

THE APPLICATION AND ACCURACY OF GEOLOGICAL INFORMATION FROM A LOGGING-WHILE-DRILLING DENSITY TOOL

by

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ABSTRACT

Since their introduction in 1986 electrical borehole images have become the major source of geological information from log data. Structural dip, sediment transport direction, reservoir geometry, thin-bed analysis, dual porosity systems, even permeability can be recognized or estimated with greater confidence by using high-resolution images.

Recently a clear industry trend toward geosteered, highly deviated wells has emerged. This is particularly apparent in the high stakes offshore development arena where Logging While Drilling (LWD) tools are often the preferred, if not the only logging choice, and where the range of imaging tools is limited. A new 4¾ in. LWD density sonde measures Bulk Density (RHOB) and Photoelectric effect (Pe), in sixteen sectors around the borehole. In a 6 inch hole, it can provide formation images with a pixel size of about 1.2 in. The tool functions in conductive, non conductive and oil-based muds. Initial trials have shown that lithology boundaries are well defined, and allow the computation of dips for structural analysis. For net pay estimation, the density image provides an azimuthally selected density trace that is relatively free from hole effects.

These applications are demonstrated in two horizontal wells from the Gulf of Mexico, deep-water Ram Powell project. The examples illustrate the successful application of density images for computing structural dip, estimating net pay and identifying large scale stratigraphic features. Recommendations on the acquisition and use of density images are made.

INTRODUCTION

The relationship between geology and wireline logs began on a day in 1927 when the first log was

annotated with formation boundaries. Today the geological information sought from logs is not limited to lithology but includes structural dip, sedimentary structures, porosity systems in carbonates, and the presence and orientation of faults, folds, and fractures. The integration of this data within a reservoir modeling framework is critical for field development.

Lithology can be inferred from logs in a number of ways, from a simple Spontaneous Potential cut-off, to solving a set of simultaneous equations for an extensive list of mineral constituents. However, structural or stratigraphic data had to be derived from dipmeter measurements, until the advent of borehole imaging. Images provide much greater confidence in defining the mode of origin of a feature. The ability to categorize dips into bedding, foreset-bedding, natural or drilling-induced fractures or faults is a very powerful interpretation tool. It eliminates the guesswork and assumptions necessary in an old fashioned dipmeter interpretation. The image example in Figure 1 shows a sandy conglomerate with bedding planes defined by a change in clast size. A dipmeter tool with an automatic cross-correlation process would produce a "Bag-O'-Nails" pattern of low-quality dips, which some would interpret as a conglomerate or bioturbated sand and others might simply call a bad dipmeter.

The Formation Micro-resistivity Imager (FMI*) data in Figure 1 was acquired on wireline after the well was drilled. Today's LWD images do not match the resolution of wireline images, but they are acquired while drilling. Their timely interpretation can be used for geosteering, guiding changes in the wells trajectory based on geological information. The use of LWD images will continue to move geosteering technology forward, especially when real time data rates improve and images can be transmitted and interpreted in real time.

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There are two LWD tools with image capabilities. The Resistivity-at-the-Bit (RAB*) tool produces detailed images from 56 measurements around the borehole (Prilliman J, et al., 1997). The tool is a laterolog resistivity device and requires a conductive mud. It is sized for operation in 8½ in. to 12¼ in. holes. VISION475*, a new 4¾ in. LWD tool, generates borehole images of the formation derived from azimuthal density and Pe measurements. The small outside diameter of the tool allows images to be acquired in holes as small as 5¾ in. The density and Pe measurements are able to produce an image in both conductive, non conductive and oil based muds. Azimuthal density measurements have proven their value to log interpretation, log quality control, completion decisions and geosteering (Carpenter W., et al, 1997). However, density images, due to source-detector spacings and tool physics, inherently lack the resolution of micro-resistivity images.

This leads to questions about the accuracy and the application of geological information derived from density images. This paper discusses the inherent and processing accuracy of such information. It examines the merit of using density and Pe images to compute formation dip, estimate net pay, and interpret large scale stratigraphic features. Field examples of well data are presented and applications of the measurement recommended.

IMAGE ACQUISITION

The VISION475 system combines surveying with full formation evaluation in slim boreholes. Formation evaluation measurements include multi-depth 2MHz resistivity (Bonner, et al, 1995), neutron porosity, and azimuthal measurements of gamma ray, Pe, and bulk density (Holenka, et al, 1995). While log measurements are transmitted to the surface real time, the density and Pe images are currently only available from a recorded data set. This data is accessible when the bottom hole assembly (BHA) is brought to surface, or may be downloaded while the BHA is still in the wellbore via an inductive coupling conveyed on wireline. The system can be run slick, with 5⅞ in. integral blade stabilizer or with a 6¼ in. clamp on stabilizer.

The VISION475 system acquires azimuthally oriented density and Pe measurements while

rotating. The detector count rates are binned into 16 sectors around the borehole defined by a pair of magnetometers. An image is generated by assigning a graduated color scale to the range of density measurements. Absolute color scales vary and are routinely altered to optimize image definition and contrast. The color convention used is dark brown for low densities, shading through red, orange and yellow, to white for high densities. The image may be displayed with respect to the top of the borehole, or oriented with respect to geographic north. Images can be created from density or Pe data, or both. The best image to use will depend upon environmental conditions and the dynamic range of each measurement over the interval of interest.

FIELD EXAMPLES

Two horizontal wells drilled from the Ram Powell platform, and logged with VISION475 serve as examples of the use of density images. Ram Powell is a deepwater field in the eastern Gulf of Mexico which was discovered in 1985 and is currently under development (Figure 2). A tension leg platform was moved to location in May, 1997 and production began in September, 1997.

Computing Geological Dip

The A-1 well is the first Ram Powell producing well with production from the L Sand. It is a horizontal well with a completion interval of 2,256 feet. The L Sand is a laminated levee deposit with alternating pay (sand/siltstone) and non-pay (mudstone) with an average bed thickness of less than one inch (Figure 3). The pay laminations have widely varying permeabilities ranging from less than 10 millidarcies to greater than 500 millidarcies (generally increasing with bed thickness). The initial production is from the gas cap and the well has a sustained production rate of around 100 MMCFPD and 9,000 BCPD.

The A-1 well is located on the proximal (thickest) part of the L Sand levee reservoir (Figure 4). There are several methods that can be used to compute geological dip. First, the structural top or bottom of the formation (or a key marker bed) can be mapped using seismic and well data. Here, this dip data is inconclusive and depending on assumptions azimuths range from 215 to 345 degrees and dips range from 1.8 to 3.1 degrees. Second, a dipmeter or image log may be used. One of the exploratory wells (Viosca Knoll 912-2) penetrated, cored, and

logged the L Sand very near to the A-1 location, and served as the pilot well for the A-1 horizontal well. The dipmeter data from this well (Figure 5) has consistent dip between 5 and 8 degrees at an azimuth of 265 +/- 5 degrees.

Dips are computed from density images by the analyst identifying a bed boundary on the image using an interactive workstation. A density contrast of at least 0.1 g/cc, or better still 0.2 g/cc, is required for good definition of bed-boundaries. The density tool cannot image the detail of the finely laminated L sand. However dips can be derived with confidence by picking sinusoids on the density contrasts (Figure 6). The density contrast responds to the varying litho-density facies and can be assumed to have the same dip as the laminated pay. Based on the 35 facies boundaries picked, the data suggests a mean dip of 7 degrees with an azimuth of 240 degrees (Figure 7). This agrees well with the dipmeter from VK 912-2, although the azimuth is different by 25 degrees. This is probably due to the A-1 well sampling a much larger portion of the reservoir.

Estimating Net Pay

Net pay is difficult to determine from logs in a highly laminated reservoir such as the L sand. In the VK 912-2 pilot hole net pay was estimated by using both core and conventional log analysis (Figure 3 & Figure 8). A computer program based on the "Density-Gamma" cross plot method (Thomas and Steiber, 1975) was used to compute the Net pay to Gross thickness ratio (N/G) in this formation. The method extracts values of both laminated shale volume and pore filling clay volume from Gamma Ray and Bulk Density logs. The computed N/G using this method was 58%. This agrees closely with optical analysis of the core photo which indicated a N/G of 57%.

In the A-1 well, using similar methods, the laminated pay is computed to have a N/G of 58% over the interval from 13450-15730 ft (Figure 9). There are three different groupings of sand present. The interval from 15240-15730 ft is very sand rich and has a computed N/G of 79%. The interval from 13860-15240 ft is less sand rich with a N/G of 58%. The mean grain size of this sand is fine to very fine. The poorest sand from 13450-13860 ft is very thinly laminated and the method suggests a N/G of 33%. The mean grain size in this interval is very fine to coarse silt.

The density image based net pay method uses a sector density curve extracted along a user determined azimuth and a cut-off separating pay from non-pay. The density images are used to zone and define the cut-off values used. In a short uniform interval one cutoff should be sufficient, but in sections where thin pay is sandwiched by relatively thick non-pay, the density response to sand is considerably weaker than in sand-rich sections. This requires a change in cut-off. The analyst first zones the well based on the density image response then identifies pay and non-pay in each interval and derives a density cut-off value. The advantage of this method is an increased confidence in recognizing individual beds by observing the borehole as a whole. Additionally the sector density curve is less averaged than a quadrant density or average density, which is important at high apparent dip, unless the dip is taken into account in the averaging process.

The density image method compares very well with the core calibrated Density-Gamma approach, providing an independent determination of Net Pay. For the total interval the N/G derived from the density image is essentially the same as that derived by Density-Gamma methods (58%). The most significant deviation occurs in the uppermost, finely laminated section, which has a discrepancy of 5% (Figure 10 and Table 1). Differences in the crossplot and image based methods are probably related to resolution limits. However, the image based value is much closer to the value optically derived from core.

From cores it is known that sands in the levee complex range from several inches in thickness to laminations less than 1 in. thick (Figure 3). Such thin features are beyond the resolution of a density or Pe measurement in a well that is drilled perpendicular to bedding. However, in a well crossing the beds at 85 degrees, a 1 in. layer assumes an apparent thickness of about 1 foot and moves into the resolution of the measurement. Data will be averaged over several layers as the volume of investigation of the tool covers several laminations. The layering seen on density images is not pure sand or pure silt, but a sand-rich (pay) facies versus sand-poor (non-pay) facies.

Stratigraphic Features

The second example well, Ram Powell A-3, was

drilled horizontally into the J sand oil rim. The J Sand is a massive sheet sand that is capped in places by a laminated levee type reservoir. The well has approximately 2050 feet of massive sand completed, with an initial production of 25 to 30,000 BOPD and a gas-oil ratio of 1600 scf/stb. While drilling the horizontal section, significant intervals of hard drilling were encountered. The hard zones were characterized by a low rate of penetration, significant bit wear and very dense log response (Figure 11). Analysis of cuttings suggest the hard streaks are calcite-cemented sands. These hard sands had not been detected in any of the previous exploratory or pilot wells either by drilling, logging, or in core. The primary concern surrounding these hard streaks was their geometry. In the worst case the streaks could be vertically oriented and located along fault or shear zones. This could lead to reservoir compartmentalization in this supposedly well connected turbidite sheet sand. The answer to this question was important due to the potential impact on reservoir performance and bit selection. After drilling through the hard zones the bits were severely undergauge with damaged cutting structures. Due to potential cone loss, the bit life was much shorter than expected. Under-gauge bits also limit directional control which is very important in the Ram Powell long reach horizontal wells.

Image data was able to provide significant insight concerning the calcite-cemented zone geometry. The image was analyzed and a sinusoid was placed at the boundary of each event (Figure 12). The widely disparate dip results suggest that the hard events are not planar. A planar event would be expected to have a similar dip magnitude and azimuth on both boundaries. In several places along the borehole these events are not detected on all sectors of the density measurement. For example, at 15330 ft the hard zone is only seen on the top and sides of the hole, indicating a discrete event. This conclusion is supported by petrographic data which suggests that the calcite cemented zones are nodules formed very early in the depositional process.

ACCURACY DISCUSSION

These two examples compare geological data inferred from density images to other sources of data. In order to consider the absolute accuracy of the geological information, uncertainties related to both the measurement and the processing must be

taken into account. Due to source-detector spacings and measurement physics, density and Pe images inherently lack the vertical and lateral resolution of micro-resistivity images. The depth of investigation of a density measurement is larger than a micro-resistivity measurement, and varies slightly with changing formation density. The measurement also has a smaller dynamic range, and is subject to statistical variation.

When an image is used for dip computation, other factors must be taken into account. The tool magnetometers measure its orientation with respect to the earth's magnetic field with an azimuthal standard deviation of +/- 2 degrees. If this accuracy could be carried through to the true dip computation, it would be certainly better than the dip and azimuth a geologist measures on an outcrop. Experience with dip measurements in high-angle wells highlight issues that may not normally be considered by dip interpreters. The items presented below are not specific to density or Pe images, but apply to all dipmeter tools, LWD or wireline. Data is collected from the borehole wall, or a short (tool dependent) distance inside the formation. In deviated wells the intersection between the well and strata give us the formation dip relative to the borehole. This must be referenced to geographic north and a horizontal plane. It is how uncertainties entering the computation of true formation dip effect the result, that is of interest here.

The errors entering a dip calculation are associated with the tool and borehole position and the correlation procedure that leads to a dip. A special problem for LWD tools is based on their two axes magnetometer design which requires the knowledge of magnetic inclination and makes azimuthal positioning in wells inclined parallel to magnetic field lines impossible. Tool and borehole uncertainty can be estimated based upon the measurement specifications (Table 2).

The correlation or correlation error on a density image was estimated by asking five individuals to correlate repeatedly the same bedding plane (Figure 13). The results of the 55 trial measurements gave a mean apparent dip of 82.7 degrees, with a standard deviation of 0.72 degrees, and a mean apparent dip azimuth of 3.3 degrees, with a standard deviation of 2.5 degrees.

In order to demonstrate the relationship between borehole and formation geometry, and the effect of measurement uncertainty, three scenarios were considered. All three assume a formation dipping west at an angle of 5 degrees. Case 1, a vertical pilot well is drilled. Case 2, a well is drilled downdip (west) at an angle of 88 degrees. Case 3, a well is drilled north along strike, also at an angle of 88 degrees. Magnetic declination is assumed to be zero and magnetic inclination 60 degrees (approximate Gulf of Mexico values). Dip and dip azimuth errors were predicted for the three scenarios, based upon measurement uncertainties (Table 3).

When only borehole and tool uncertainties are considered, the error in dip magnitude is negligible (<2 degrees), but can be significant for dip azimuth, up to 22 degrees in a well drilled down-dip. When correlation error, based on a multiple sinusoid picks, is included in the calculation, the dip and azimuth accuracy are further decreased. In a vertical well, the standard deviation of the dip is 8 degrees. The azimuthal error in a down-dip well increases to 38 degrees with only a small error of 1 degree in dip. In a well drilled along strike it is the azimuth error that is small only 4 degrees while the dip error reaches 3.7 degrees. Errors in dip-azimuth are largest in wells drilled down-dip, while errors in dip are largest in wells drilled along strike. These considerations are valid for all dipmeter and image tools be they wireline or LWD, but it is the correlation error which may suffer with density images. The better the image resolution the less will be the correlation error. Errors related to sinusoid placement due to the low resolution of the density image can be significant (Figure 14). Correlation uncertainty can be significantly reduced if the interpreter picks a boundary several times, and uses the average dip and azimuth and concentrates on bedding-planes that are well-defined.

RECOMMENDATIONS AND CONCLUSIONS

Density and Pe images do not contain as much geological information as micro-resistivity images. However, if for hole size, mud or other operational reasons other logs are not run, the VISION475 images can be used to estimate dip and net pay. The resolution and dynamic range of the density measurement limit its ability to identify some structural and stratigraphic features, such as

bedding planes in shales. A greater density or Pe contrast is required than is typically present in shales. Bed boundaries are visible with density contrasts greater than 0.1 g/cc, or preferably 0.2 g/cc. Therefore, we do not expect density and Pe images to be useful for identifying fractures, cross-bedding or small scale stratigraphic features.

Image quality will be controlled by the same factors that control density quality, that is, standoff and borehole rugosity. Therefore, the best geological information will come from a stabilized tool. If the tool is run slick, or considerably under gauge, the images may still be useful for visualization, but computed dip accuracy will be affected. Both example wells were drilled with 6½ in. bits and a 6¼ in. stabilizer on the tool. In order to obtain the necessary data density for image generation, the drillstring should be rotating at less than 60 revolutions per minute, with a rate of penetration of 150 ft/hr or less. This assumes a 10 second memory sample rate and 2 samples per foot.

In order to reduce error related to sinusoid placement on a coarse image, the interpreter should rely on statistics to gauge the correlation uncertainty. A correlation should be made several times, and the mean dip calculated after any extreme results are excluded from the set.

The examples presented in this paper show successful application of density images for computing structural dip, estimating net pay and identifying large scale stratigraphic features. Application of this data at Ram Powell compared well to results obtained by more conventional means. Error analysis suggests that the interpreter himself has the largest impact on dip interpretation uncertainty.

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Erhard "Ted" Bornemann received his geological schooling at the Technical University in Hannover, Germany and the University College of Swansea, UK, finishing in 1979 with a Ph.D. from Syracuse University, NY. While in Syracuse and later with the Kansas Geological Survey, Ted specialized in sub-surface sedimentology and computer applications in geology. Ted has worked for Petrobras in Rio de Janeiro and for the last sixteen years he has been with Schlumberger in various interpretation assignments mainly in Alaska and the Middle East concentrating in dipmeter and borehole image interpretation. Presently he is working on applications of Logging-While-Drilling image data in Sugar Land, Texas. He is a member of AAPG, SEPM and SPWLA.

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David Maggs works for Schlumberger, New Orleans, in the Interpretation Development Group. He has specific responsibility for Logging While Drilling measurements, and their use in formation evaluation. He has 9 years experience with Schlumberger Wireline and Testing as a field engineer, working in South America and the North Sea. He graduated in 1988 with a M.Eng. degree in Mechanical Engineering from Southampton University, England, and is a member of the SPWLA

TABLES AND FIGURES

Table 1: Net to Gross Comparison

Interval	Petrographic Description	Density-Gamma	ADN-Images(sand/silt)
13450-13860 (410 ft)	Very fine to coarse silt	33%	28%
13860-15240 (1380 ft)	Fine to very fine	58%	58%
15240-15730 (490 ft)	N/A	79%	80%
13450-15730 (2280 ft)	Total Interval	58%	57%

Table 2: VISION475 Expected errors

Error Source	Error Amount	Comment / Source
Tool Azimuth	+/- 2 degrees	Estimate based on Tool specifications
Borehole Azimuth	+/- 1 degree	From D&I package specification
Borehole Inclination	+/- 0.1 degree	“
Caliper	+/- 1 inch	Combines Caliper and Measurement Diameter
Correlation error, azimuth	+/- 3 degrees	Experiment (multiple picks) Figure 13
Correlation error, dip	+/- 1 degree	“

Table 3: Error in dip calculations based on borehole tool and correlation uncertainties

Case	Bedding Dip/ Azimuth	Wellbore Angle/ Azimuth	Borehole and Uncertainties Tool only		Borehole, Tool and Correlation Uncertainties	
			Dip Std. Dev.	Azimuth Std. Dev.	Dip Std. Dev.	Azimuth Std. Dev.
1	5/270	vertical	0.3	2.3	7.5	3.8
2	5/270	88/270	0.4	21.8	1.0	37.9
3	5/270	88/0	2.1	2.0	3.7	2.2

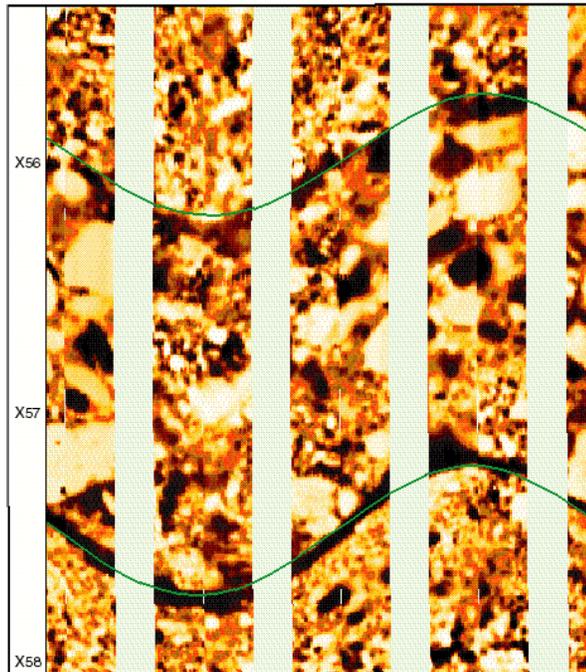


Figure 1: FMI Image of a Bedded Conglomerate.

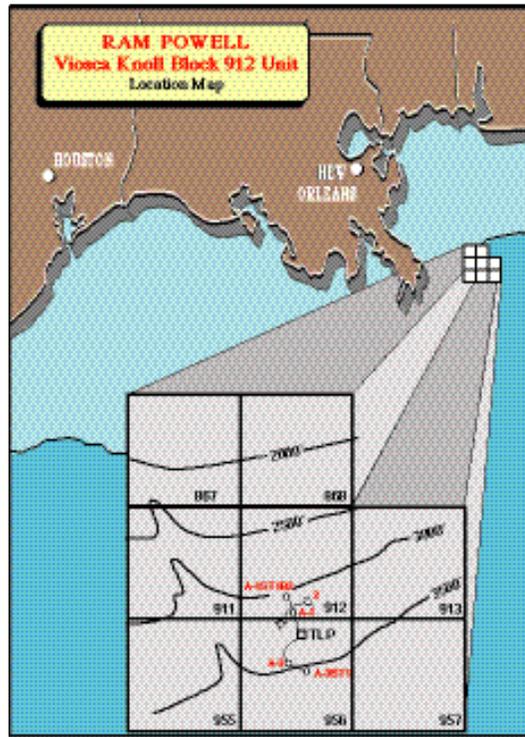


Figure 2: Ram Powell Location Map

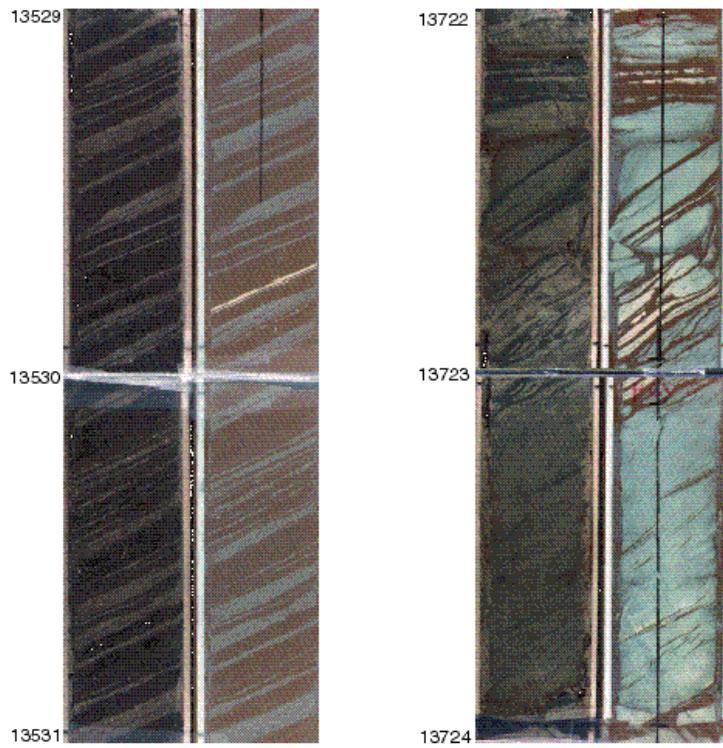


Figure 3: VK 912-2 Core Photographs (Well deviation 48 degrees)

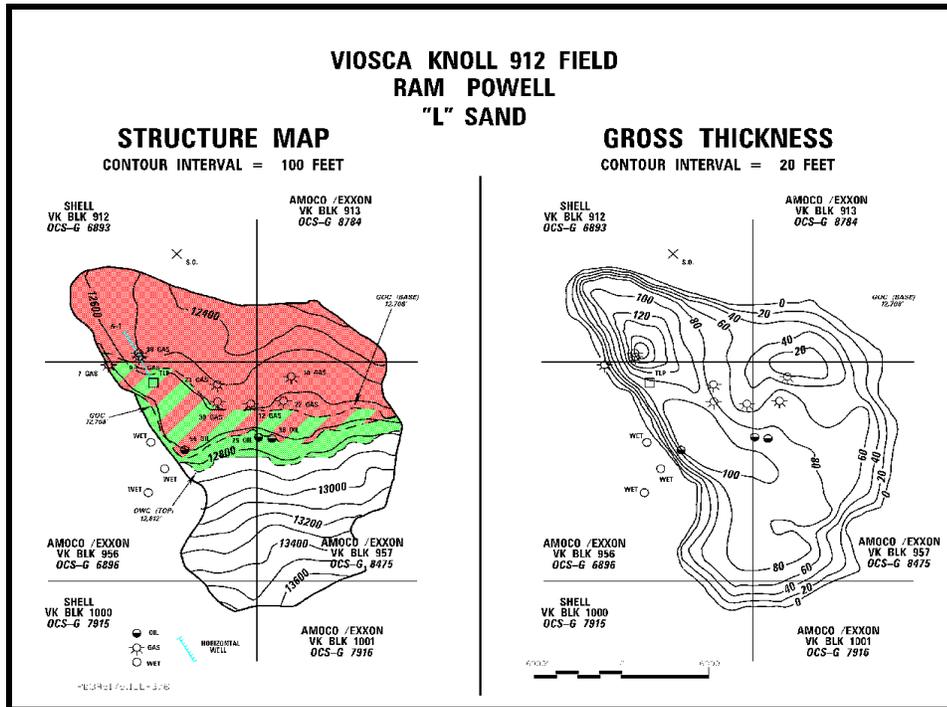


Figure 4: Structure and Gross Thickness Maps

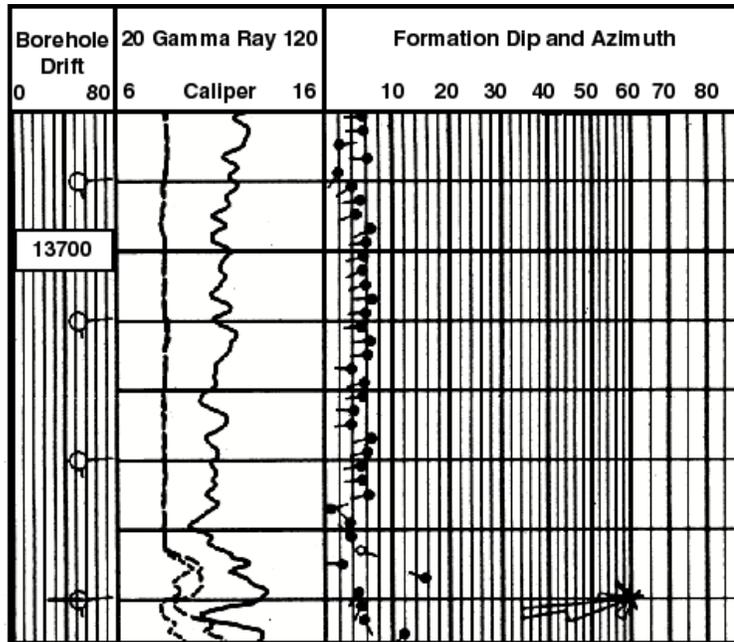


Figure 5: 912-2 dipmeter plot

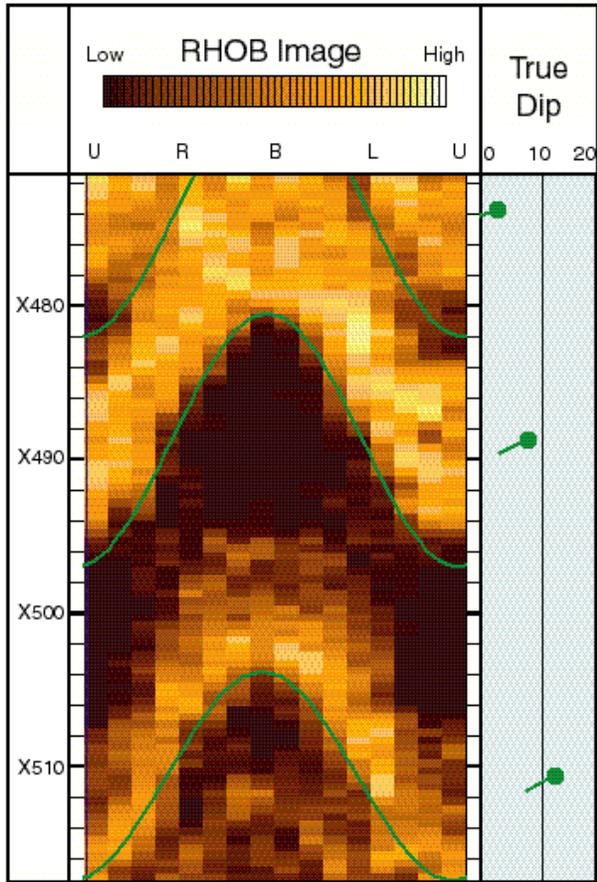


Fig.6: A-1 Data. Well-defined bedding and dips (density contrast about 0.2 g/cc).

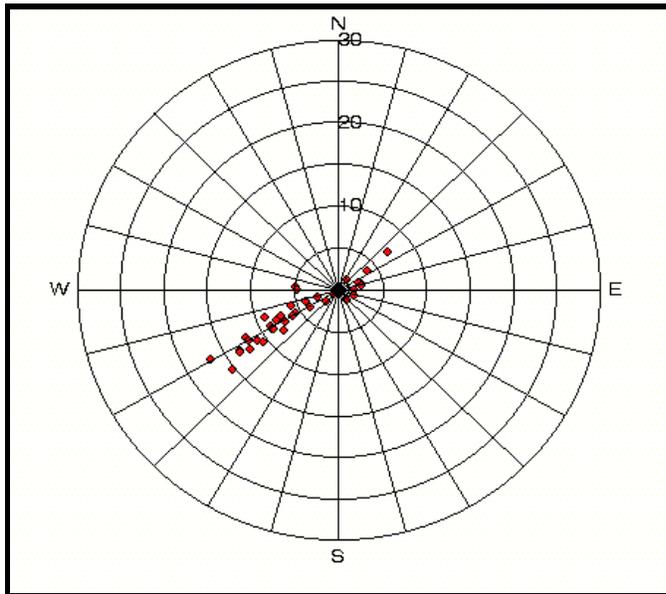


Fig 7: Stereonet plot of dips computed from density images. Mean dip is 7 degrees with an azimuth of 240 degrees

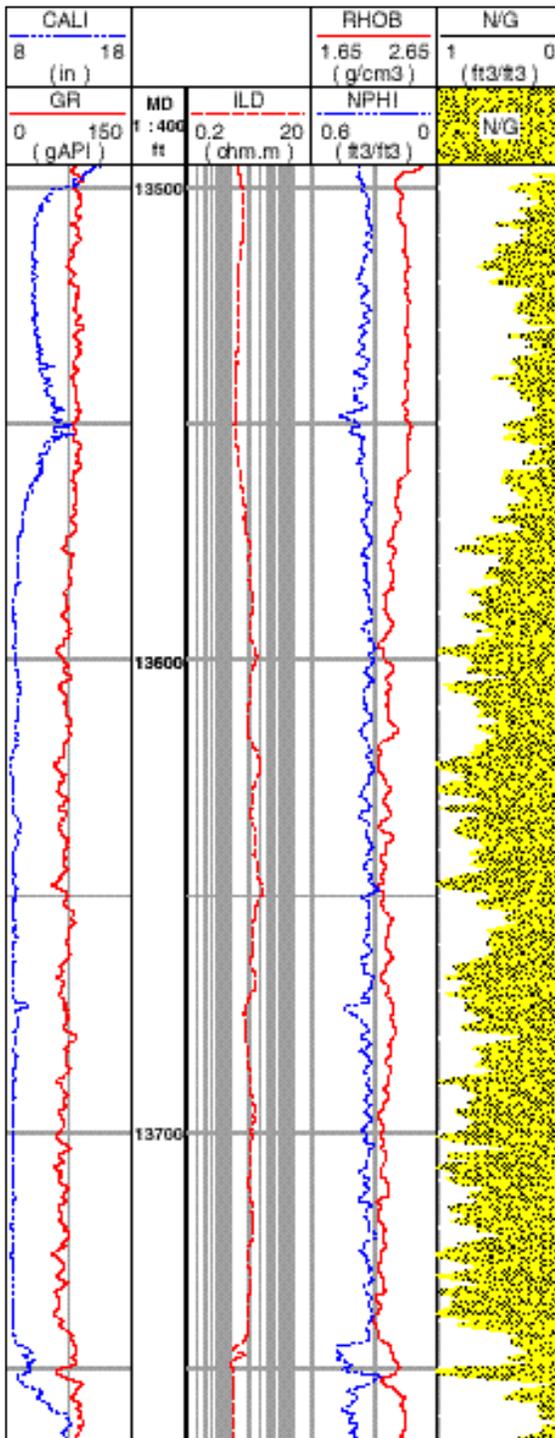


Figure 8: VK 912-2 Log Data

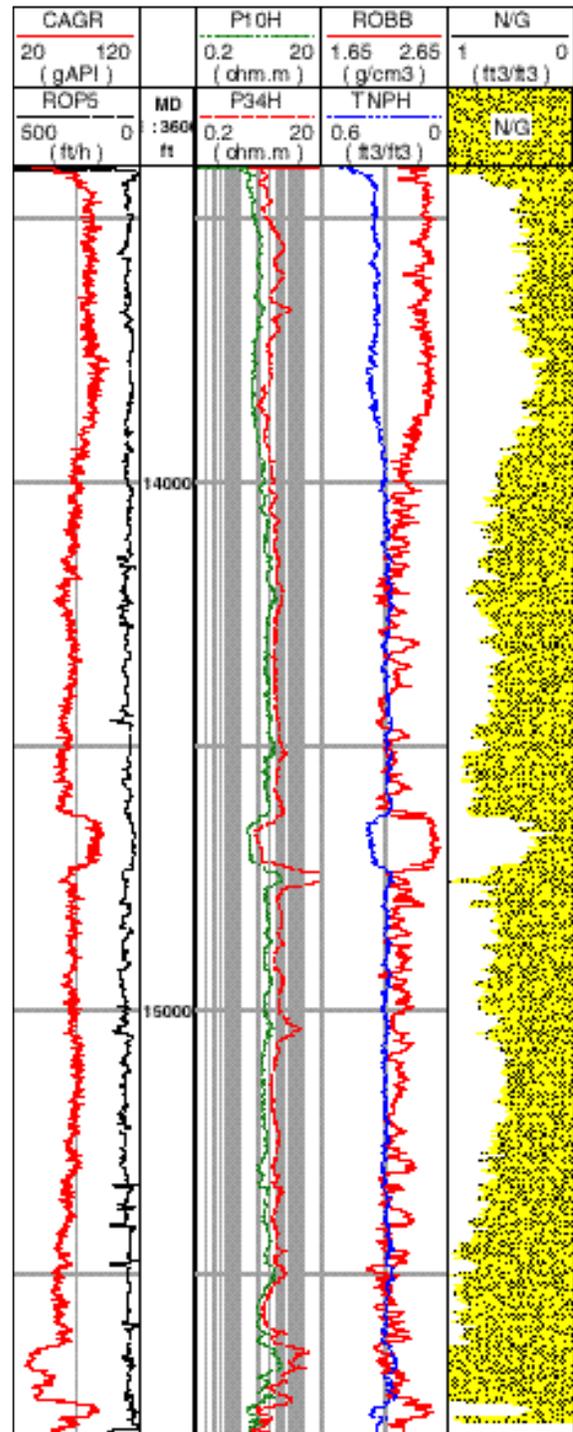


Figure 9: VK 956 A-1 Log Data

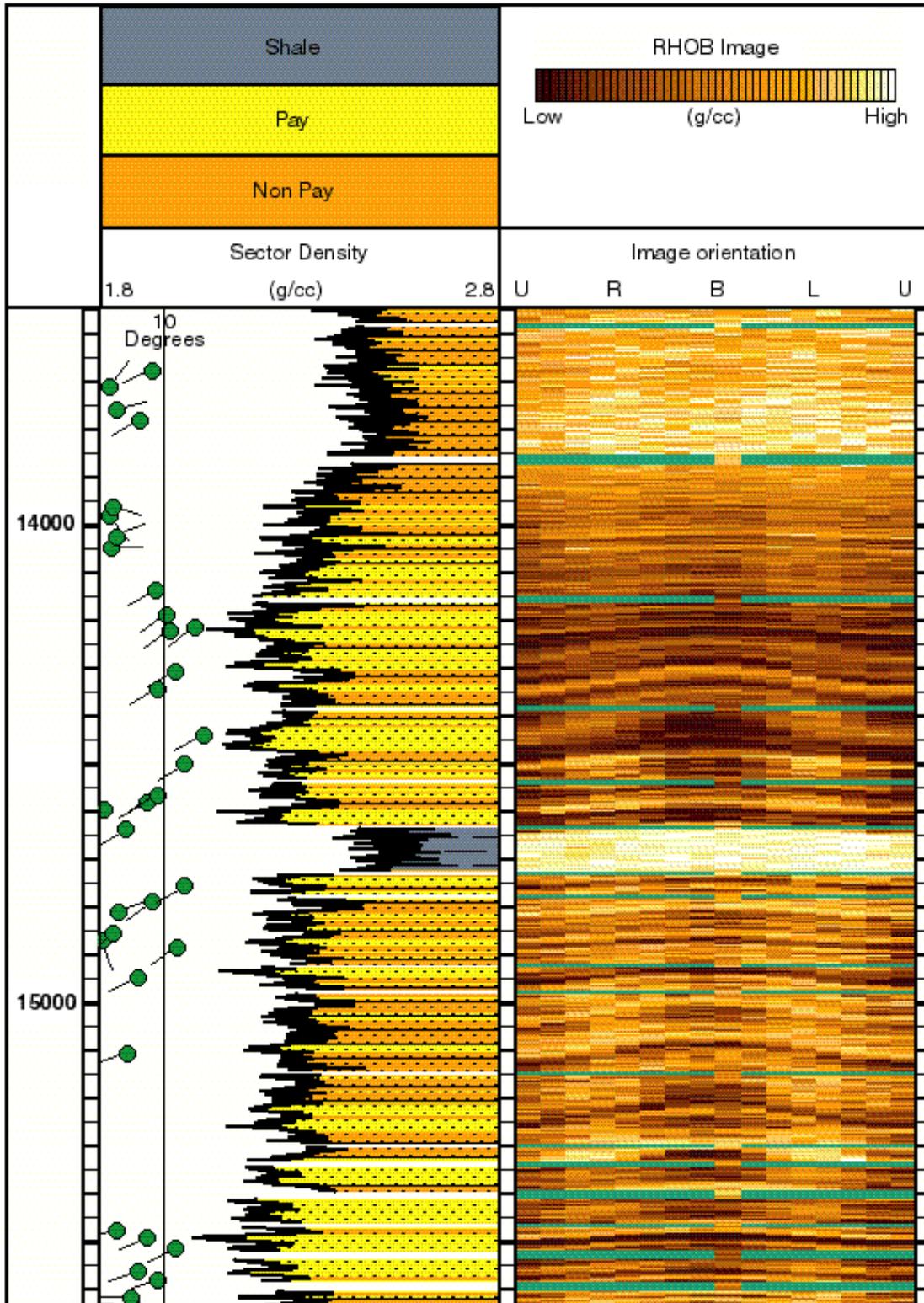


Figure 10: Net pay. (Density Facies and Dip Data)

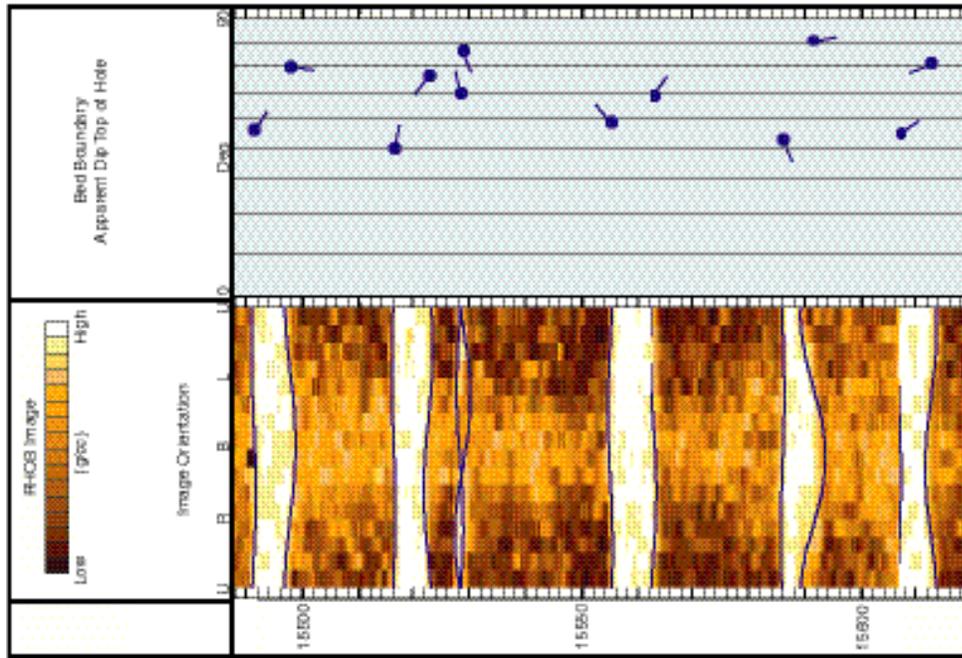


Figure 12 Image and Dip Data

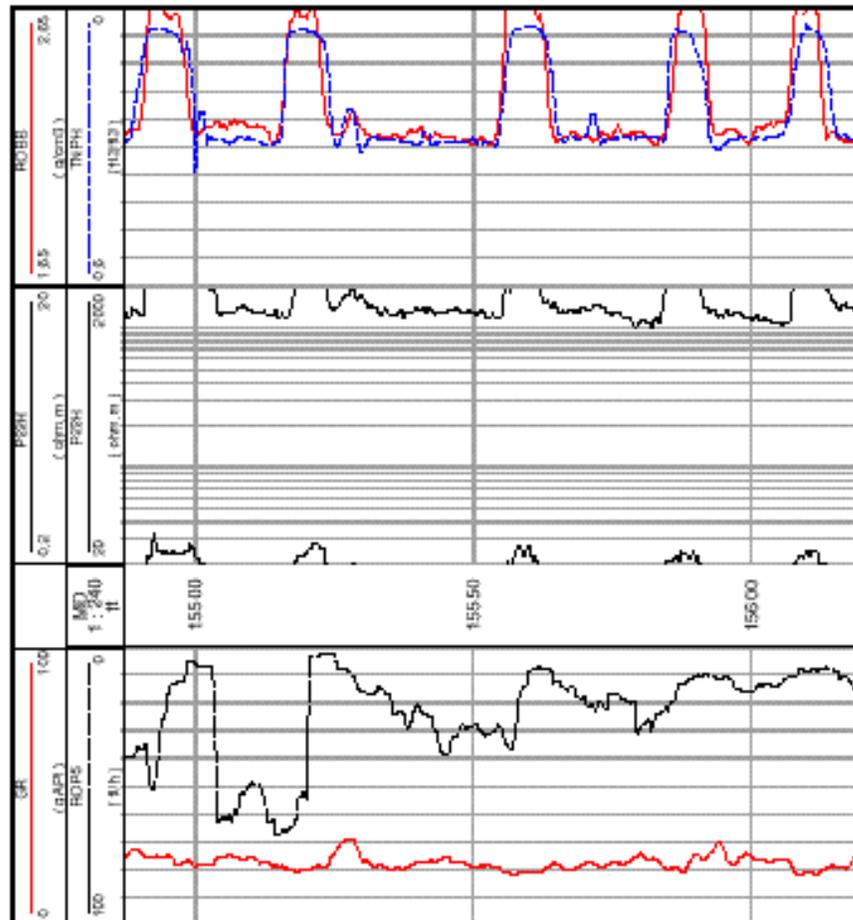


Figure 11 Real Time Data through Hard Streaks (A-3 Well)

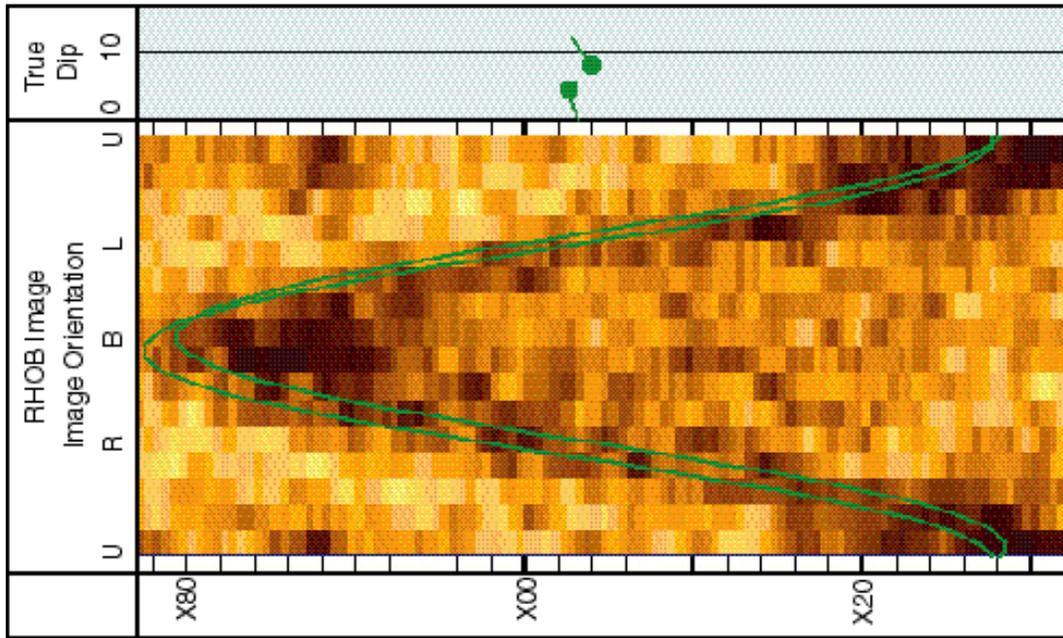


Figure 14: Sinusoid Placement Error.

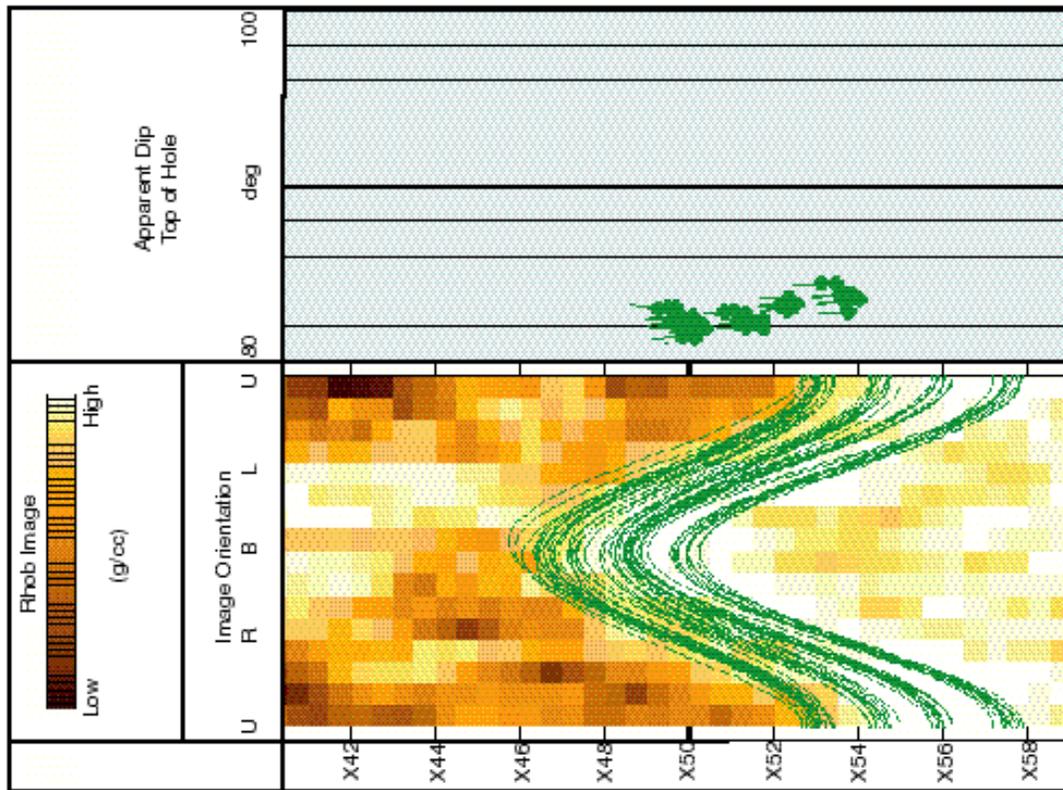


Figure 13: Correlation Uncertainty Experiment.