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Advances in Diplog® Data Processing for Stratigraphic Analysis

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Abstract: Detailed log-derived stratigraphic interpretation requires the use of high vertical resolution logging devices such as a dipmeter. The Dresser Atlas Strata Dip® program, originally introduced in the early 1980's, is a computer program designed to give a detailed point-wise estimate of the orientation and depth of very fine formation laminae. Numerous improvements in the computational algorithms coupled with features such as the removal of the effects of structural dip and intelligent handling of floating pad data have resulted in a second generation product which is described in this paper.

The accuracy of the program's results was tested using synthetic data generated by a dip simulation program. The repeatability of the program (in fact of the entire data acquisition and processing system) is demonstrated by separate analyses of three independent runs over the same well interval. Two field examples demonstrate the value of this new program as an aid to stratigraphic analysis.

INTRODUCTION

The Strata Dip program is an important, if not vital, tool for stratigraphic studies of the subsurface. With a vertical bed resolution of less than two centimeters, the dipmeter is the best logging device available for obtaining the detailed information necessary for stratigraphic evaluations. The program enhances this data by showing the detailed cross stratification found in the subsurface. By careful study of the program's results in conjunction with other data from the case well and offset wells, a detailed analysis of the stratigraphy and sedimentology of an area can be made.

Since its introduction in the early 1980s, numerous improvements in the program have resulted in a second generation product. A description of the program logic is given so that others may gain a greater understanding of the correlation technique employed. While this technique is an intuitively valid approach to detailed dip analysis, experiments were conducted to verify its application in practice. The first of these experiments demonstrates the accuracy of the program in estimating the location and orientation of bedding planes traversed by the borehole. The second experiment demonstrates the repeatability of the entire Diplog® system which comprises both data acquisition and Strata Dip processing.

The usefulness of the program as an aid to stratigraphic analysis is shown via two field examples. The first of these examples is an eolian dune analysis in which the program clearly indicates the individual dune sets and the paleo-wind directions. The second example is an analysis of a sandstone formation comprising sediments deposited in a fluvial environment. This formation is interpreted as a point bar sequence consisting of channel lag, trough cross set, and ripple cross laminae deposits.

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PROGRAM LOGIC

Programs that use conventional interval correlation techniques compute results from vaguely defined "average" displacements among the pad traces that do not represent any specific subsurface feature. In contrast to this, the objective of the Strata Dip program is to define the distinct formation laminae surveyed by the Diplog instrument.

The program begins by computing the slope (derivative) of each of the four pad conductivity traces, sample by sample. For each pad, those depths at which its slope has a peak or trough (a local maximum or minimum) are the depths at which the pad may have crossed bedding planes. If the magitude of the slope is larger than a user input noise threshold, the depth is saved and referred to as a characteristic depth. The planes constructed by the program are obtained by matching the characteristic depths of the four pads with one another.

When either the number of characteristic depths found on at least one pad trace reaches a preassigned limit, or 640 samples (2 meters) of data are read in, the program begins the dip computation process. The interval of data read in up to this point is called a processing segment. The program now begins the process of modeling the geometry of the formation in the processing segment.

First, each of the six possible pairs of pad traces is examined to determine point-to-point correlations between their characteristic depths. Two characteristic depths from different traces form a potential match if:

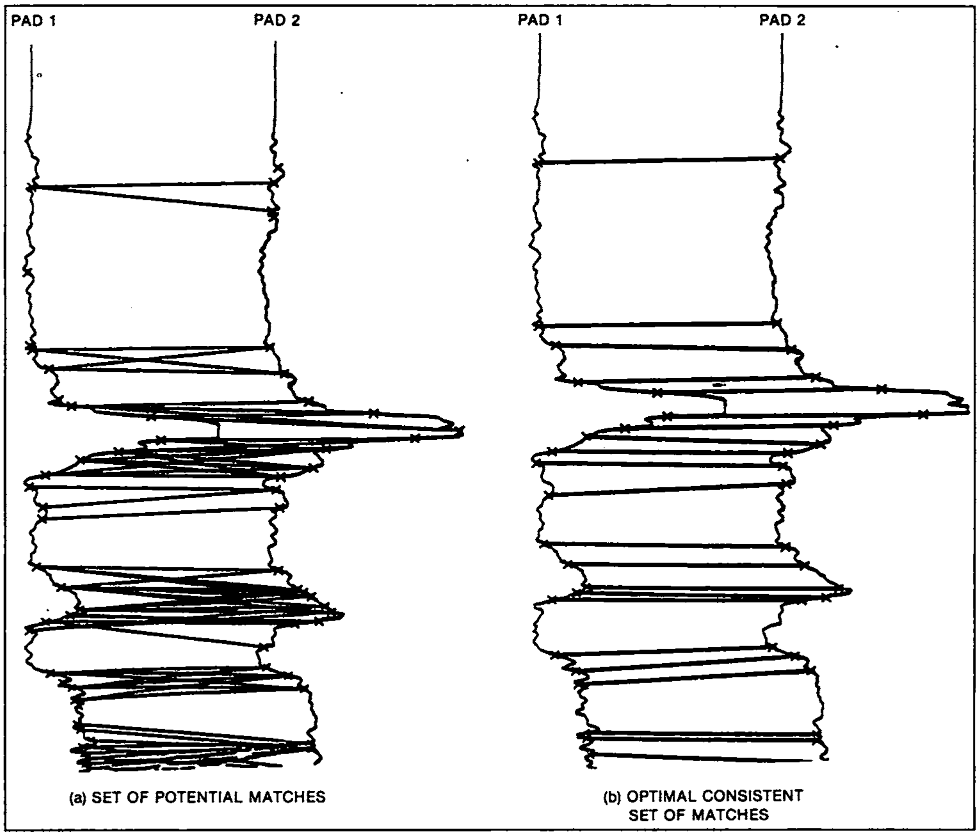
a. they differ by less than a preassigned search length,

b. the slopes at those depths have the same sign,

c. the ratio of the slopes is nearly 1.

A potential match can be considered as a line drawn between the two pad traces joining the two characteristic depths. The set of all possible potential matches in the processing segment is formed, making a crisscross pattern of lines joining the two curves (Figure 1a).

In order to reduce the number of potential matches, two data shifting options are available—The Plane Removal option and the Dominant Trend Removal option. Both options are used to shift the depths of the pad traces relative to one another so that similar features on the different traces are more nearly at the same depth. These pre-shifting options decrease processing time considerably by reducing the number of characteristic depths that require matching. More importantly, the options reduce the chance that incorrect matches will be made. The first option lines up any pad features due to strata parallel to a preassigned plane. If the preassigned plane is horizontal, this option will remove the effect of borehole deviation, and if it is the structural dip plane, the effect of structural dip is also removed. The second option uses interval cross-correlation techniques to remove the effects of the dominant planar trend in the processing segment. One or the other, or both of these options may be used; however, if both options are used, the data is pre-shifted via the Plane Removal option before correlations are computed.



(a) SET OF POTENTIAL MATCHES

(b) OPTIMAL CONSISTENT SET OF MATCHES

Figure 1: Illustration of Strata Dip pad-to-pad matching process.

The program now sorts through the potential matches to find an optimal consistent set of matches (Figure 1b). A set of matches is consistent if its members do not crisscross, and is optimal if the matches are as nearly parallel as possible. This does not mean that the program forces the matches into being parallel, but rather that among all the consistent subsets, the program chooses the one whose matches are the most parallel overall. The actual degree to which the matches are parallel is determined by the physical structure of the formation strata.

More precisely, optimality is defined as follows: let $p_k=(x_k, y_k)$, where x_k is a characteristic depth on one pad and y_k is a characteristic depth on the other pad that is a potential match with x_k. Let

$$S = \{p_1, p_2, \ldots, p_N\}$$

be a consistent subset of potential matches. We define the cost of S to be the number

$$C(S) = \sum_{k=1}^{N-1} \left| (y_{k+1} - x_{k+1}) - (y_k - x_k) \right| - W \cdot N$$

where N is the number of matches in S and W is a pre-assigned weighting factor. A consistent set S* is optimal if it is of minimal cost, i.e., if

$$C(S^*) \leq C(S) \qquad \text{for all consistent sets S.}$$

Increasing the weight W puts more emphasis on the objective of having many matches while decreasing W emphasizes the parallelism of the matches.

Since there are literally millions of consistent sets of potential matches, an efficient algorithm for sorting through them to find the one of minimum cost, called dynamic programming, is used. Nevertheless, this is the portion of the program that uses the most time.

Once the 6 optimal consistent sets of pad-to-pad matches, S12, S13, S14, S23, S24, S34, have been found, the program starts a rather complicated process of piecing them together into a set of bedding planes. Each of the planes found is tested for planarity, and its dip angle and direction are checked to determine if they lie between preset minimum and maximum values. If all these tests are passed, the plane is included in the set of potential planes. A potential bedding plane is defined as a quadruple (z_1, z_2, z_3, z_4) of characteristic depths, one from each pad curve, that roughly form a plane. The method of constructing planes from the pad-to-pad matches is best explained by example. Consider the sequence of pad pairs: 12, 23, 34 (called a route). At each characteristic depth z_1 on pad 1, the program determines if some depth z_2 on pad 2 is matched with it in S12. If there is such a match, the program checks to see if some depth z_3 is matched with z_2 in S23. If there is such a match, the program checks to see if some depth z_4 is matched with z_3 in S34. If there is again such a match, the four depths are recorded as a potential plane subject to the tests described above. If a match is not found at any stage of this process, the attempt is abandoned, a plane is not found, and the program moves to the next characteristic depth on pad 1 and starts the process all over.

There are 5 possible routes starting from each pad, consequently 20 routes altogether (provided no pads are eliminated with the bad pad option†). The program goes through the above process for each of these routes. There are four special routes that need to be mentioned. These are the routes involving only three pads, such as 12, 23, 31. The program finds the charateristic depths z_1, z_2, z_3 as before, and then checks to see if z_1 and z_3 are matched in S13. If they do not match, a plane is not formed. If they match, a fourth depth z_4 is computed to form a perfect plane with the first three, and the resultant quadruple of numbers is recorded as a potential plane. If this plane survives the optimization process described next, the plotting program will draw only two lines joining the first three depths and will not show z_4 at all.

The many potential planes found by the matching process crisscross each other as did the pad-to-pad matches. The program chooses an optimal consistent set of these potential planes as its final output. A set is consistent if its planes do not crisscross, and is optimal if its planes are as parallel as possible. This final set of planes comprises the bedding planes of the strata found in this interval.

Optimality is defined in the following manner: Let $pk=(z_{k1}, z_{k2}, z_{k3}, z_{k4}$ be a potential plane, where the characteristic depth as $z_{k1}, z_{k2}, z_{k3}, z_{k4}$ were matched via some route as described above and let

$$S = \{p_1, p_2, \ldots, p_N\}$$

be a consistent set of potential planes.

The slopes of the two diagonals of the plane p_k are proportional to $z_{k3} - z_{k1}$ and $z_{k4} - z_{k2}$. Consequently, a measure of the difference between the normal vectors of two consecutive potential planes is

$$d(k, k+1) = |(Z_{k+1,3} - Z_{k+1,1}) - (Z_{k3} - Z_{k1})| + |(Z_{k+1,4} - Z_{k+1,2}) - (Z_{k4} - Z_{k2})|$$

That is, the larger d(k, k+1) is, the less parallel the planes are. Also, let the value of the plane, $V(p_k)$, be the number of routes that matched the four characteristic depths of p_k. The more routes that found the same plane, the greater the number of pairs of its characteristic depths that were matched by the optimal pad-to-pad matches, and consequently, the greater confidence we have that the plane is correct. From these considerations, the cost of the consistent set of potential planes is defined to be

$$C(S) = \sum_{k=1}^{N-1} (d(k, k+1) - W \sum_{k=1}^{N} V(P_K)$$

As before, the consistent set S* is optimal if it has minimal cost. Increasing the weighting factor W places emphasis on finding more planes of higher value while decreasing W places more emphasis on the overall parallelism of the optimal set.

The current processing segment is overlapped with the next processing segment in the following manner:

Let N be the number of planes in the optimal set and let M=0.8×N. Only the M deepest planes from this set are used. The start of the next processing segment begins at the Mth plane. Continuity between processing segments is attained by requiring that this topmost plane be included in every consistent set of planes in the next processing segment. The program reads in new data and begins processing the next segment. The processing continues, segment by segment, until all the data has been used.

TESTING THE PROGRAM

Evidence of rigorous testing of dipmeter data processing algorithms is sadly missing from the literature. The primary reason for the lack of adequate testing is the difficulty and expense involved in obtaining alternative data such as oriented cores which can be used to accurately establish the ground truth. For a program which attempts to estimate the location and orientation of relatively thin laminae, adequate testing is essential.

For this reason we have developed a computer simulation program which produces synthetic dipmeter data for formations whose structure is completely known. The simulation has two stages. The first stage allows one to describe the formation in terms of the location and orientation of the planar interfaces between its laminae, the resistivities of these laminae, the orientation and size of the borehole, and the orientation of the tool in the borehole. The program then "logs" the well, producing conductivity data of an "ideal" response (Figure 2a). The second stage adds noise to the conductivity traces to simulate natural, non-laminar variation in conductivity and random events such as borehole rugosity, mud cake thickness and pad pressure that affect the measurement process. It then smooths the data to simulate

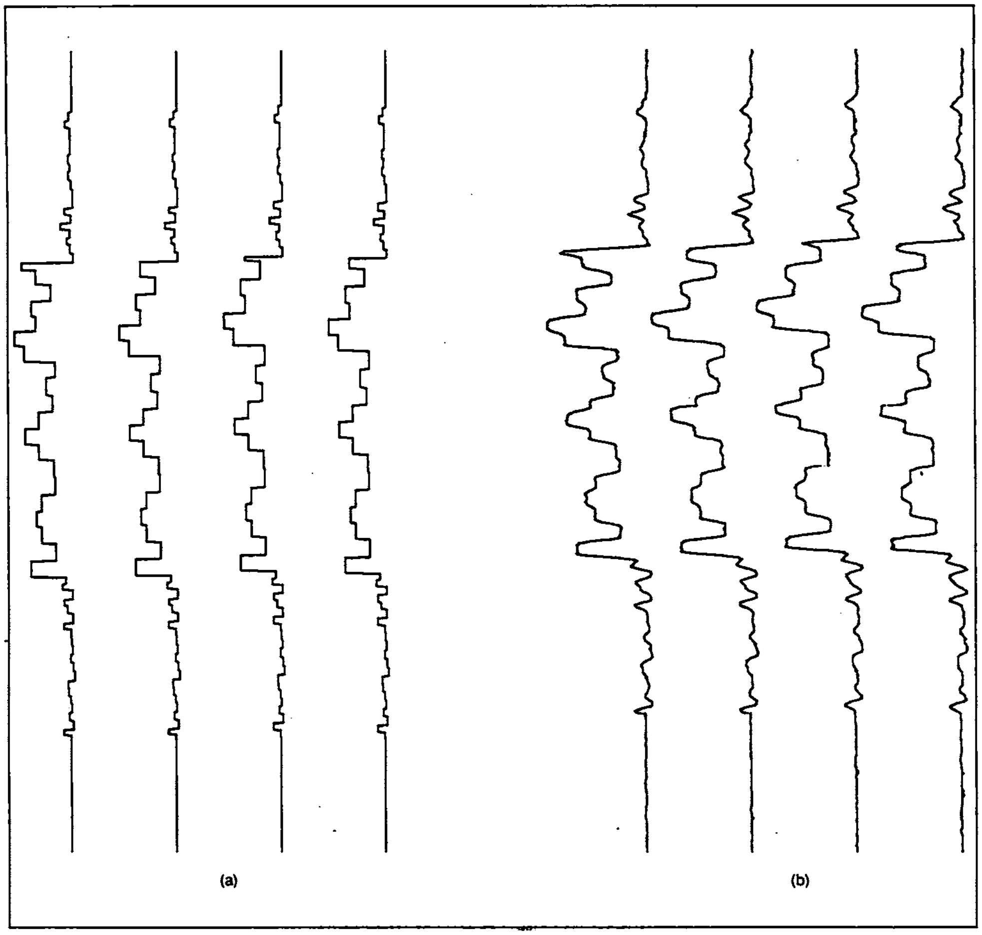


Figure 2: Illustrations of pad trace data used in testing Strata Dip accuracy: (a) the "ideal" data and (b) "realistic" data.

the pad response and the anti-aliasing filter of the instrument to produce a "realistic" response (Figure 2b). This allows us to study the effect of these factors on Strata Dip computations.

The formation for testing program accuracy was constructed by specifying the dip angle, dip azimuth, laminar thickness, and laminar resistivity over specified intervals and adding a random term to each. The random terms are all uniformly distributed on the intervals specified below.

Formation Description

Depth intervals—10 ft-12.5 ft and 17.5 ft-20 ft;

Angle=10° + e	$-1 < e < 1$
Azimuth=30° + e	$-2 < e < 2$

Thickness=1.25 ft + e	$-0.25 < e < 0.25$
Resistivity=1.1 ohm-m + e	$-0.2 < e < 0.2$
Depth interval—12.5 ft-17.5 ft:	
Angle=$10° + (\text{Depth}—17.5)^2 + e$	$-1 < e < 1$
Azimuth=20° + e	$-2 < e < 2$
Thickness=0.265 ft + e	$-0.025 < e < 0.025$
Resistivity=0.6 ohm-m + e	$-0.2 < e < 0.2$

A vector plot of this formation geometry is shown in Figure 3. Figures 4 and 5 show the vector plots obtained by processing these two data sets with the Strata Dip program.

Analysis of the results of the computations shows that for the ideal data (Figure 4), three bedding planes were not found. Two of these planes were missed because the resistivities of

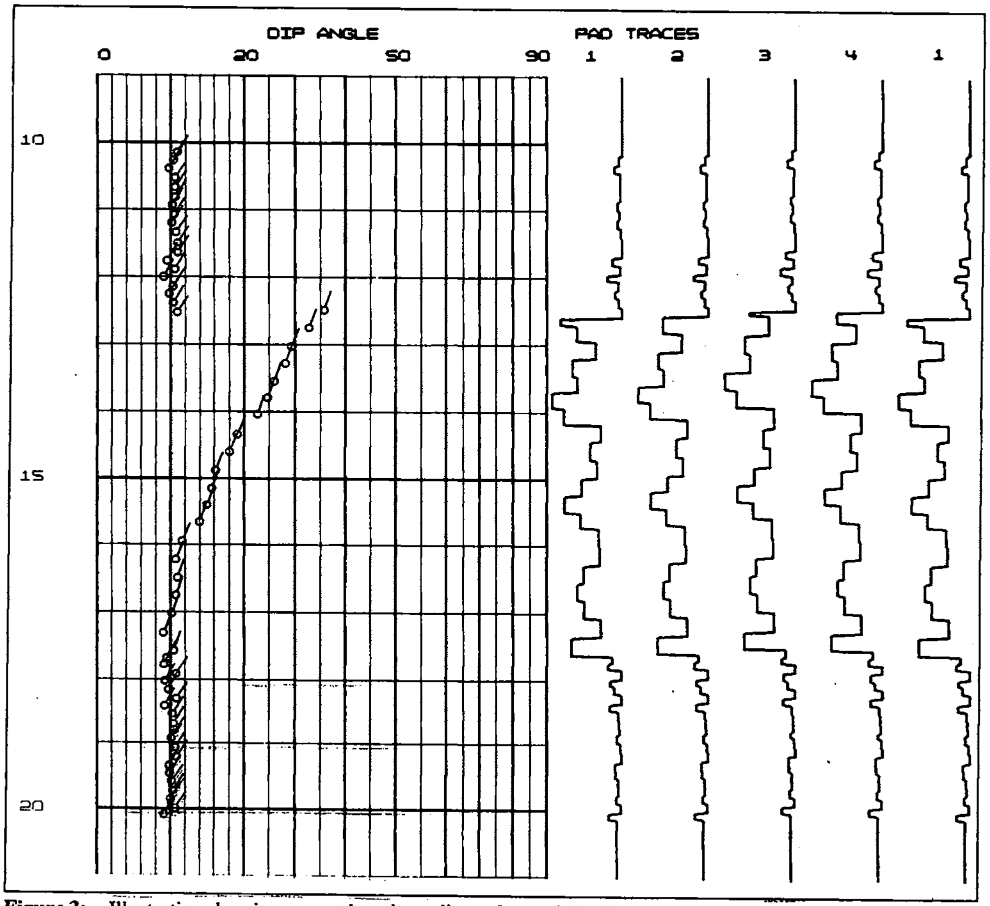


Figure 3: Illustration showing correct locations, dip angles, and dip directions of bedding planes in the simulated formation.

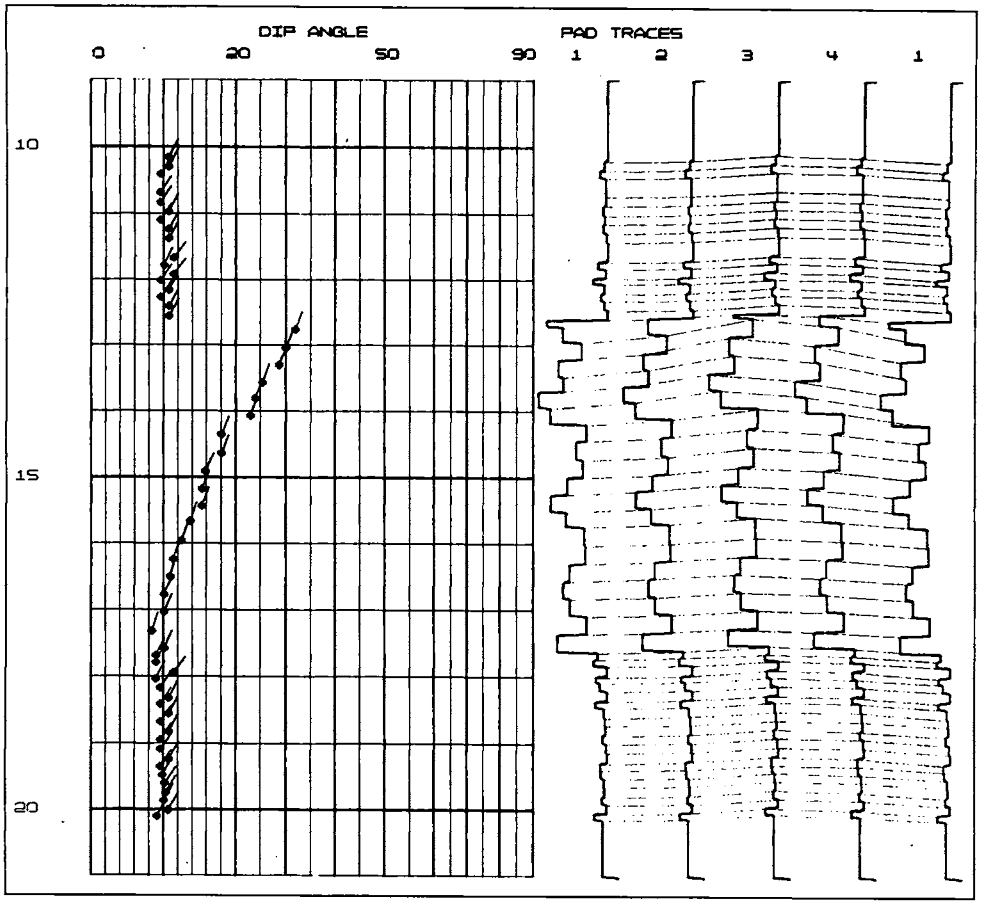


Figure 4: Strata Dip results using "ideal " pad trace data.

the adjacent laminae differed by only 0.003 ohm-m. The third plane occurred at the unconformity at 12.5 ft and only crossed pad 1. For the realistic data (Figure 5), fourteen bedding planes were not found and two bedding planes were created by noise. Most of these planes were missed because the associated resistivity contrasts lay below the noise threshold. Since the orientation of a plane is determined by its unit normal, the best measure of the overall error in the estimation of orientation is the angle between the true normal and the estimated normal. This is particularly true for small dip angles where small orientation errors can yield large azimuth errors. For the bedding planes that were found, an analysis of the error in estimation of depth and orientation was performed. The results are shown in Table 1.

While testing the program on simulated data is very useful, testing on real data is also needed. An ideal test is to use repeat logs over the same interval. This allows one to test the repeatability of the combined measurement and processing system. Results of such a repeatability test are shown in Figures 6, 7, and 8.

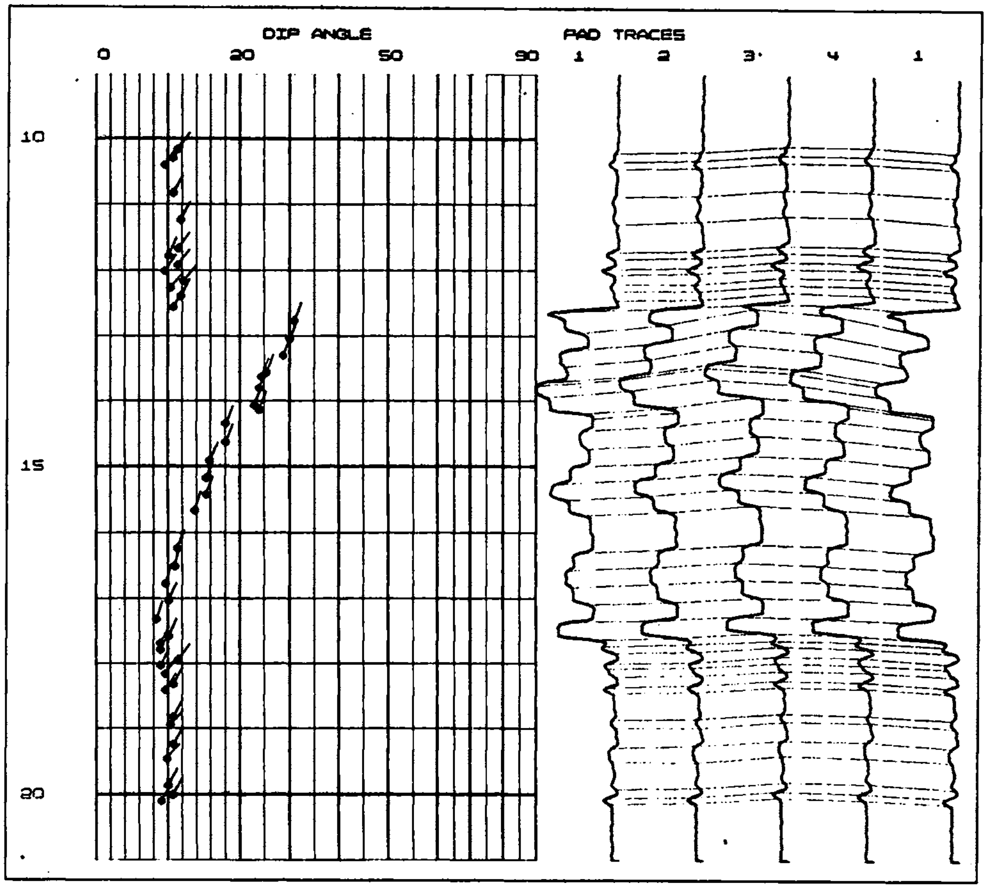


Figure 5: Strata Dip results using "realistic" pad trace data.

Examination of the relative bearing recordings from each of the runs indicates the Diplog instrument had a different orientation for each run. The difference in relative bearing between the first two runs ranges between 180 and 190 degrees, while the difference between the first and third run is a relatively constant 105 degrees. Since these differences are roughly 180 and 90 degrees, one would expect the pad traces in Figures 7 and 8 to be permutations of those

TABLE 1

ANALYSIS OF ERROR

	Depth (ft)		Orientation (degrees)	
	Ideal	Realistic	Ideal	Realistic
Mean	-0.02	-0.02	0.64	0.83
Median	-0.03	-0.03	0.56	0.63
Standard Deviation	0.01	0.01	0.32	0.57

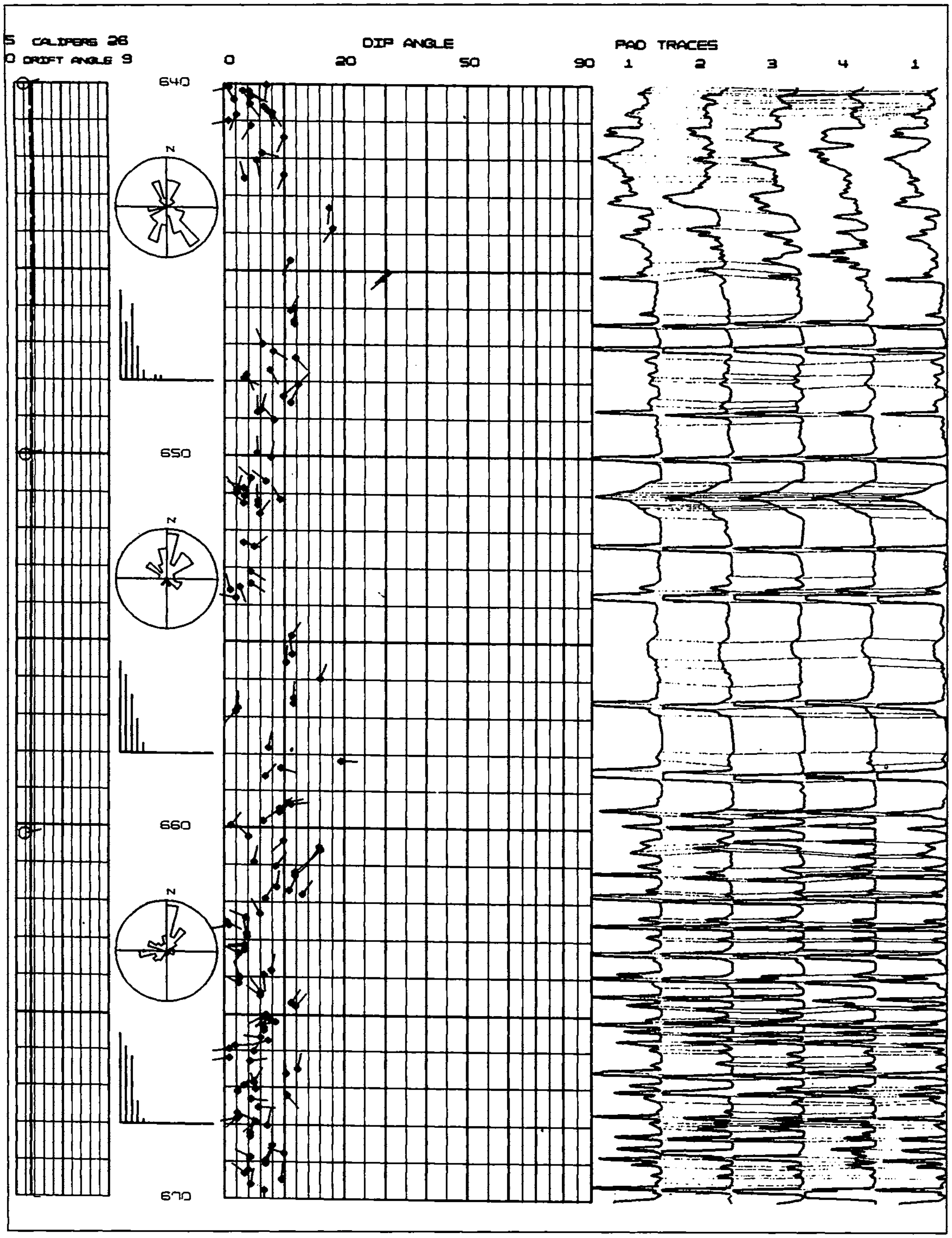


Figure 6: Repeatability test — Run 1.

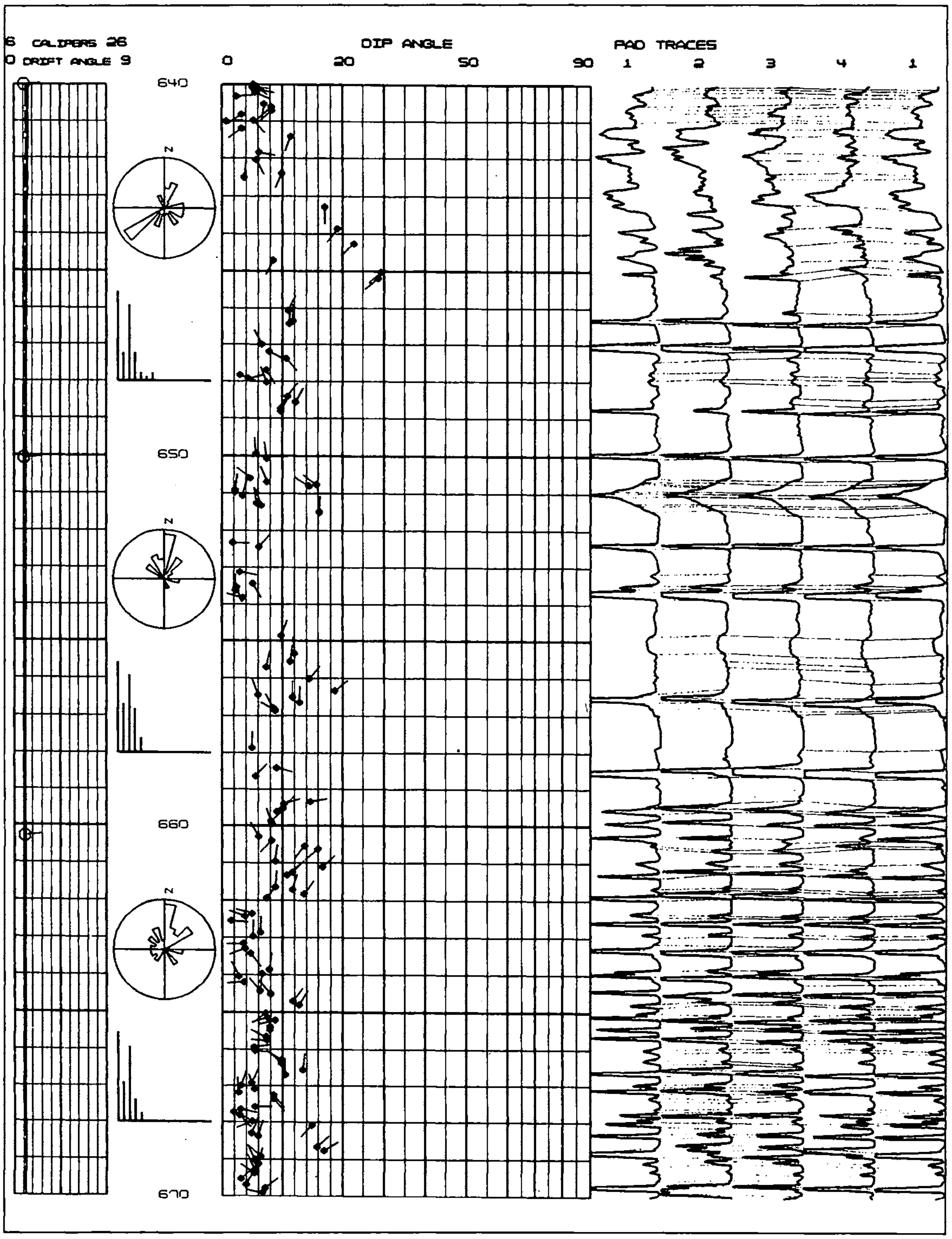


Figure 7: Repeatability test — Run 2.

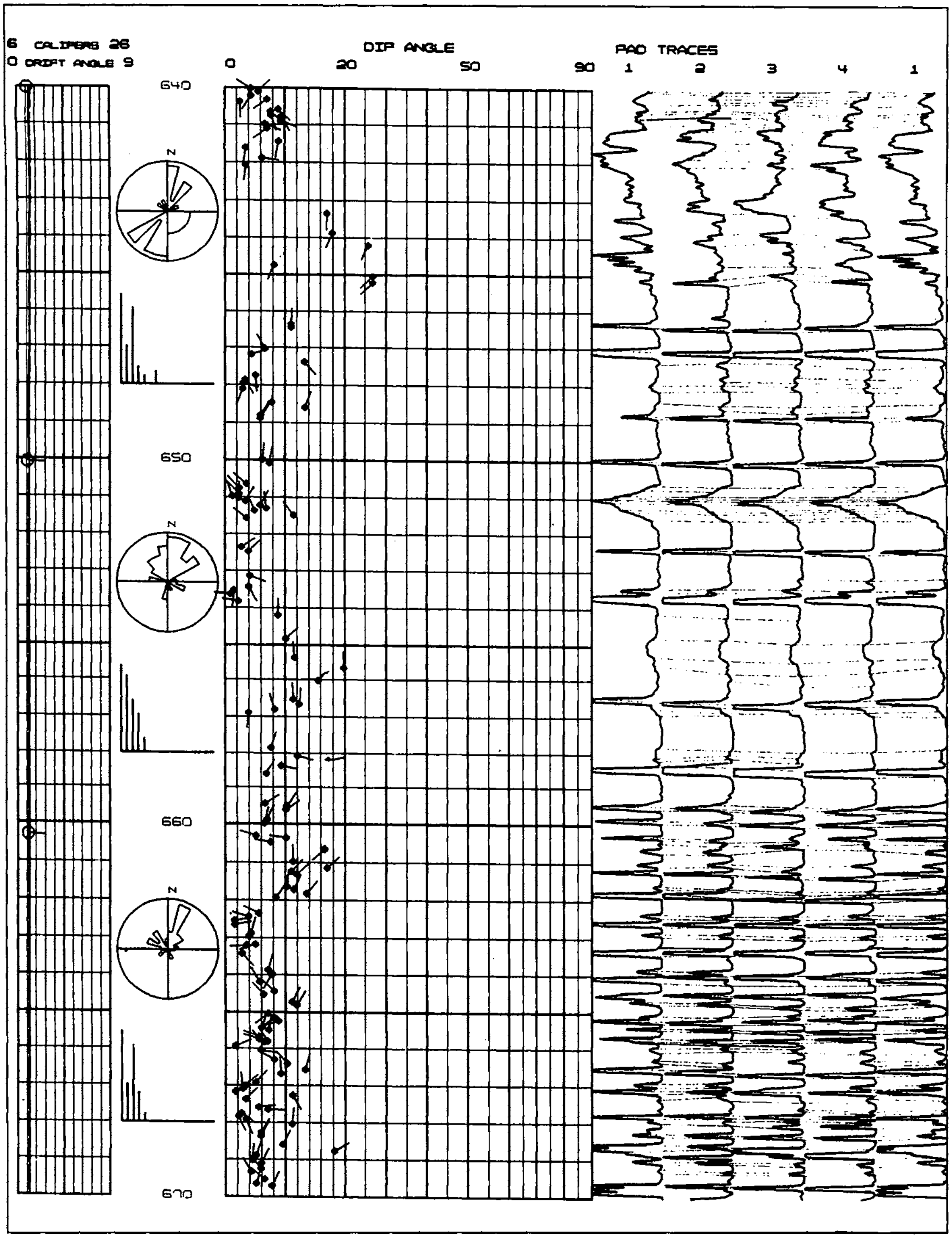


Figure 8: Repeatability test — Run 3.

in Figure 6. Inspection of the pad traces show that this is indeed the case. Moreover, these traces show a remarkable degree of repeatability in conductivity measurements.

The vector plots shown in Figs. 6, 7, and 8 indicate high repeatabiliy in the estimation of location and orientation of bedding planes. However, some planes are found on each run that are not found on the other runs. This is due primarily to differences in noise levels. Noise also causes differences in the estimation of the characteristic depths (bed boundaries) which leads to the differences in the estimation of the location and orientation of the bedding planes found simultaneously on two different runs. Table 2 shows the results of an anlaysis of the differences in depth and orientation of the bedding planes found in common between Run 1 and Run 2 and between Run 1 and Run 3.

TABLE 2

ANALYSIS OF DIFFERENCES

	Depth (ft)		Orientation (degrees)	
	Run 1 - Run 2	Run 1 - Run 3	Run 1 - Run 2	Run 1 - Run 3
Mean	-0.02	-0.04	1.97	2.60
Median	-0.04	-0.05	1.13	1.25
Standard Deviation	0.04	0.03	1.78	2.38

Number of bedding planes common to both 6 and 7: 117
Number of bedding planes common to both 6 and 8: 120

FIELD EXAMPLES

The Strata Dip program has been successfully used to assist in interpreting clastic sediments that have been derived from various sources. Eolian environments display obvious dips on most dipmeters, but the highly detailed computations of the program gives the geologist the ability to differentiate individual dune sets and distinguish the toe sets from the avalanche or foreset beds. (Figure 9) Also, accurate dip angles and directions of these cross beds are computed. From these information, paleo-wind direction is easily determined, and interpretation of dune geometry and morphology is enhanced.

The complexity of fluvial regimes demands the detail of a point-to-point correlation program. Vertical changes in clay content or grain size and identification of cross bedding type can be inferred from all of the information presented on the plot generated by the program. Interpretation of the patterns in the computed stratigraphic dips allows the geologist to estimate paleo-current direction. Figure 10 shows an example of an analysis of a fluvial sandstone formation. Apparent on this log is a sharp contact with the underlying shale (X786). This contact probably represents the channel scour. This is overlain by a massive zone that is interpreted to be the channel lag deposit which fines upward in grain size to X772. Cross bedding, which is characterized by bedding planes with uniform dip direction and dip angles which decrease with depth (the classic "blue-pattern"), can be seen in the interval from X777 to X782. Tabular cross bedding, displaying relatively consistent high angle dips, can be seen from X774 to X776. The dips in this interval are probably due to ripple cross lamination. The low angle stratification in the upper section of the interval probably

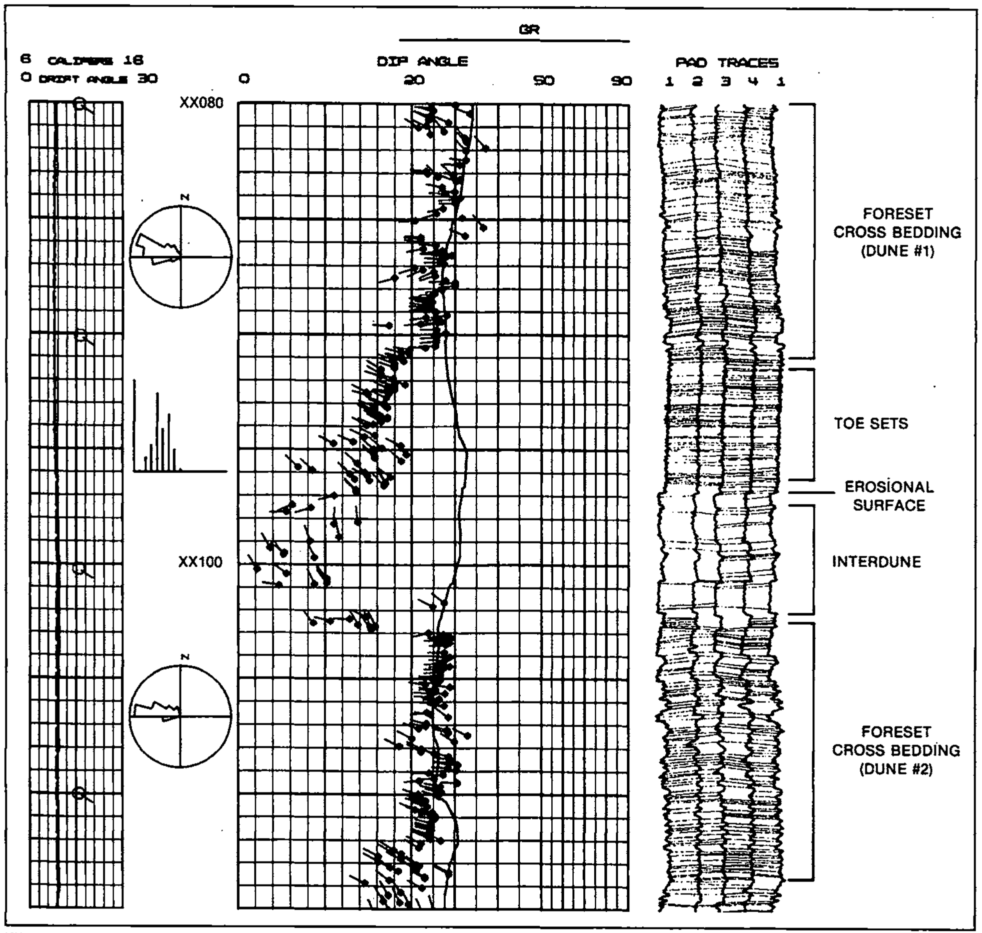


Figure 9: Strata Dip in an eolian sandstone (Nugget Formation, Wyoming). Two individual dune sets can be seen on this log. The top dune displays foreset bedding from XX080 to XX091. Below this point, toe sets are displayed (XX091-XX097). Between the two dune sets is a dry interdune sequence. Paleo-wind direction was to the west in this case.

represents bar top deposits. This entire sequence has been interpreted as a point bar deposit with paleo-flow to the southeast as determined from the cross strata.

Other sedimentary structures, such as bioturbation, can be identified by the Strata Dip program if the computations are "calibrated" to a core in an area. Features such as bioturbation can be seen clearly on a core and can leave a characteristic fingerprint on the dipmeter data. After calibration, stratigraphic dip analysis can be used in place of a core in offset wells for local stratigraphic information.

CONCLUSION

As the petroleum industry seeks more detailed information about the sedimentology and stratigraphy of hydrocarbon bearing zones, the need for high-resolution methods of forma-

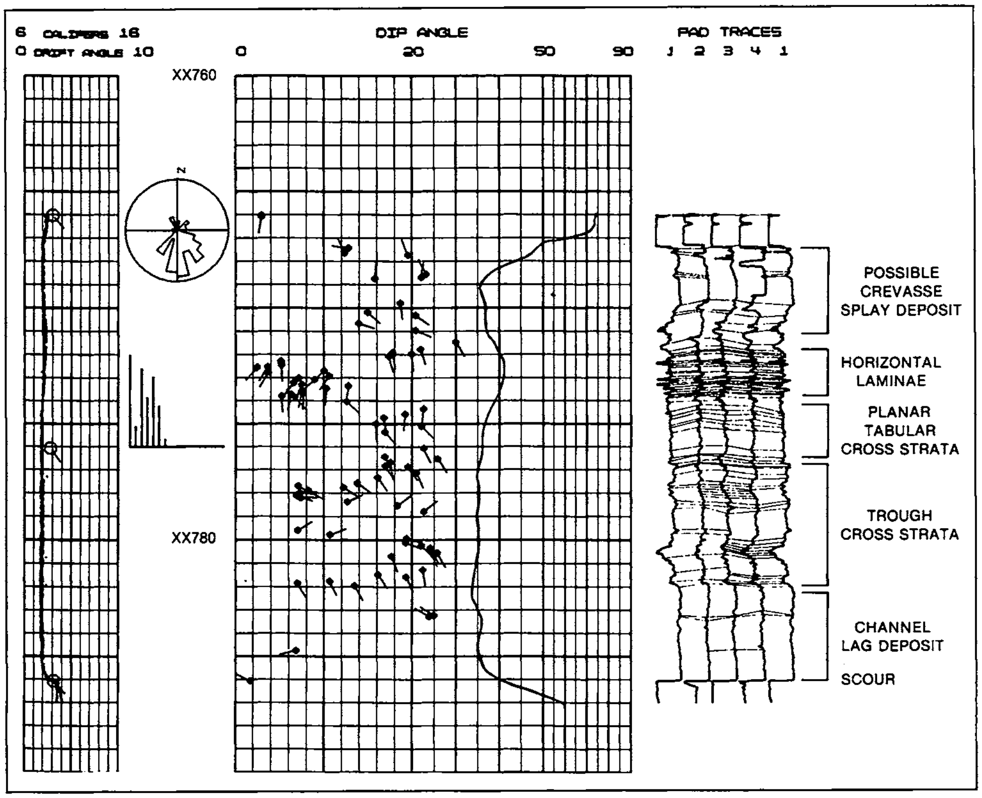


Figure 10: Strata Dip through a point bar deposit (Tyler Formation, Montana). The channel scour is apparent at XX786. Above this point, a channel lag deposit is seen (XX782-XX786). Three types of cross statification are displayed through this point bar sequence (see text for description).

tion evaluation becomes necessary. The program described in this paper provides a geologist with important information for conducting a detailed stratigraphic analysis of a field.

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