYSIS

The above dual window filtering technique is a phenomenological approach based on empirical observations in time domain only.
The behaviour of the signal picked by the first time window (early arrivals), namely the increase of the compressional energy in front of altered zone is reminiscent of what can be observed in some types of sedimentary rocks (i.e. fractured zones in a tight carbonate matrix).
This may be explained by the fact that the lithology supporting open fractures must be more rigid, less plastic than the one which is not fractured.
Regarding the lateral arrivals (picked by the second window), the decrease of the acoustic amplitude in front of the same altered zones is similar to what we observe with the Stoneley wave energy in front of permeable and/or fractured zones in sedimentary rocks.
Production tests confirm the hydraulic transmissibility which is thought to be responsible for alteration of the flowing zones.
Stoneley waves arrive late (indeed they are bound by borehole acoustics to arrive after the expected mud p-wave arrival time) and the frequencies carrying the energy which is sensitive to permeability/fluid mobility characteristics are rather low compared to the relatively higher frequency compressional and shear waves.
Spectral analysis of the composite full sonic waveforms reveals low frequency bands separated from the rest of the spectrum. Application of the inverse of the Fourier transform shows that most of the acoustic anergy carried by the lower frequencies arrives late, i.e. within the second time window.
Fig.6 displays the log obtained when extracting the energy carried by the 1-6 Khz band. It is very interesting to note the straight correlation with second window amplitude integration and the other logs when used like alteration/permeability indicators.
The experimental technique here described seems to be worth for detection of the most probable zones of fluid production in future geothermal wells of the field, or in similar situations.
A future step will be the study of the relationship between permeability measurement from cores and the value of the energy carried by Stoneley waves, to try to define directly a relative value of permeability from the waveform analysis.

ACKNOWLEDGEMENTS

The authors wish to thank the management of AGIP for the permission to publish this paper. They extend their appreciation to the SCHLUMBERGER staff who cooperated in this work.

SAFEN * : Società autonoma forze Endogene Napoletane.

ENEL ** : Ente Nazionale Energia Elettrica.

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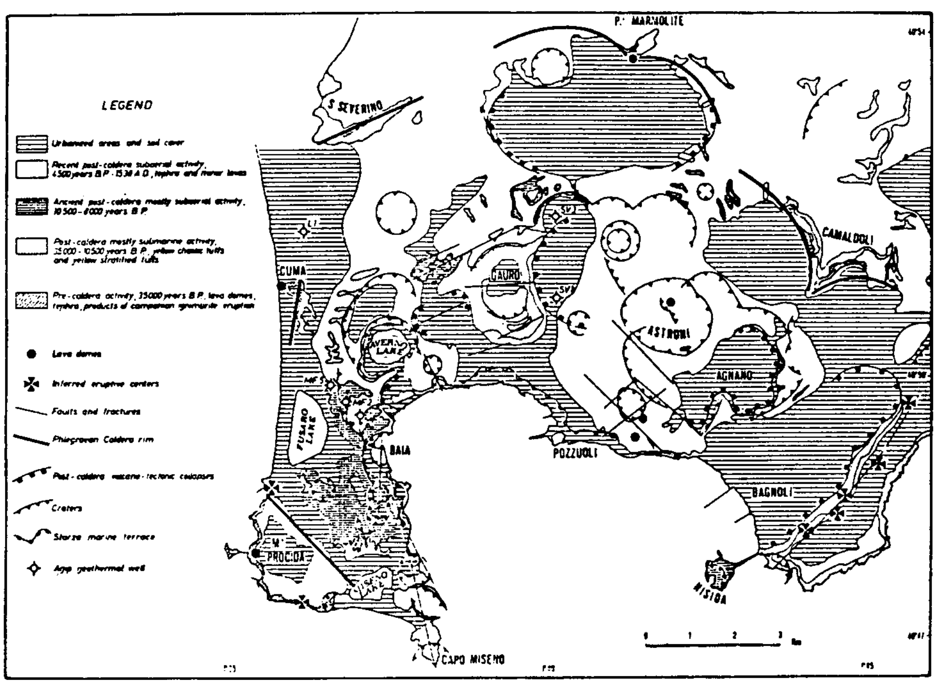

FIG 1 - PHLEGREAN FIELD VOLCANIC COMPLEX

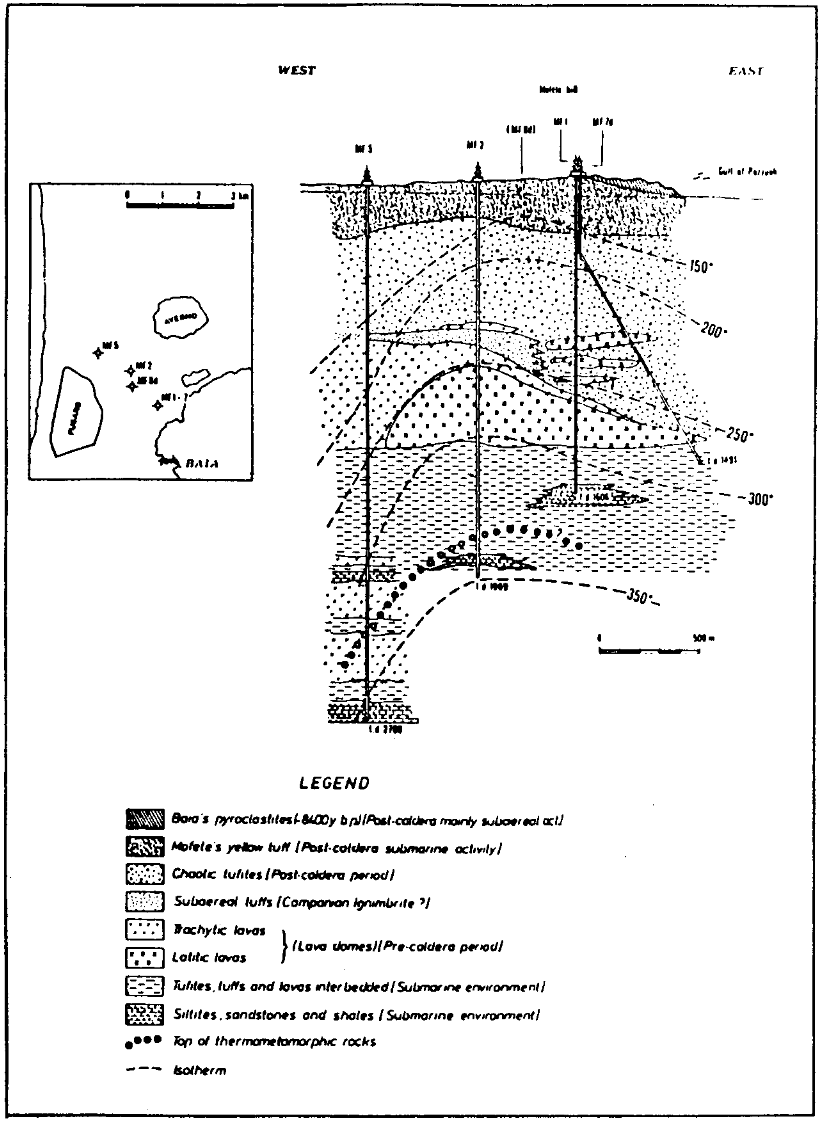

FIG. 2 - CROSS SECTION IN THE WESTERN PART OF PHLEGRAEAN FIELDS

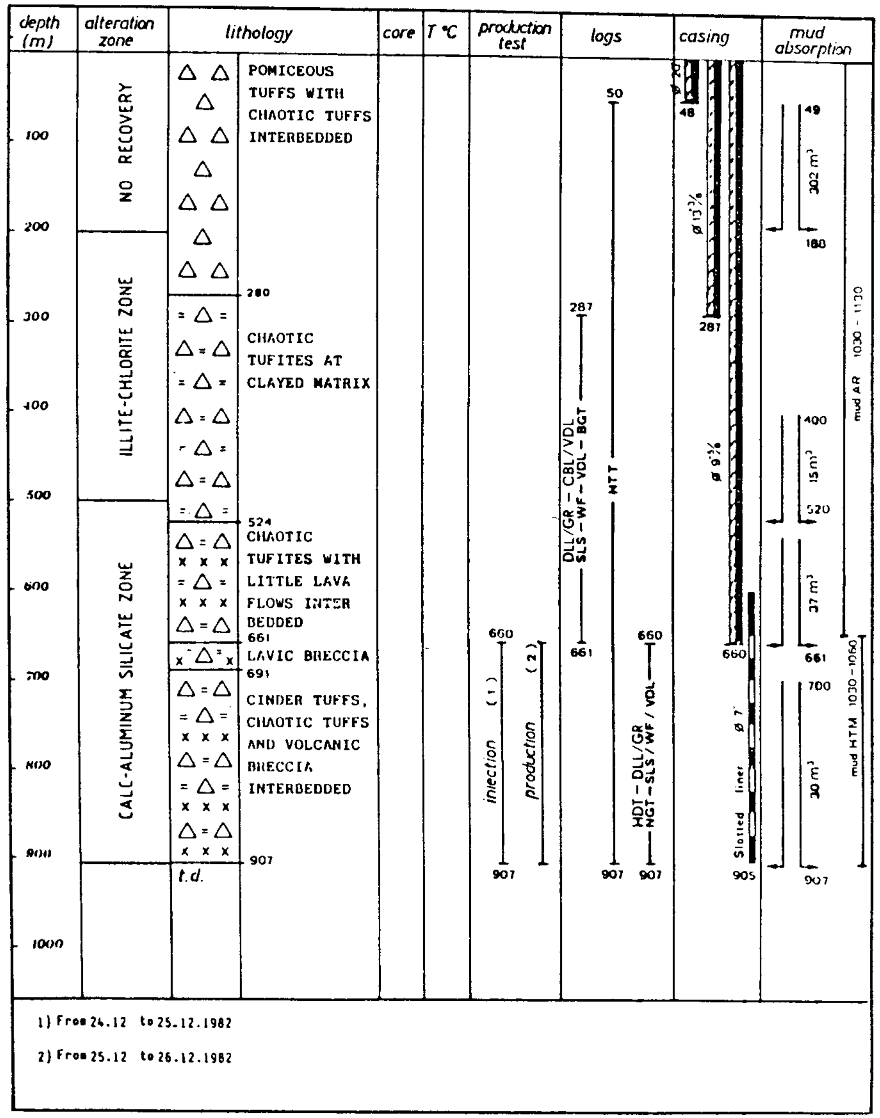

FIG. 3 - WELL MOFETE 8D, SUMMARIZED COMPOSITE LOG

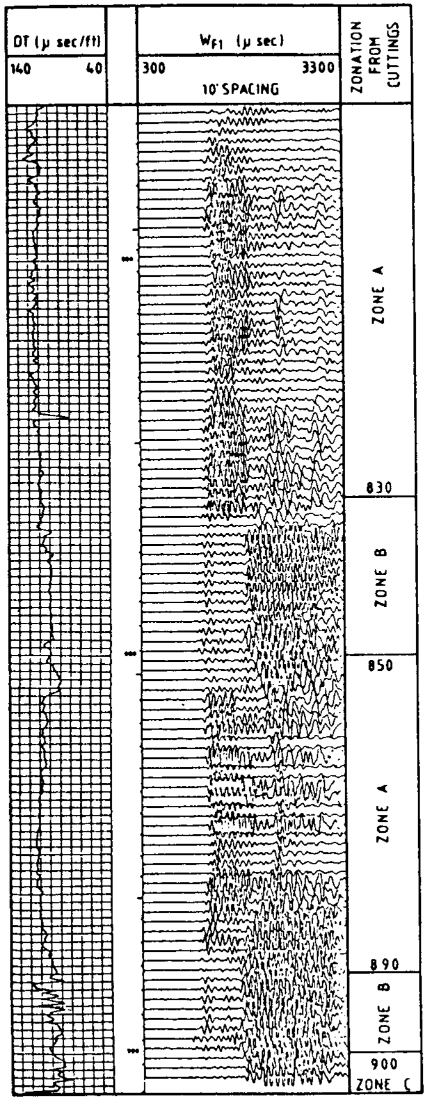

FIG. 4 - WELL MOFETE 8D, CORRELATION BETWEEN WAVE FORMS RECORDING FROM SLS (10' SPACING) AND MINERALOGY

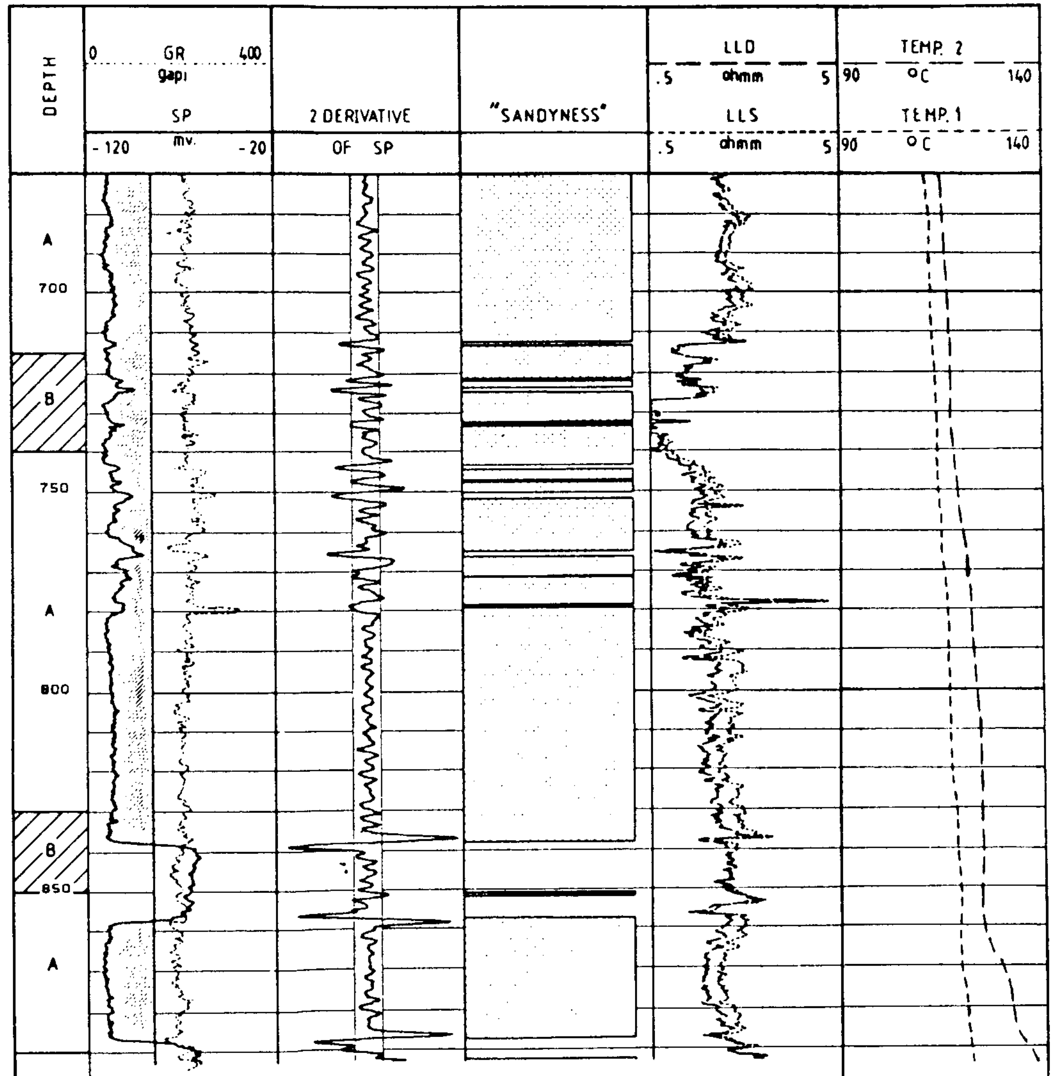

FIG. 5 – WELL MOFETE 8D, WELL LOG DATA AND DERIVED INFORMATION Vs. DEPTH

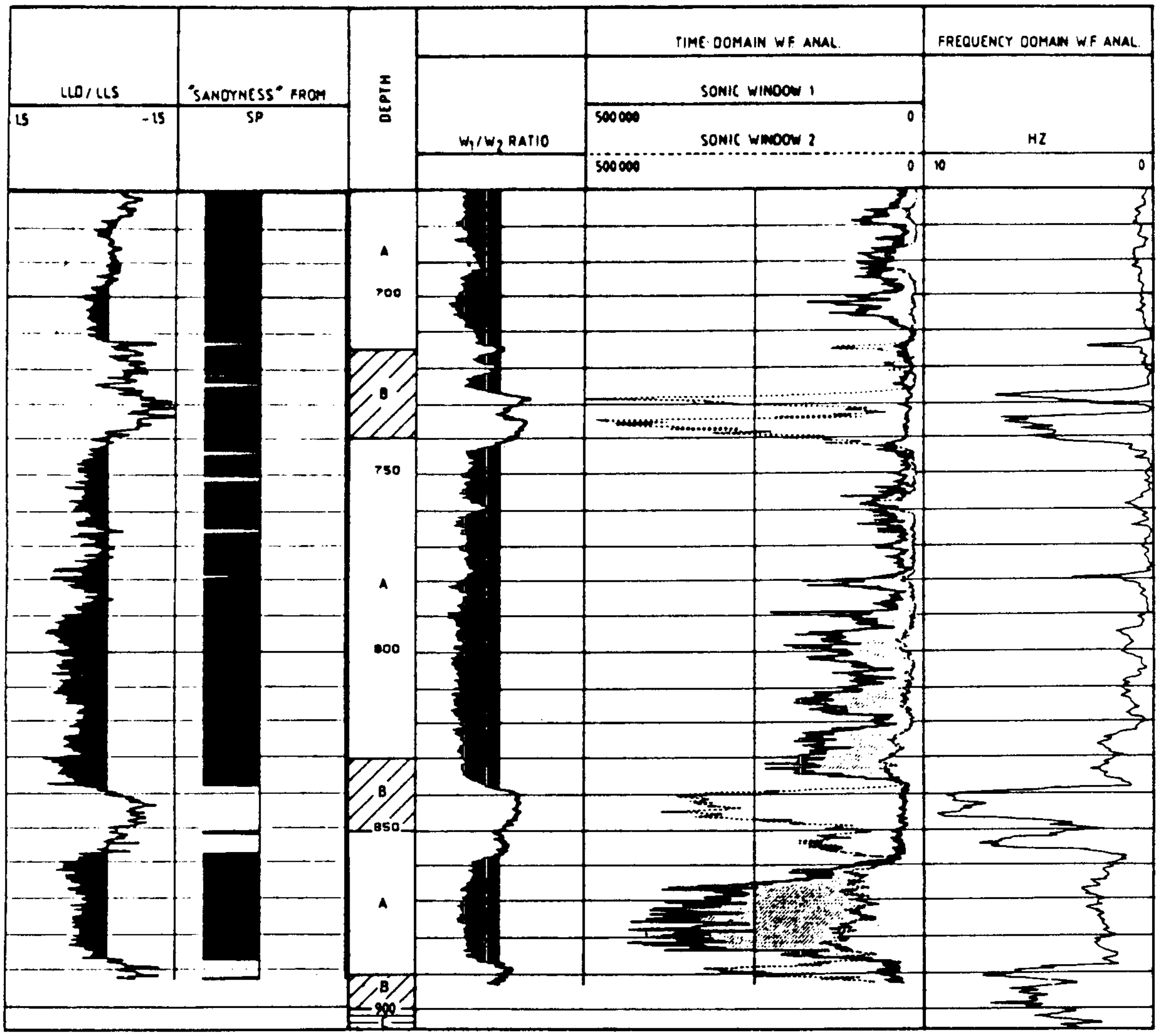

FIG. 6 - WELL MOFETE 8 D - COMPARISON BETWEEN RESULTS OF TIME DOMAIN / FREQUENCY DOMAIN WAVE FORM ANALYSIS AND OTHER PERMEABILITY RELATED RESULTS