DEPARTMENT OF THE INTERIOR

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Multivariate Analysis of Geophysical and Mineralogical Data from Uranium Bearing Sandstones

by

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Introduction

Exploration for "roll-front" type deposits of uranium depend on extensive drilling programs. The cuttings from the holes are examined for evidence of alteration (oxidation) of the uranium bearing sands which indicates the passage of oxidizing fluids. The holes are routinely logged (typically for gamma count, resistivity, and self potential) to obtain information on lithology and the presence of uranium or its daughter products. A major need for such exploration programs is a methodology to determine distance from the roll front; or at least to determine in which direction the roll front lies.

The purpose of this research was two fold: 1) we wanted to determine if hole position relative to the roll front could be determined from geophysical and mineralogical data and 2) we wanted to evaluate the relative values of the geophysical and mineralogical variables for hole position and redox (reduction-oxidation) state discrimination.

A stepwise discriminant computer program, BMD07M from the University of California biomedical series, was used to analyze the data. This program provides for dividing the data into class groups for subsequent analysis. The mean vectors for each group are computed along with the covariance and correlation matrices for all of the data. F ratios (statistic to test equality of means between each pair of groups, see Dixon, 1974) are used to select the order in which the variables are used for discriminating between the classes. The F ratios provide a measure of the relative importance of all variables.

Finally, the variables are canonically transformed (Feal, 1964) and the data plotted against the first two canonical variates. This shows the separability of the classes and the existence of any trends between the classes.

Data from three regions were analyzed: 1) Bruni, Texas, 2) Irigaray, Wyoming and 3) Lamprecht, Texas. Only the data from Bruni, Texas were adequate for the research proposed. At Irigaray the holes which had been cored were too close to the roll front to establish valid redox or distance classes. At Lamprecht the entire region had undergone secondary reduction which resulted in a very confusing redox status across the roll front. Only 6 feet (2 m) of core showed a distinctly greater oxidation status compared to all of the other footage. This is not an adequate sample of a population. The results of the analyses are presented separately for each region.

Bruni Data

The Bruni data consist of five boreholes traversing the known roll front (see fig. 1). Two boreholes are located on the unaltered side, two on the altered side and the fifth hole is in the roll front. It should be noted that the holes range out to 3,000 feet (100 m) from the roll front.

A total of 234 feet (72 m) of core was analyzed. The core consisted of sandstone and shale units within the uranium bearing strata and neighboring units both above and below the ore zone.

The data used were supplied by Wyoming Mineral Corporation (WMC). They consisted of a lithologic log and both geophysical and mineralogical information as well as the redox state for each foot (1/3 m) of core. The geophysical logs were interpreted by WMC at ½ foot (15 cm) intervals. Since the mineralogical information was recorded at one foot (1/3 m) intervals, the geophysical information was averaged to one foot (1/3 m) intervals. The following geophysical logs were run by WMC for this study: gamma, SP dipole, SP single point, resistivity, IP, and IP ratio. WMC also provided bulk mineralogy in ppm on: pyrite, garnet, zircon, monazite, maghemite, ilmenite, lights, and limonite. In addition, WMC also furnished x-ray data on the relative presence of feldspar, clay, and calcite. The weight percentage of heavy minerals was also used. Therefore, a total of six geophysical and twelve mineralogical variables were recorded for each one foot (1/3 m) of core. These eighteen variables were transferred to computer cards and used to analyze the statistical parameters of the 235 feet (72 m) of Bruni section.

Hole Discrimination

First, the Bruni data were grouped according to its five boreholes before running the stepwise discriminant analysis to see if the data were sufficient to distinguish the five different boreholes. Four runs were made using four different sets of variables. The first run used all eighteen variables. The second run used only the six geophysical variables. Its canonical plot (see fig. 2) indicates much overlap.

The third run used the five best log variables from the second run and the best variable from the first run, maghemite. Figure 3 shows the canonical plot of the third run. The addition of maghemite greatly aided in distinguishing between the holes. The fourth run (see fig. 4) gave the best discrimination. It used the best six variables from the first run.

Redox Discrimination

Then the data were regrouped according to their redox states which had been indicated by WMC as altered, unaltered, or ore. The initial redox run using the stepwise discriminant analysis revealed erroneous data points. Therefore, data points with a high probability of belonging to a group other than their present group were regrouped or removed. Additional stepwise discriminant analysis runs were made with additional cleaning until a tight grouping with good separation between groups was achieved. Figure 5 shows the canonical plot of the cleaned data using all eighteen variables. This cleaning and regrouping indicated that the sixteen feet (5 m) of section above the ore located in hole 47 was also ore. When using all eighteen variables maghemite and gamma were the most important variables in discriminating between redox states.

Figure 6 gives the canonical plot of the cleaned data when the six geophysical logs were used exclusively in the stepwise discriminant analysis. Here gamma was the most critical variable.

Figure 7 is the canonical plot of the cleaned data using the six best variables determined from the run using all eighteen variables and it shows excellent discrimination between the three redox states.

Finally, the stepwise discriminant analysis was run using the five best geophysical log variables and maghemite. This plot is shown in figure 8 and displays good separation between groups as well as trends from one group to another.

Sand-Shale Discrimination

The next step was to test the ability to separate the sandstone units from the shale units using the information available. This was done by dividing the sandstone and shale into two groups based on lithologies before running the stepwise discriminant analysis. The first run used all eighteen variables (see fig. 9). The computer analysis disagreed with only one sandstone data point and six shale data points, with all six of the questionable shales being a sandy shale. The most important variables in distinguishing the two groups were resistivity, IP ratio, and monazite.

The stepwise discriminant analysis was run again on this data, but this time using only the six geophysical variables. The sands were all accepted as correctly grouped but eleven of the shales data points were questionable. Again, all eleven were sandy shales. For this analysis IP ratio and resistivity were the most important distinguishing variables (see fig. 10).

Therefore, since the program could distinguish the pure sand units from the pure shale units but had difficulty with the combination sandy-shaly units, the data were regrouped into three classes: pure sand, pure shales, and "dirty" sandy-shaly units. The stepwise discriminant analysis program was run using these three classes and all eighteen variables (see fig. 11). The canonical plot showed good grouping even though a good separation was lacking. Here IP ratio, monazite, and IP were found to be the most important distinguishing variables.

A second run was performed using only the six geophysical variables on the same three classes. This resulted in a somewhat tighter grouping of the shales (see fig. 12). Here, IP ratio, resistivity, and IP were found to be the most important distinguishing variables.

Redox Discrimination - Sands Only

Finally, the sand data points were used exclusively and grouped according to their redox state. The data were grouped into three classes: altered, unaltered, and ore. When using all eighteen variables in the stepwise discriminant analysis the three groups were well separated and with the exception of a few altered data points they were grouped tightly (see fig. 13). The most important distinguishing variables were maghemite, gamma, and ilmenite.

When the six geophysical variables were used exclusively on the sands there was a good separation of the ore data points but a poor separation of the unaltered from the altered data points. The ore grouping was not as tight as when all eighteen variables were used (see fig. 14). Here, gamma, IP, and then SP single point proved to be the most important variables.

Irigaray Data

The irigaray data consisted of nine boreholes. The nine holes were drilled as three groups of three holes, each group ideally having one hole in the roll front, one hole on the altered side, and one on the unaltered side of the roll front (see fig. 15). Unfortunately, the holes were not spaced widely as at Bruni, but were spaced so closely that it is possible that there is no difference in the redox states between the holes.

A total of 1230 feet (375 m) of core were analyzed. This core included the ore bearing strata plus the units above and below the ore bearing strata. A minimum of 1440 feet (439 m) of core per hole were used. The strata consisted of sandstones, shales, conglomerates, and one thin coal seam.

The data used for statistical analysis were supplied by WMC. They consisted of six geophysical logs: gamma, SP dipole, SP single point, IP, IP ratio, and resistivity. Bulk mineral analysis was provided on: garnet, apatite, zircon, monazite, maghemite, ilmenite, epidote, amphibole, biotite, chlorite, and pyrite with two x-ray analyses: feldspar and clays. In total, there were nineteen variables recorded for each one foot (1/3 m) of core. These data were transferred to computer cards and used in analyzing the statistical parameters of the Irigaray data.

Redox Discrimination

The data were subdivided into four groups based on redox information provided by WMC. The four groups included: unaltered, altered, strongly altered, and mineralized. These four groups were then put through the stepwise discriminant analysis program. This was done to see if there was a significant difference in the parameters of each group such that the four groups were distinguishable. Since there was a great deal of overlap within the groups, the data were cleaned by removing the data points which the computer listed as in the altered and unaltered groups but which WMC had listed otherwise. At the same time the points which the computer gave high probability as being highly altered and mineralized were moved into their correct category.

After cleaning, a second stepwise discriminant analysis was run. This run represents the best distinction between groups that could be obtained and still retain the original grouping (see fig. 16).

All of the above Irigaray runs had been made using nineteen variables. Next, the stepwise discriminant analysis was run on the cleaned data using only the six geophysical variables to determine the usefulness of geophysics in determining the redox state of each sample. Figure 17 shows the plot of this run. There is extreme overlap among the four groups. The low F values indicate very little difference between the classes.

Irigaray 9S

The data from the nine Irigaray holes were not giving good canonical plots as the Bruni data had. This could be because the data did not actually represent three distinctly different redox states because the holes were drilled so close together. After reexamining the position of the nine holes with respect to the roll front, it was decided to reexamine the data using only three holes: 9-1, 9-2, and 9-3 (see fig. 15), because these holes showed a greater spacing between each other and the altered hole and unaltered hole were located further from the roll front.

Using holes 9-1, 9-2, and 9-3, the data were again grouped according to redox states. A stepwise discriminant analysis was run using all nineteen variables (see fig. 18). The canonical plots showed some distinction between redox groups. Unfortunately, this plot looked very similar to the first redox run using all nine holes. But here, the three most important variables were listed as resistivity, biotite, and zircon.

Since this run did not show any improvement, the data from the three holes were regrouped according to the original redox states given by WMC. The previous Irigaray runs were based on the second redox states given by WMC.

The canonical plot seen in fig. 19 resulted from using the nineteen variables on the original redox groupings of holes 9-1, 9-2, and 9-3. Here, there is a stronger distinction between the redox groups, even though the grouping is not as tight as in the Bruni data. Clay, apatite, and epidote were the most important distinguishing variables.

The canonical plot using just the geophysical variables showed no distinction between redox states.

Hole Discrimination

Next, the data from the three holes were regrouped according to the three holes so that a stepwise discriminant analysis could be run to see if there was a distinction between the three holes. Figure 20 is the canonical plot of this run using all nineteen variables. It shows that there is a difference between the holes. The most important discriminating variables were feldspar, SP single point, and SP dipole.

Lithology Discrimination

Finally, the data from the three holes were grouped according to lithologies: shale, sandstone, and conglomerate. The canonical plot using the nineteen variables shows a distinction between the shale and the sandstone conglomerate units. It also shows an overlap between the sandstone and conglomerate (see fig. 21). Here, garnet, SP single point and biotite were the most important variables.

Evaluation

The Bruni data gave good canonical plots of the redox states. The plots showed tight grouping and distinct separation between groups. Even when using the geophysics alone a distinction could be seen.

However, the Irigaray data did not give the same good plots. The plots were improved somewhat when using the three boreholes and by using the original redox grouping given by WMC. But, the plots did not show a good distinction in redox states. However, when grouped according to borehole or lithologies good plots resulted. Therefore, this suggests that either there is no difference in redox states or that the mineralization in the Irigaray area is more complex.

Lamprecht Data

The Lamprecht, Texas, data consist of ten boreholes (hole 11 was not used) traversing the known roll front as shown on fig. 22. Five holes are in close proximity to the roll front (4, 5, 6, 7, and 8), three holes are above the roll front (1, 2, and 3), and two are below it (9 and 10).

A total of 430 feet (131 m) of core log data were analyzed. Geophysical log data were averaged over one-foot (1/3-m) intervals to correspond to the analysis of the core. The geophysical data were the same as those used for the other sites. The bulk mineralogy and other lab data which were available for analysis at this site include: pyrite, limonite, hematite, garnet, zircon, monazite, apatite, rutile, tourmaline, magnetite, ilmenite, biotite, clay lights, weight heavies, weight pyrites, clay, molybdenum, selenium, magnetic susceptibility, and calcite.

Hole Discrimination

The data were separated first according to the ten holes to be analyzed. The hole discrimination results using all 26 variables are given in fig. 23. Although a great deal of apparent overlap between the holes is indicated by fig. 23, the classification results using all 26 variables were very good. In general, the errors in classifying data by holes were in the order of 10 to 20 percent except for hole 2 which had 50 percent of its data classified as being from hole 1.

The most important variables for hole discrimination were (in the order of their importance) IP ratio, SP dipole, gamma, pyrite, selenium, limonite, clay lights and monazite. All other variables were of too little significance to be of any consideration.

Next, the six geophysical variables were used for hole discrimination and the two-dimensional canonical plot for this analysis is given in fig. 24. More overlap between the hole classes is obvious and we found that the actual classification accuracies were very greatly degraded, with correct classifications ranging from less than 50 percent to as high as 90 percent. It was particularly interesting to note that hole 2 was no longer confused with hole 1 when only the geophysical variables were included for discrimination. Figure 25 shows the canonical plot of the data samples when pyrite was added to the five best geophysical variables. A general improvement in classification accuracies resulted from the addition of pyrite but the improvement was not significant. Perhaps of greatest interest is the fact that now 50 percent of the data from hole 2 are again classified as being from hole 1. It is apparent, therefore, that the pyrite data is actually causing confusion in the hole classifications between holes 1 and 2.

The data were then divided into three redox classes which were designated as being unoxidized, oxidized and high uranium (ore). We should stress that there was really apparently very little difference in the oxidation characteristics of the core samples and that only seven feet (2 m) of core were indicated as being highly oxidized. These data were first classified using all 26 variables. The classification results were very good, with only seven feet (2 m) of the 378 feet (115 m) of unoxidized data being misclassified as high uranium. All of the seven feet (2 m) of oxidized data were correctly classified and three feet (1 m) of the 45 feet (14 m) of high uranium data were misclassified as being unoxidized. This is consistent with the very tight, well-separated groupings of the data shown on fig. 26. The most significant variables for the redox classification were pyrite, clay lights, zircon, gamma, apatite, and ilmenite. The highest F value for these variables was 212.

The data were then classified using only the six geophysical variables with the results shown on fig. 27. Obviously, there is now a great deal of confusion between the three redox classes. For instance, 111 feet (34 m) of the 378 feet (115 m) of unoxidized data were now classified as being oxidized. Considerable improvement was noted when pyrite was added to the five best geophysical variables, but a plot of these results is not available for display.

The poor results obtained for the Lamprecht site up to this point, along with relatively low correlation between variables (compared to the other sites) suggested that perhaps the core and geophysical log footages were not well correlated. To investigate this possibility, the one-foot (1/3-m) data were averaged over three-foot (1-m) intervals and then subjected to the same analyses described for the one-foot (1/3-m) data. From a comparison of fig. 23 and fig. 28, it is obvious that the data for the holes are now in more compact groups with greater separations between the groups. The classification results, however, were not significantly better. The most significant variables were essentially the same, but their F values were considerably reduced. This reduction in F values is somewhat surprising considering the comparison between the plots on fig. 23 and fig. 28.

Figure 29 shows the redox classification plot for the 3-foot (1-m) averaged data using all 26 variables. Again, the best variables are essentially the same and in this instance the F values for both the 1-foot (1/3-m) and 3-foot (1-m) data are relatively unchanged. The classification results for these 3-foot (1-m) averaged data were perfect. That is, all data for the three redox groups were correctly classified. No further analysis on these data was undertaken because the correlations between variables were not significantly affected by the averaging. This would tend to indicate that the original data were properly correlated relative to depth positions.

Conclusions

The analysis of the data for Bruni, Texas, is far superior in terms of the significance of the results and the behavior of the variables and the groups of classes. It is unfortunate that the data at Irigaray were all obtained from holes very close to the roll front and that the data from Lamprecht, Texas, were obtained in an area having a very confusing oxidation characteristic. Despite these difficulties, the multivariate analysis of geophysical and mineralogical data appears to be a very powerful tool for obtaining a greater understanding of the geologic, geophysical and mineralogical status of a region.

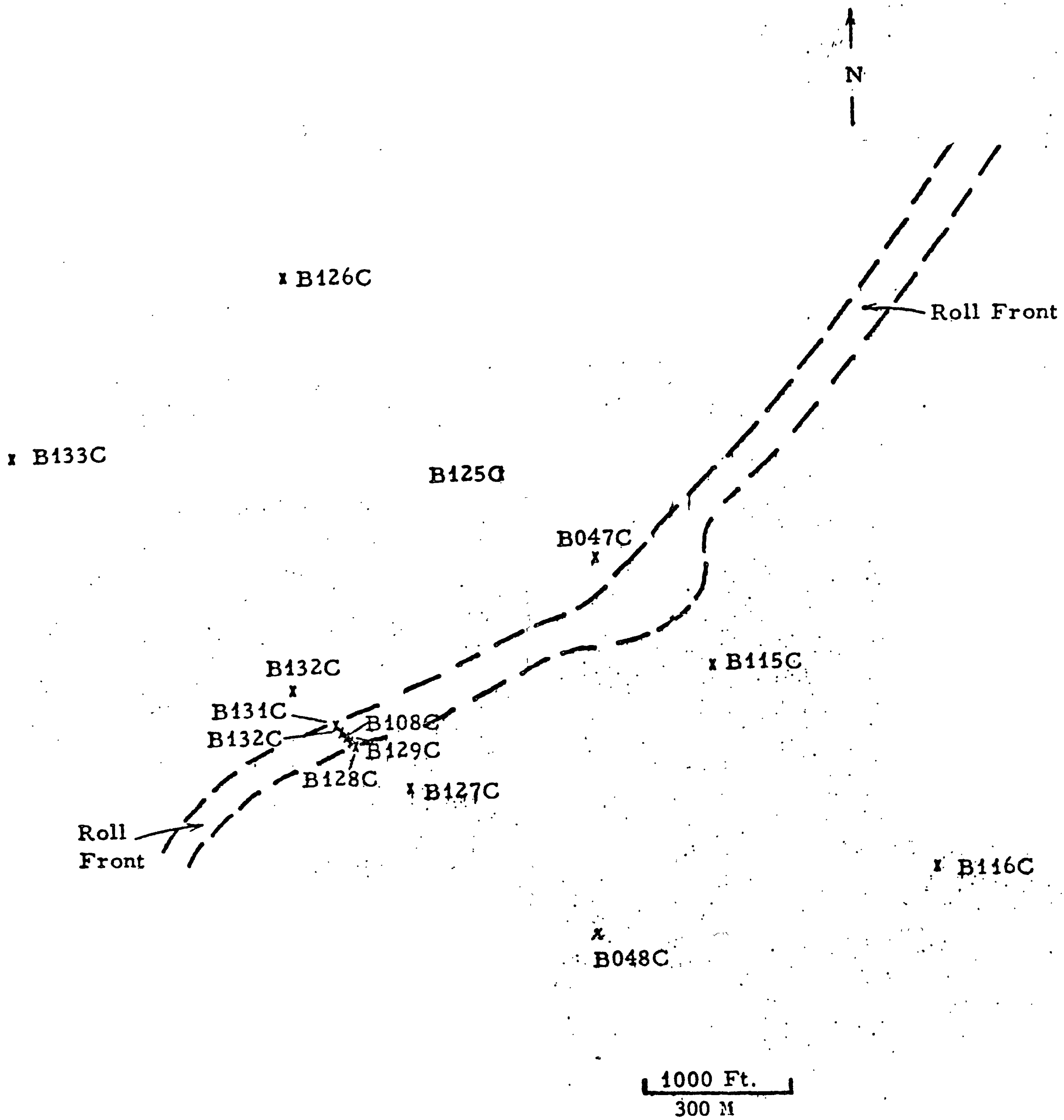


Figure 1 Location of Drill Holes - Bruni, Texas. Data analyzed for holes B126C, B125C, B047C, B115C and B116C. Information on exact location withheld.

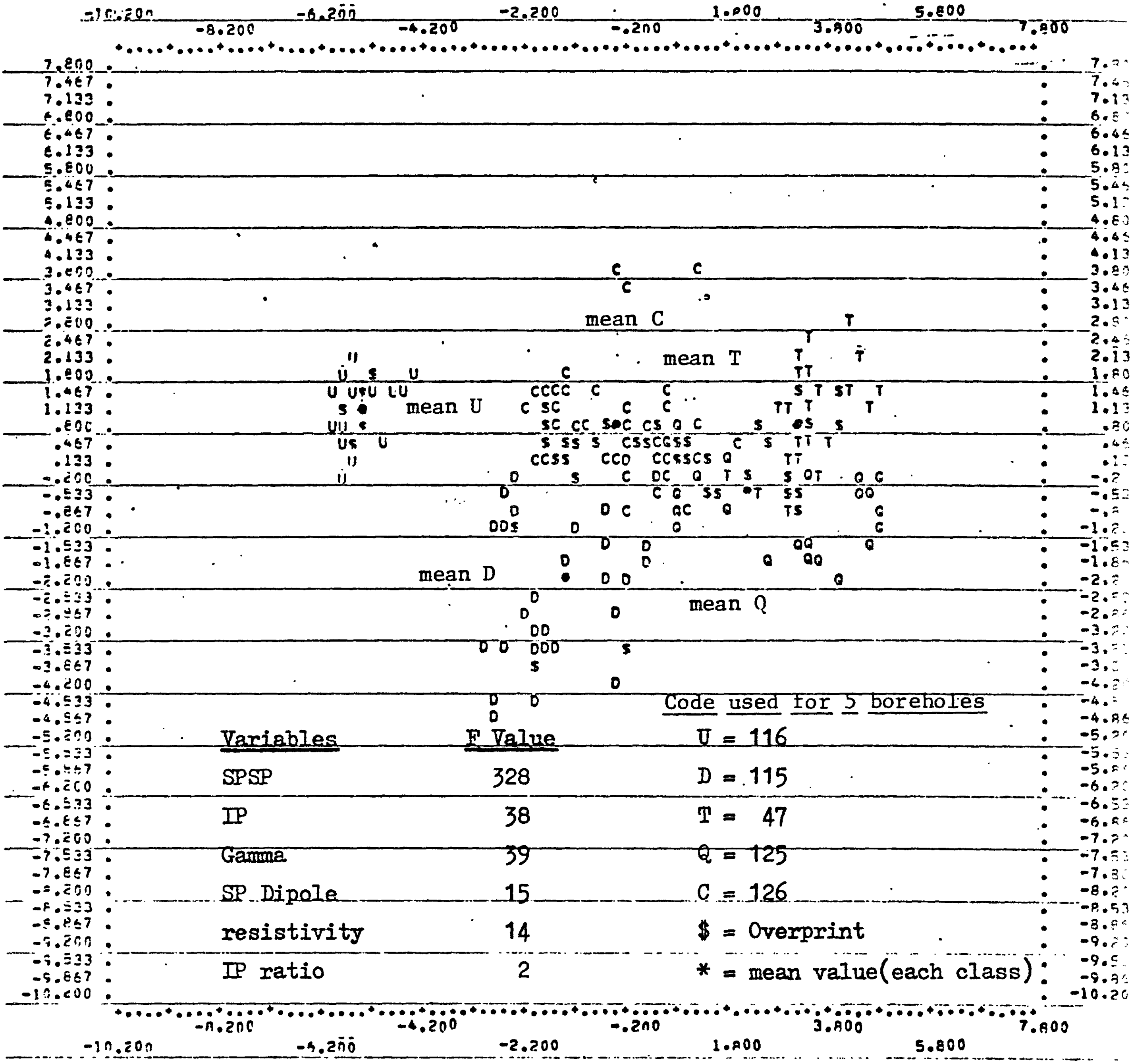


Figure 2 - Hole Discrimination at Bruni, Texas using the 6 log variables.

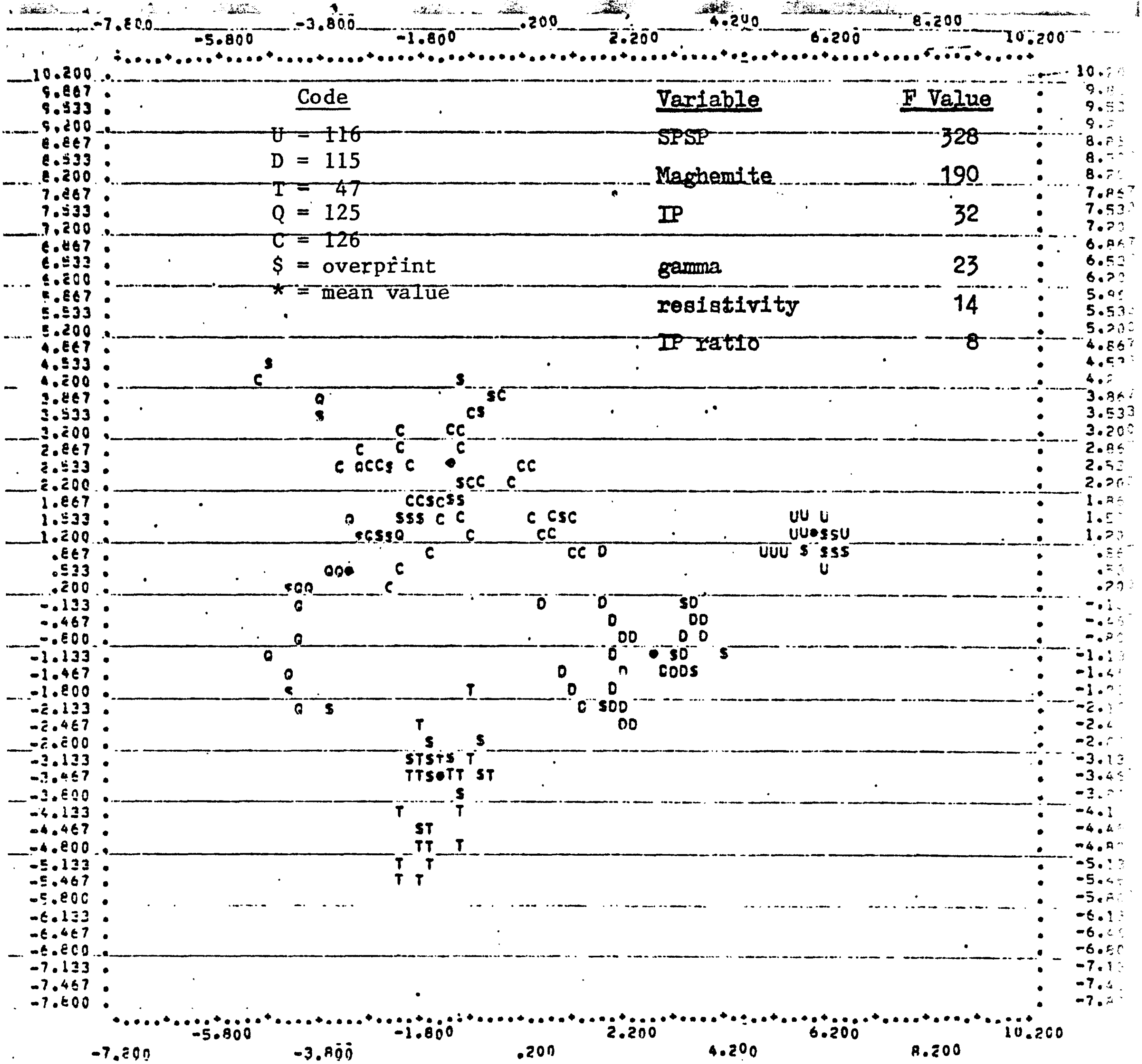


Figure 3 - Hole Discrimination at Bruni, Texas using 5 log variables and maghemite.

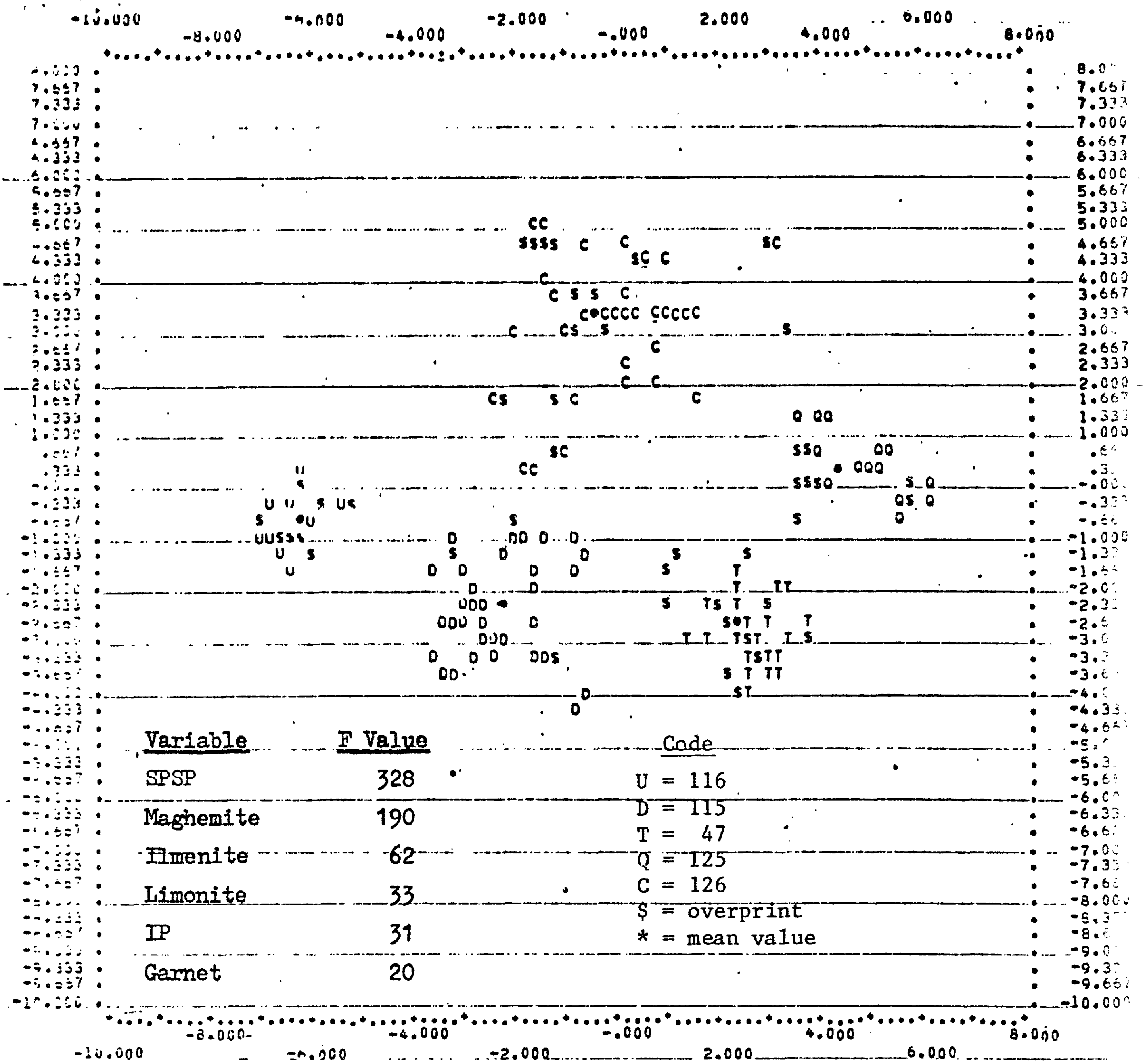


Figure 4 - Hole Discrimination at Bruni, Texas using the best 6 variables.

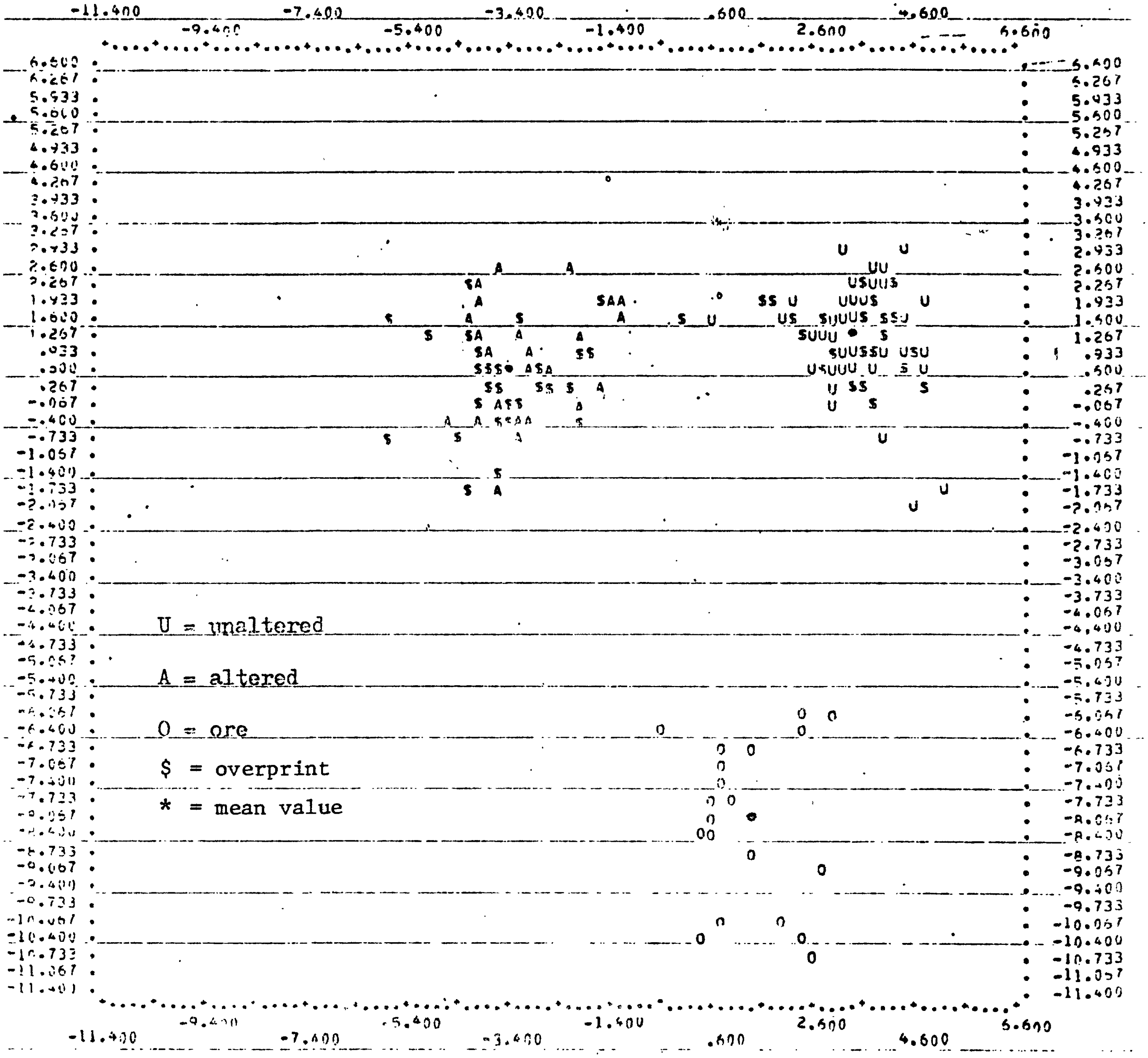


Figure 5 - Redox Discrimination at Bruni, Texas using all 18 variables.

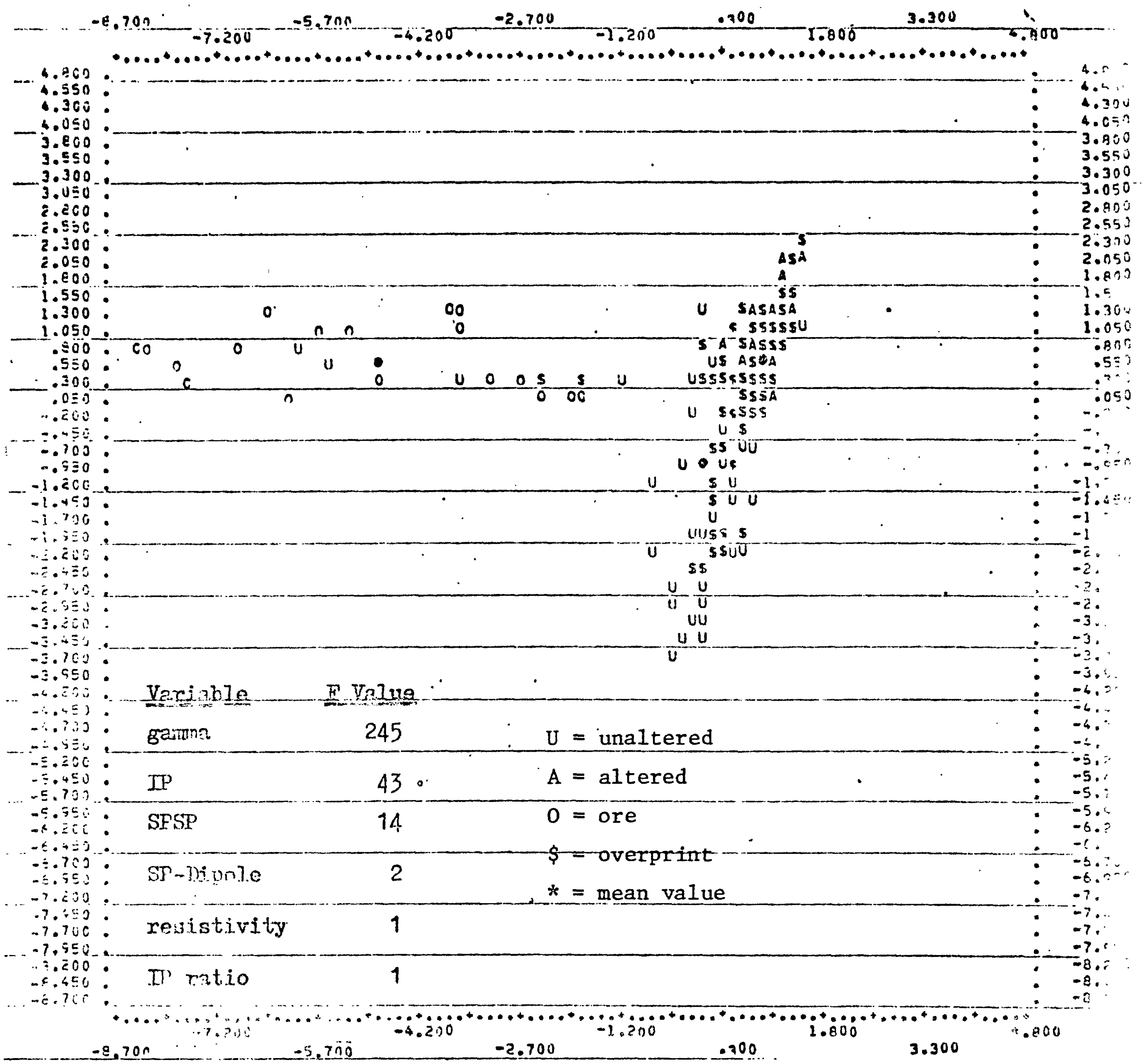


Figure 6 - Redox Discrimination at Bruni, Texas using the 6 log variables.

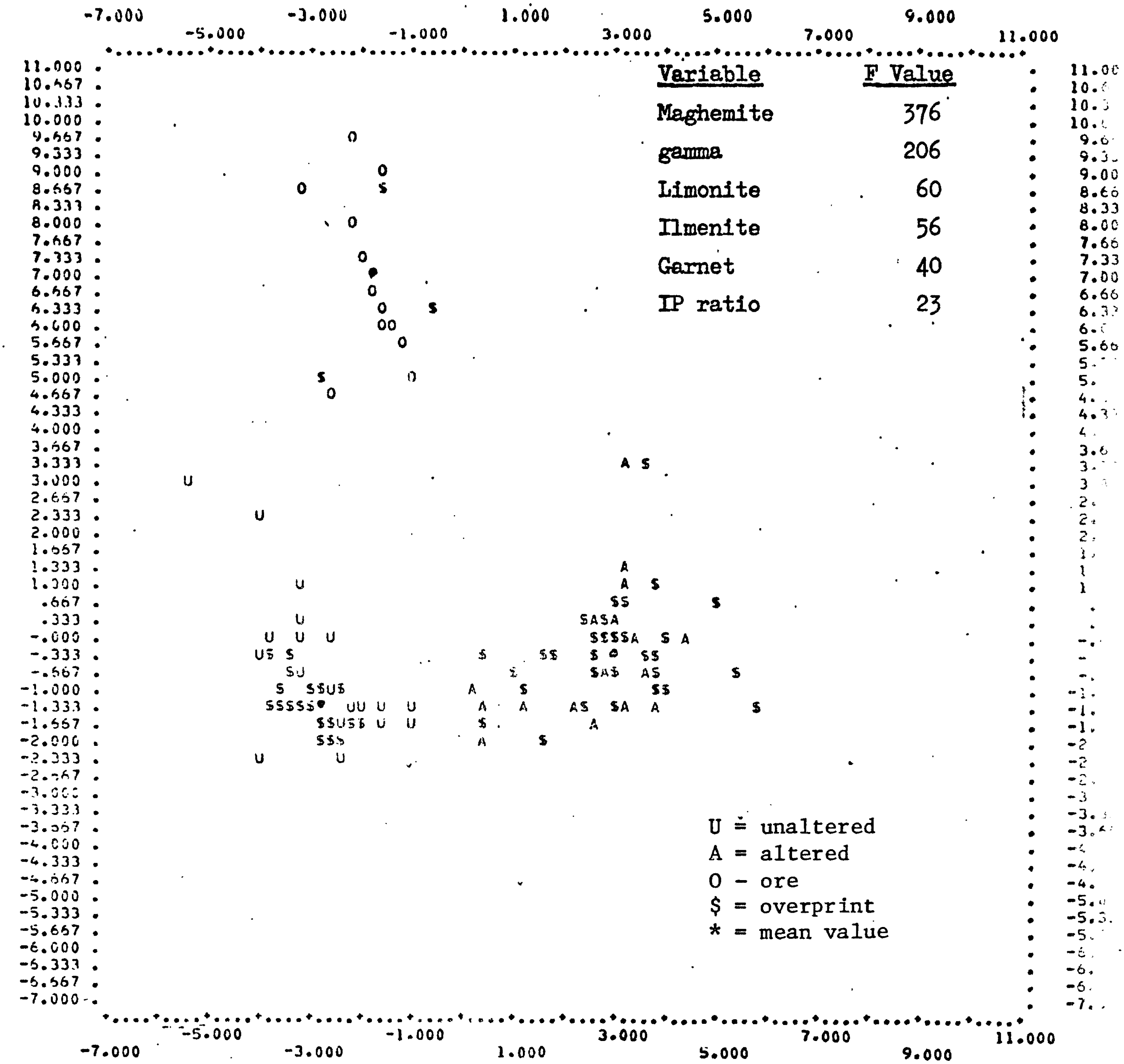


Figure 7 - Redox Discrimination at Bruni, Texas using the 6 best variables.

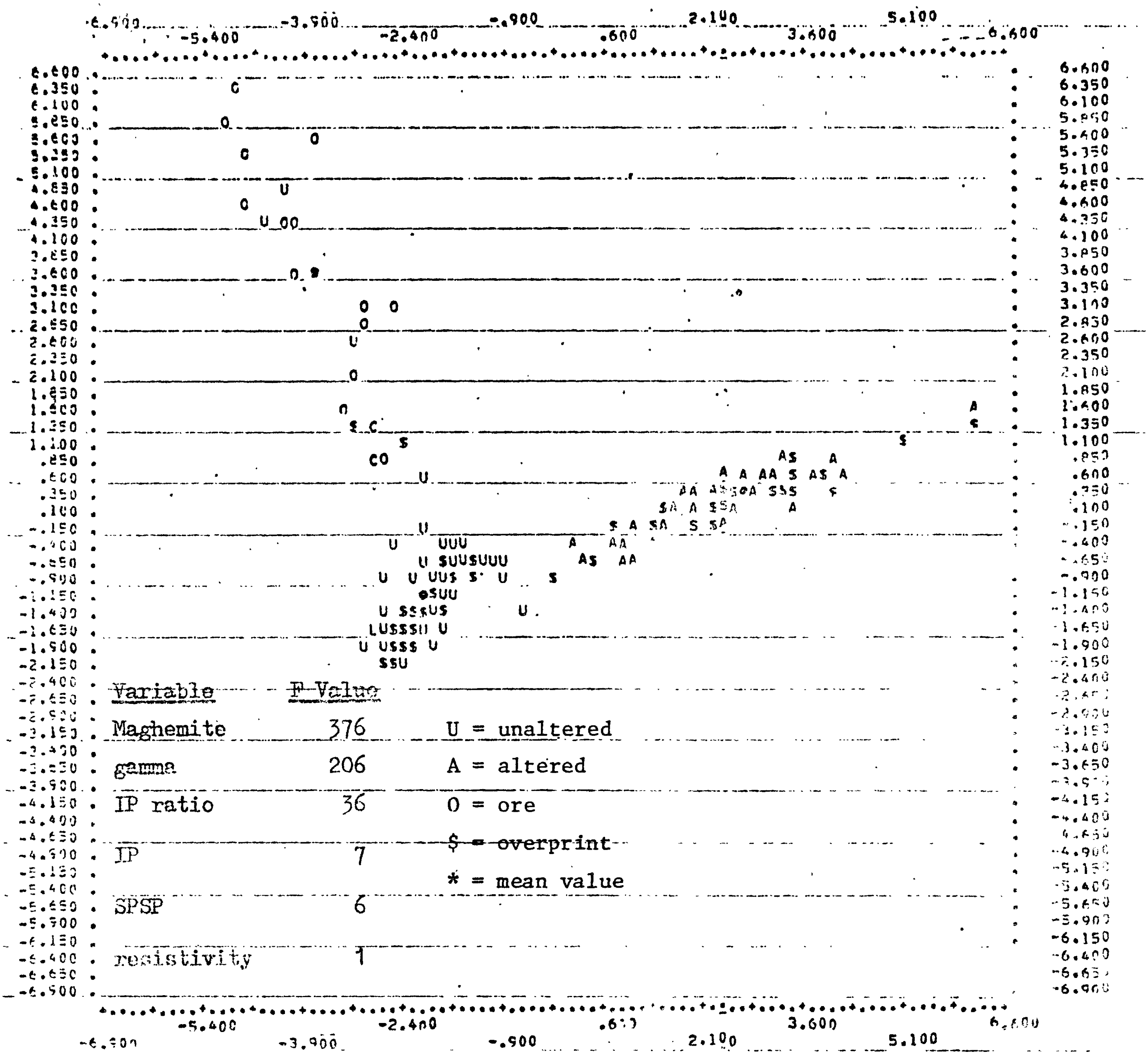


Figure 8 - Redox Discrimination at Bruni, Texas using 5 log variables and Maghemite.

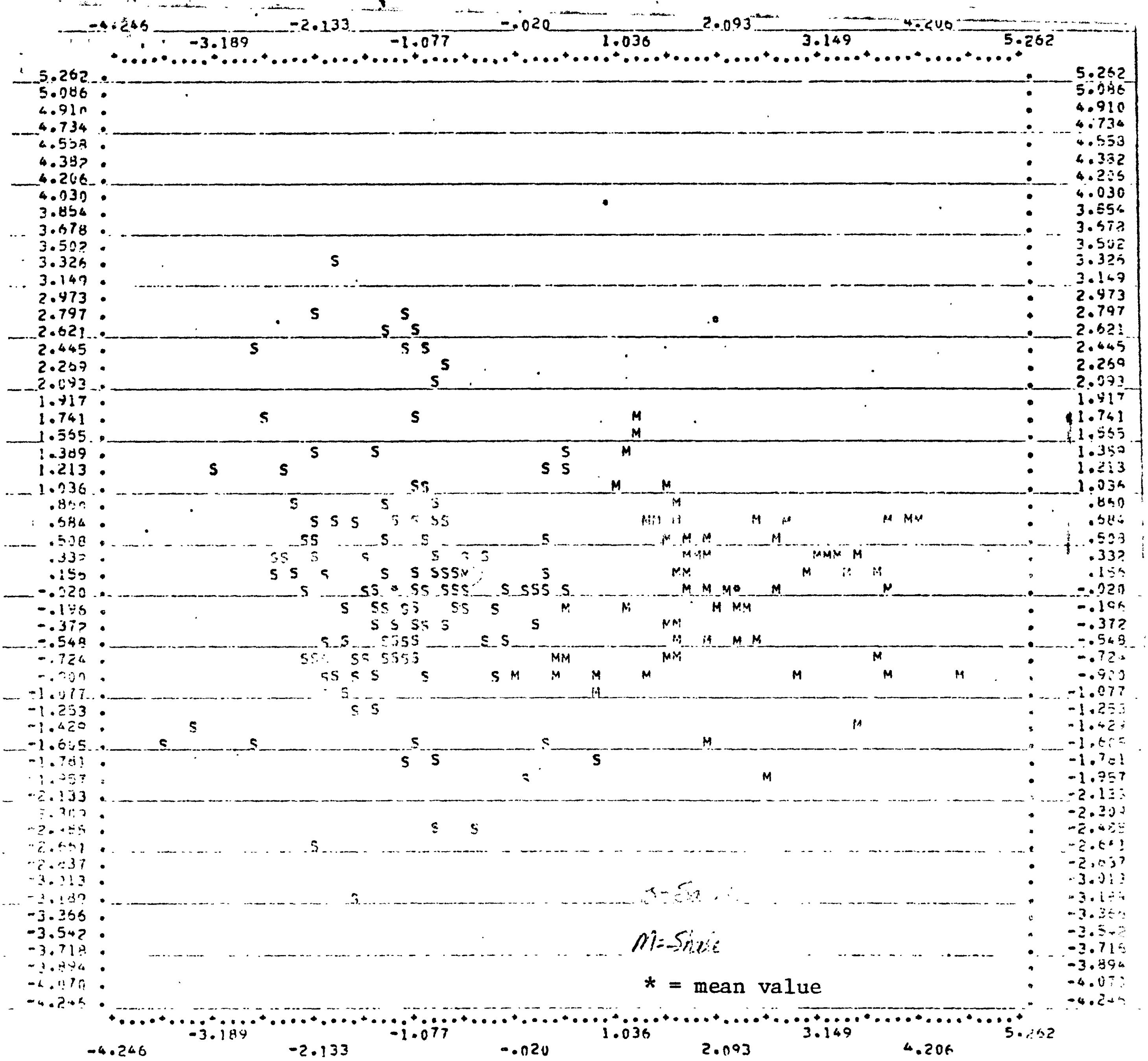


Figure 9 - Sand and Shale Discrimination at Bruni, Texas using all 18 variables.

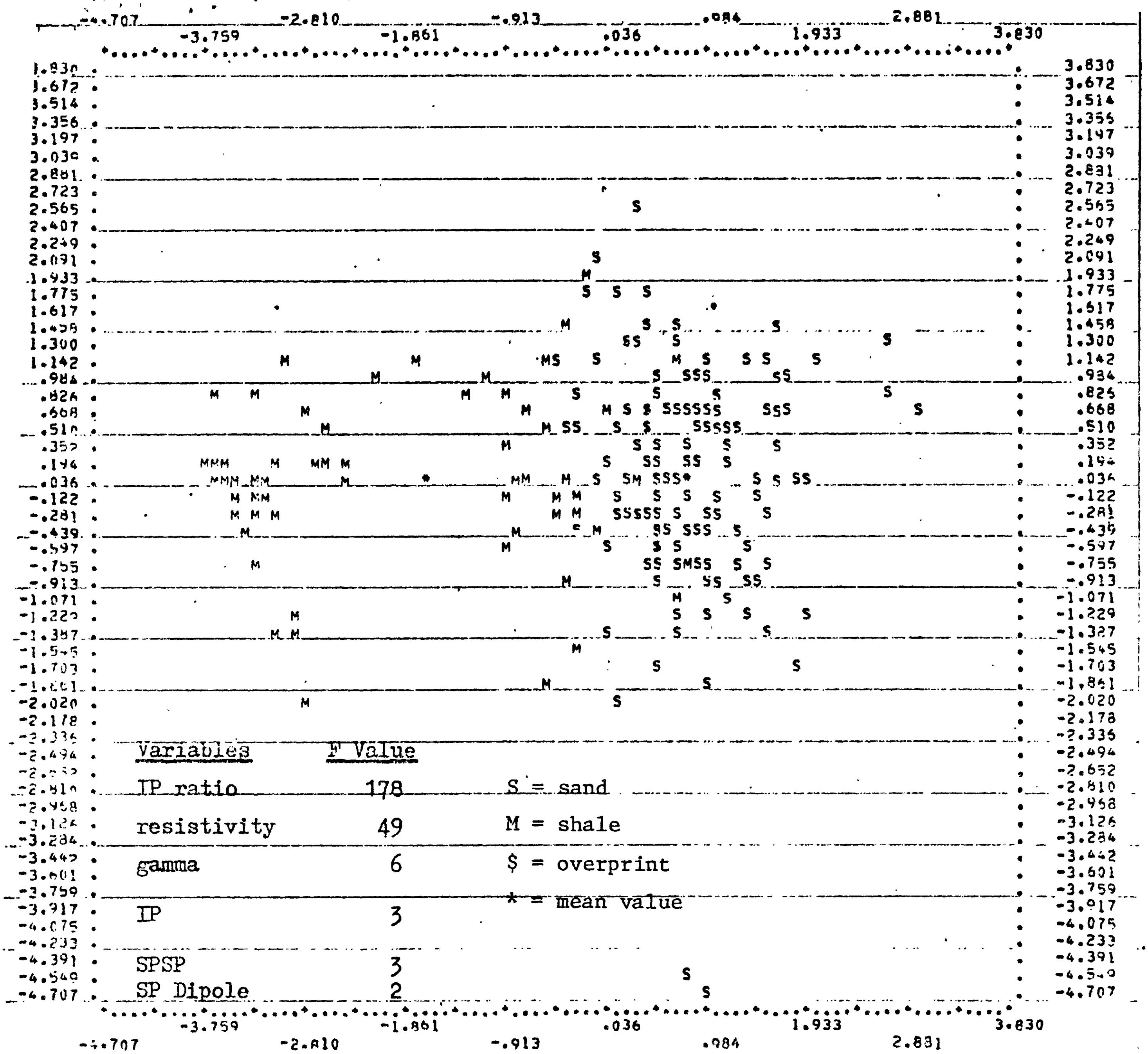


Figure 10 - Sand and Shale Discrimination at Bruni, Texas using the 6 geophysical variables.

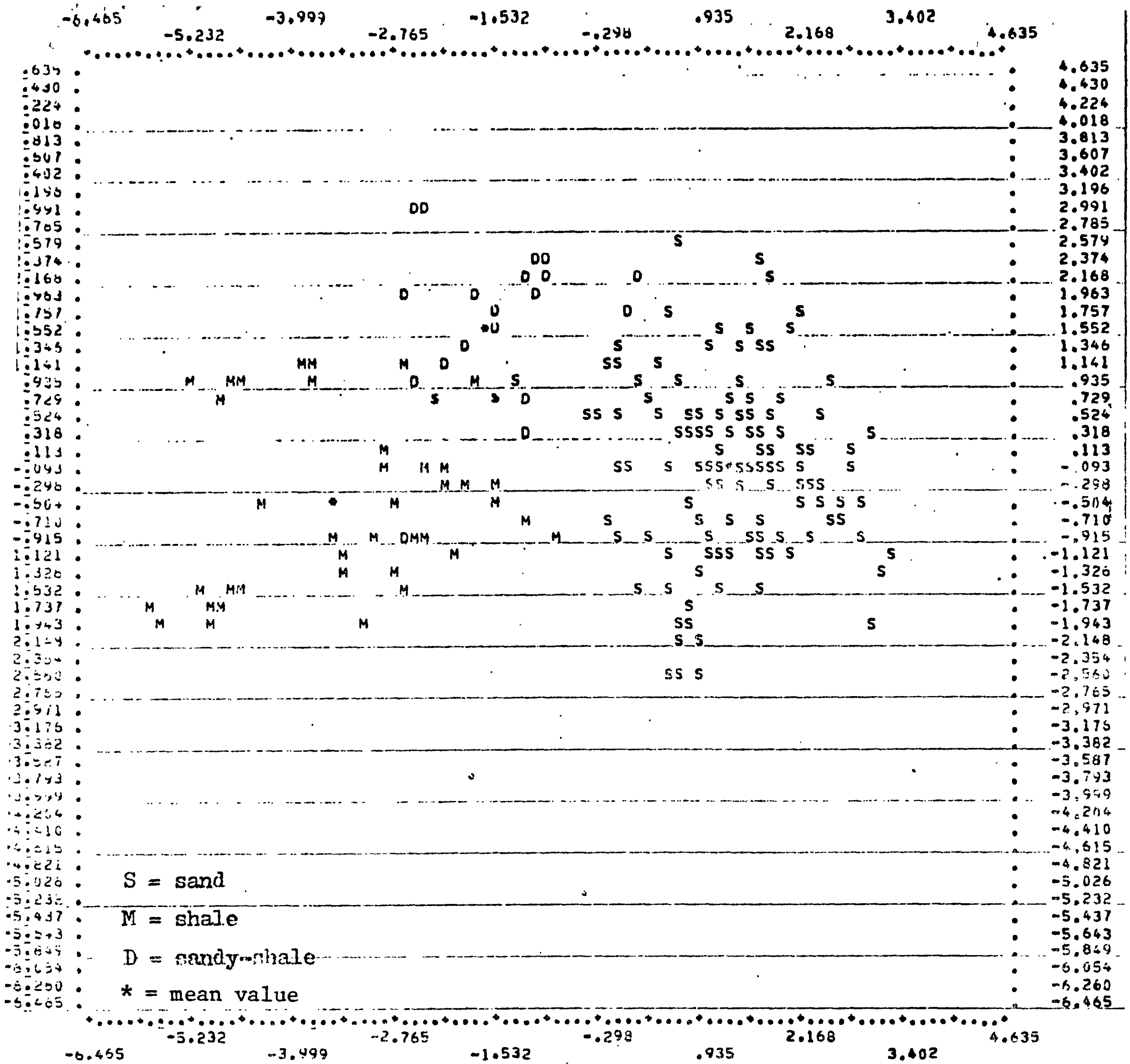


Figure 11 - Sand, Shale and Sandy-Shale Discrimination at Bruni, Texas using all 18 variables.

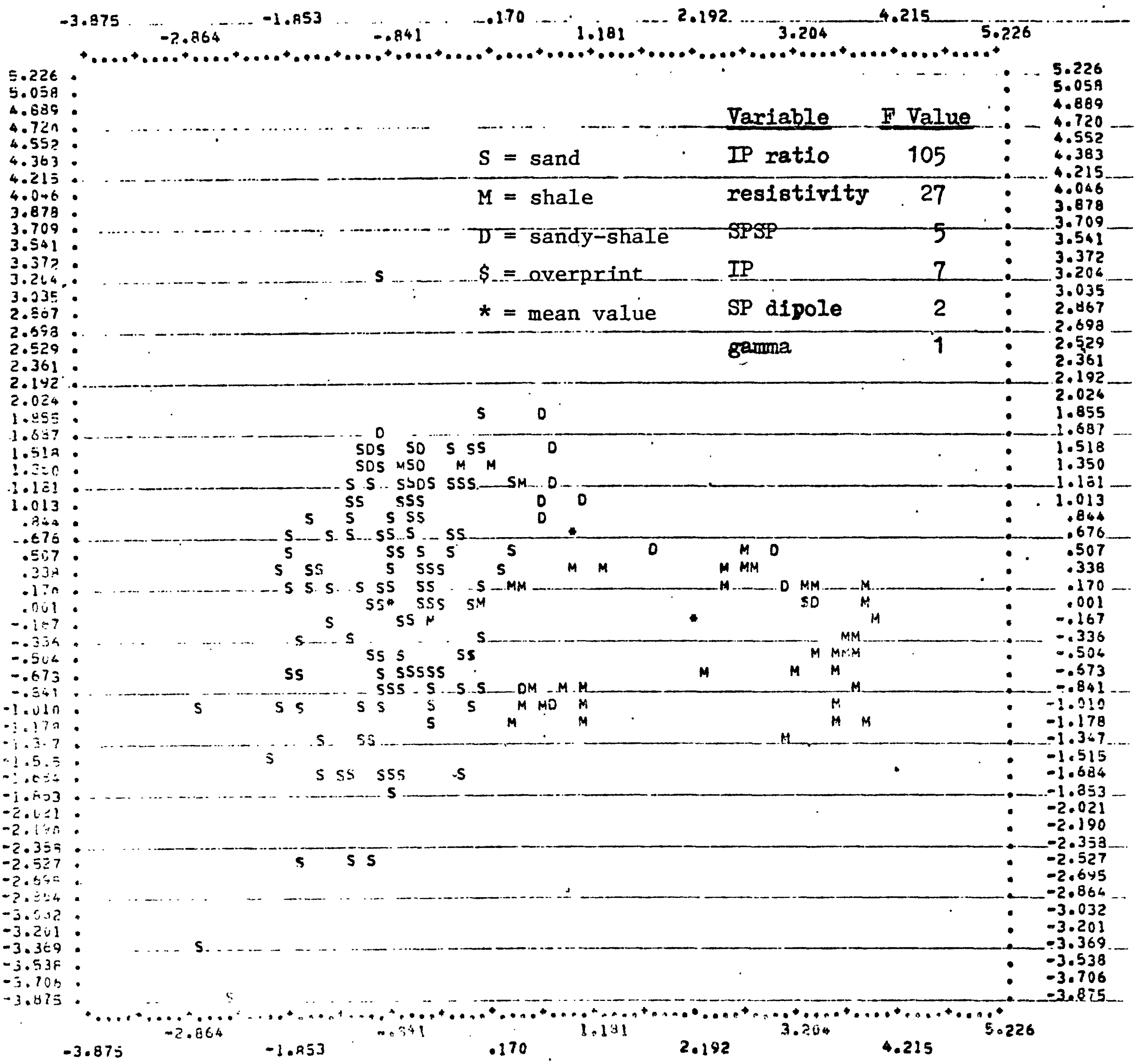


Figure 12 - Sand, Shale and Sandy-Shale Discrimination at Bruni, Texas using only the 6 geophysical variables.

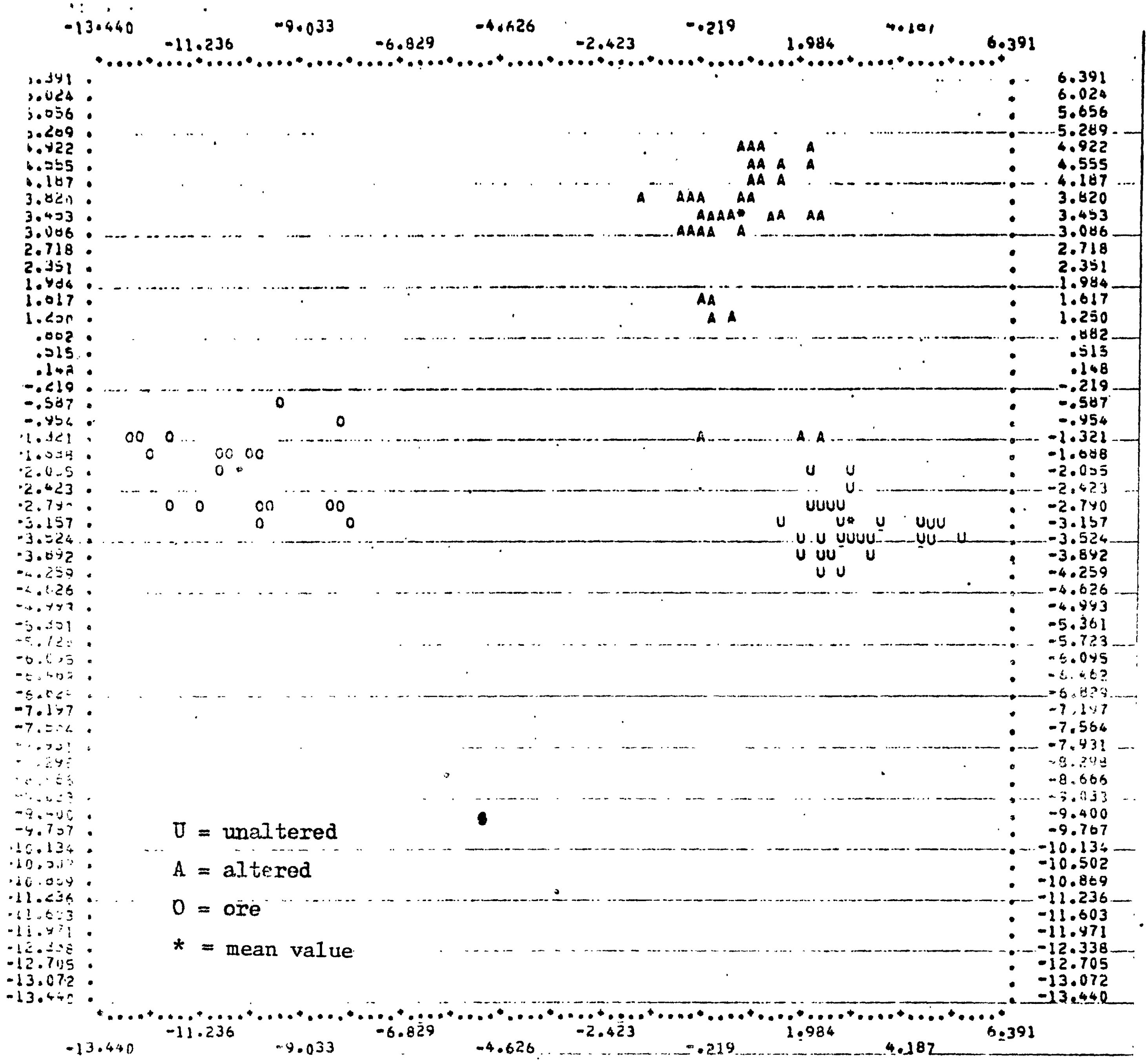


Figure 13 - Redox Discrimination at Bruni, Texas using only data from sand section - all 18 variables.

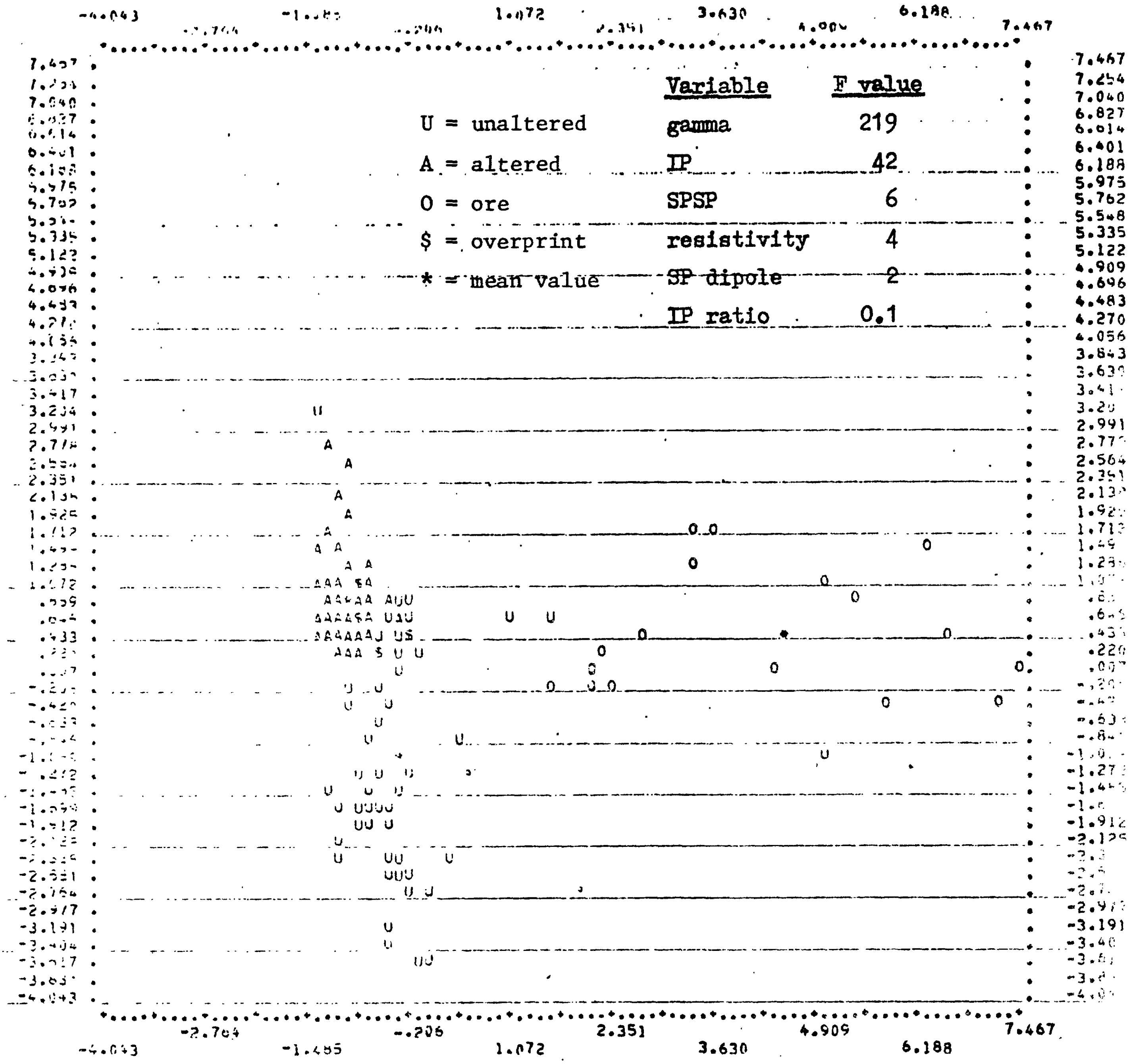


Figure 14 - Redox Discrimination at Bruni, Texas using only data from sand section - 6 geophysical variables.

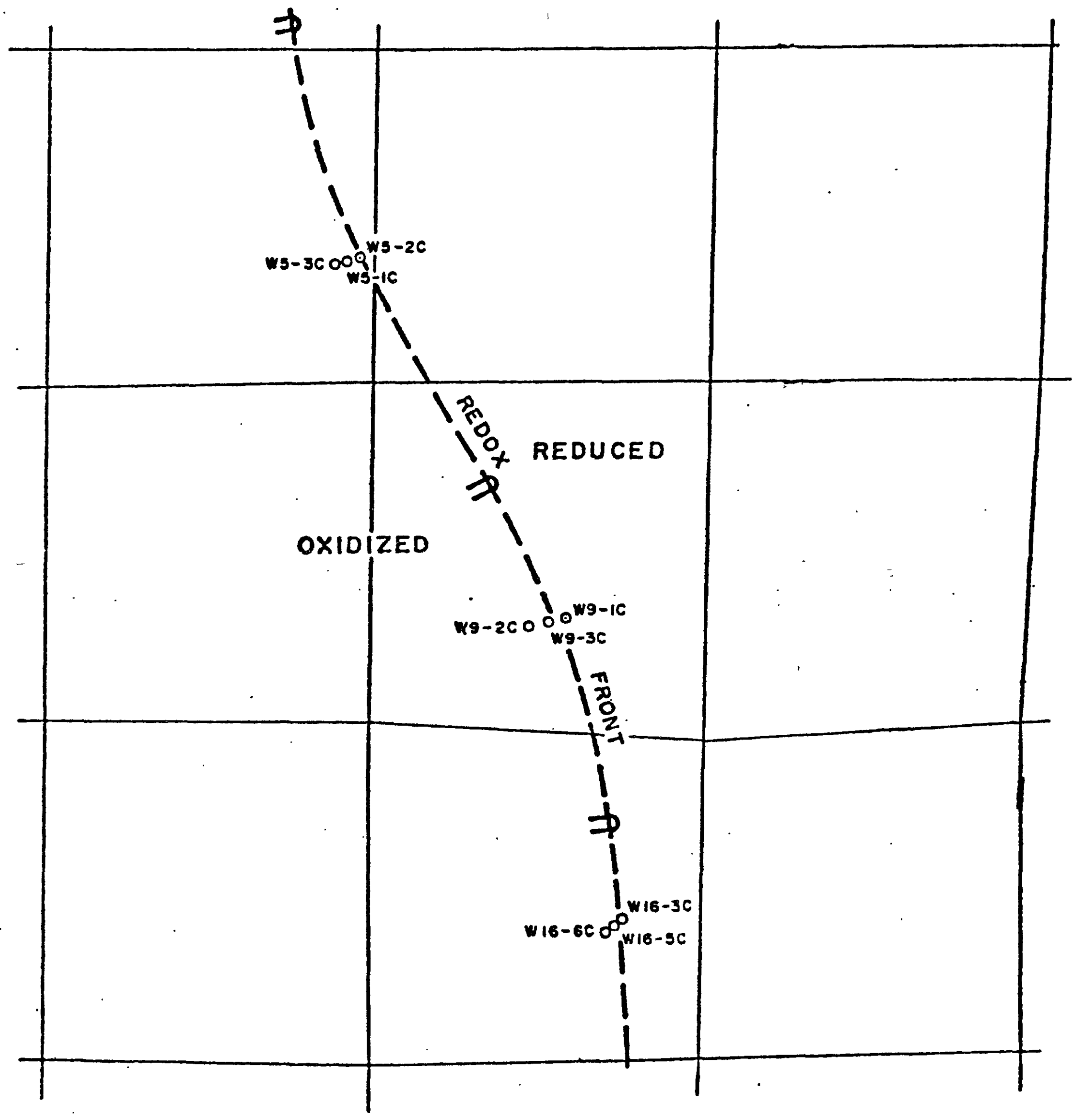


FIGURE 15 LOCATION OF CORE HOLES DRILLED TO SAMPLE THE IRIGARAY-HOE ROLL FRONT. Exact location information withheld.

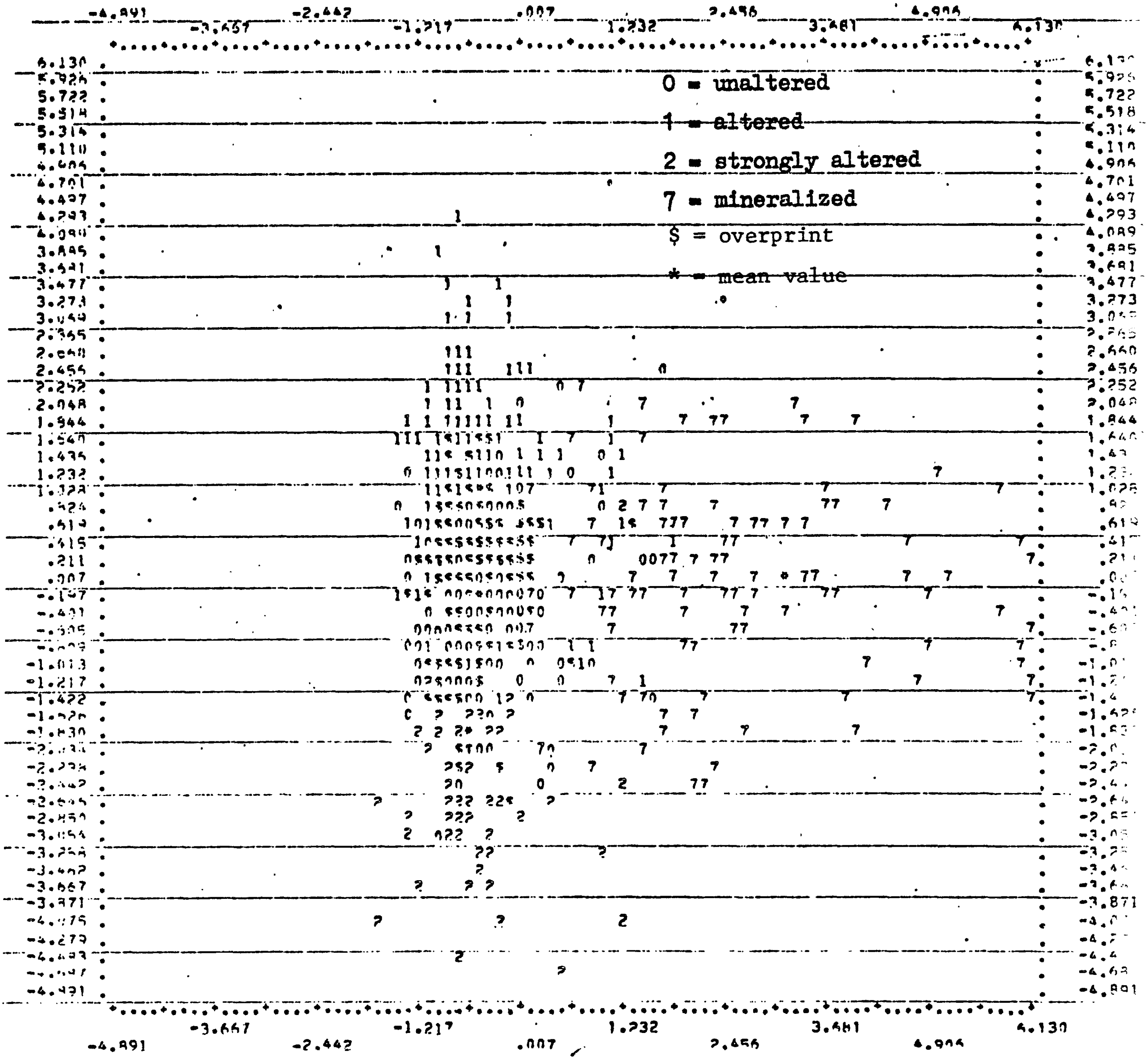


Figure 16 - Redox Discrimination at Irigarayusing all 19 variables.

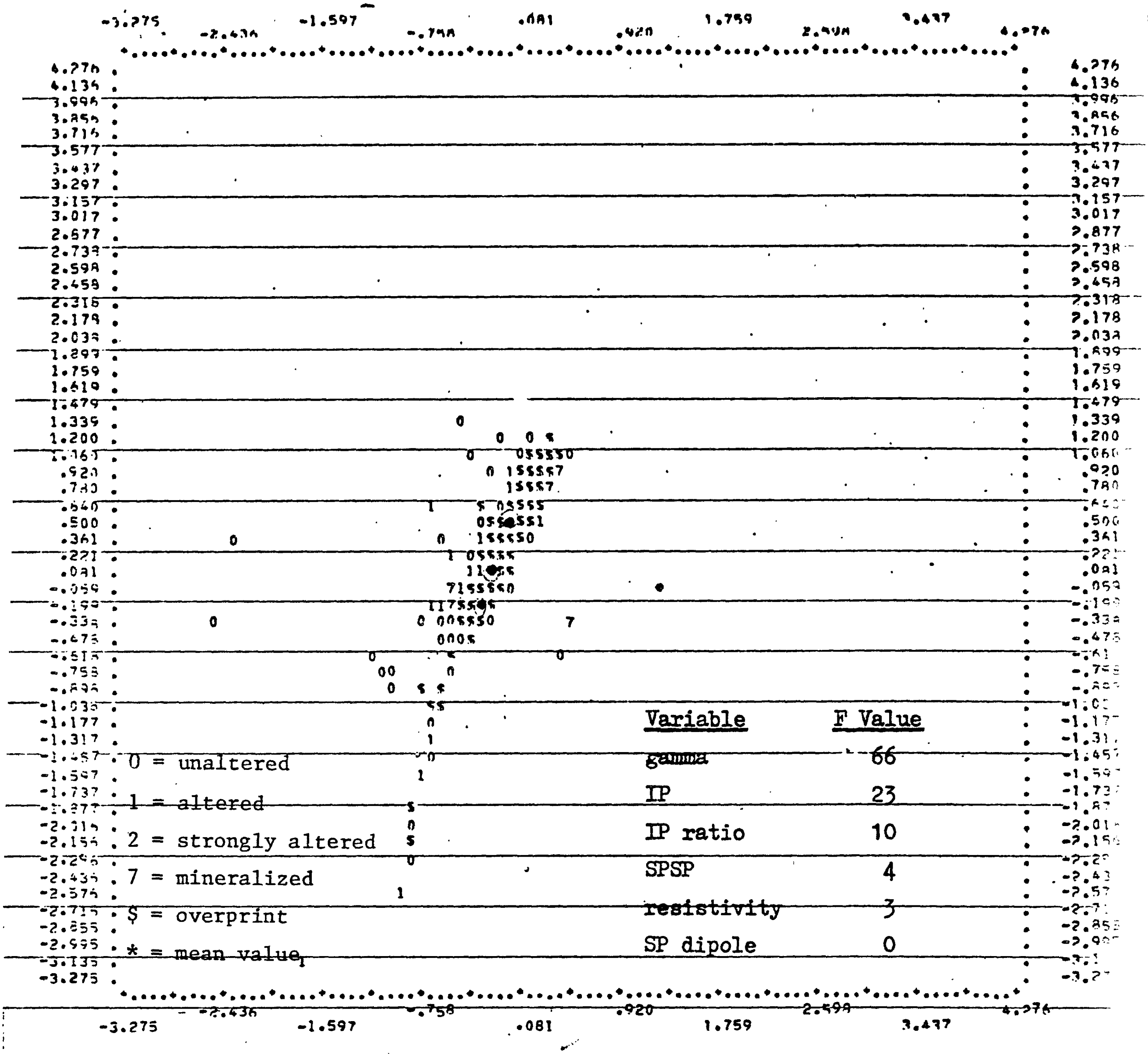


Figure 17 - Redox Discrimination at Irigaray using 6 log variables.

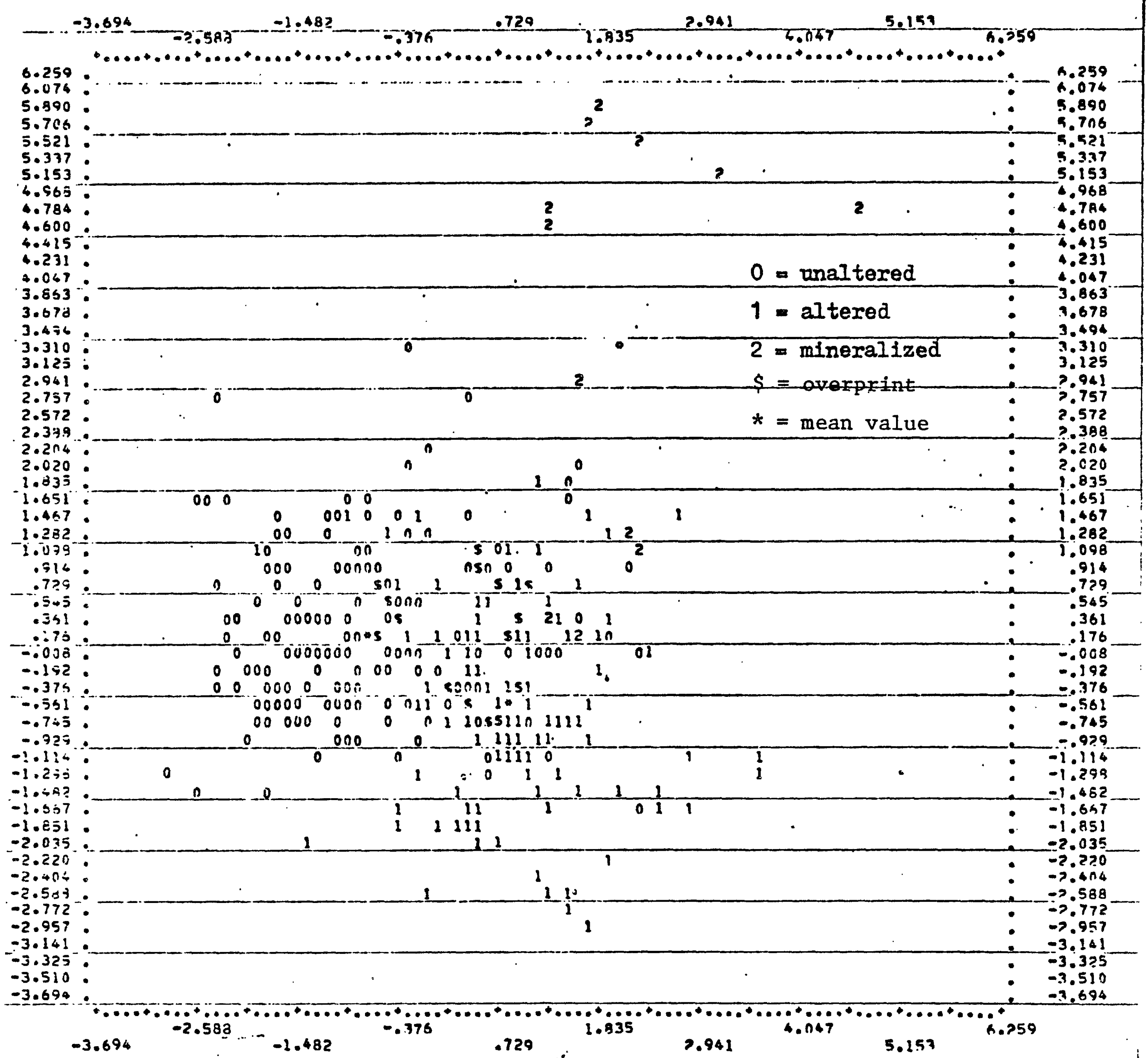


Figure 18 - Redox Discrimination at Irigaray for only 3 holes, using all 19 variables.

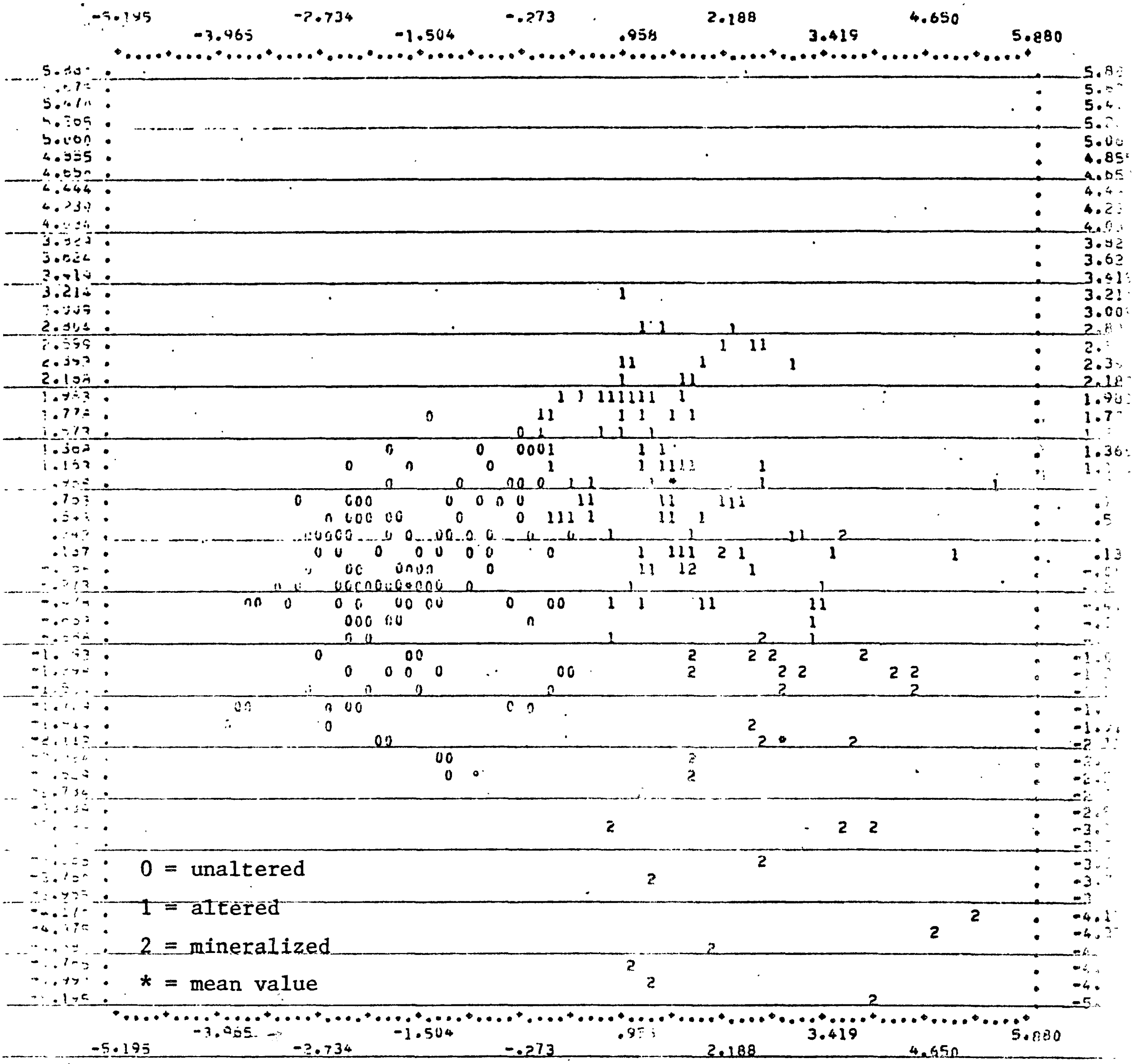


Figure 19 - Redox Discrimination at Irigaray for only 3 holes, using all 19 variables. For original designation of redox states.

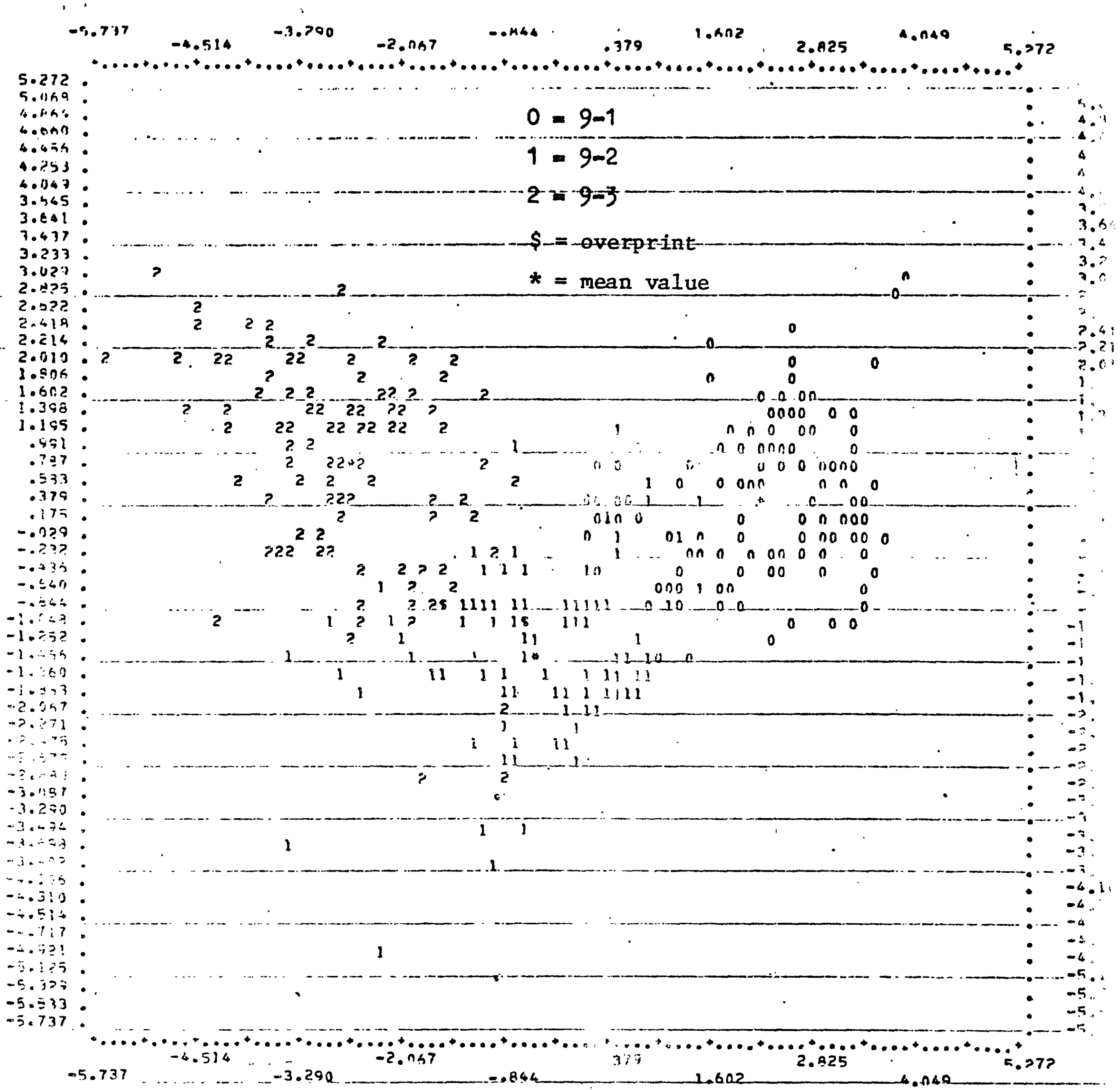


Figure 20 - Hole discrimination at Irigaray using all 19 variables.

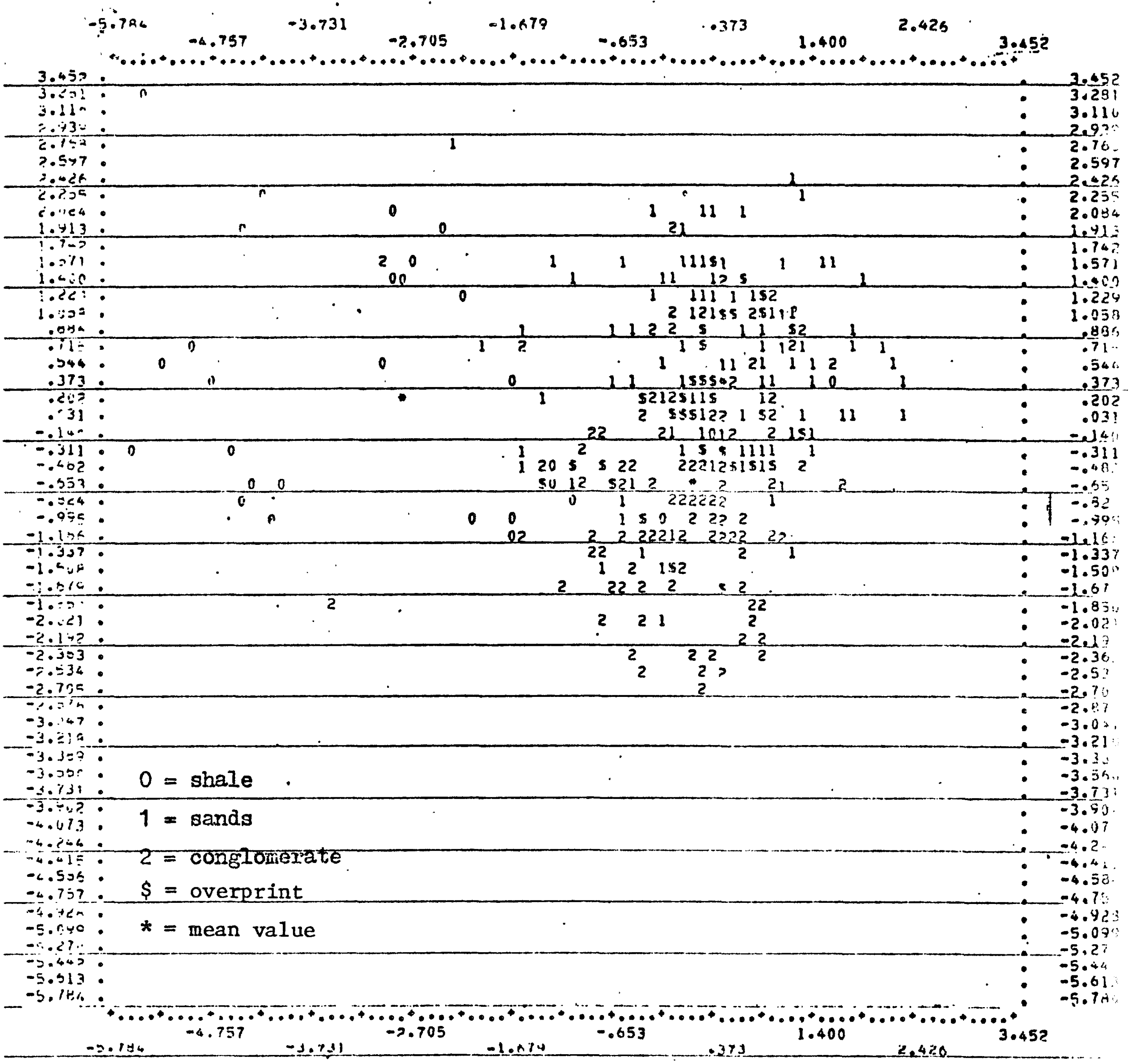


Figure 21 - Lithology discrimination at Irigaray using all 19 variables.

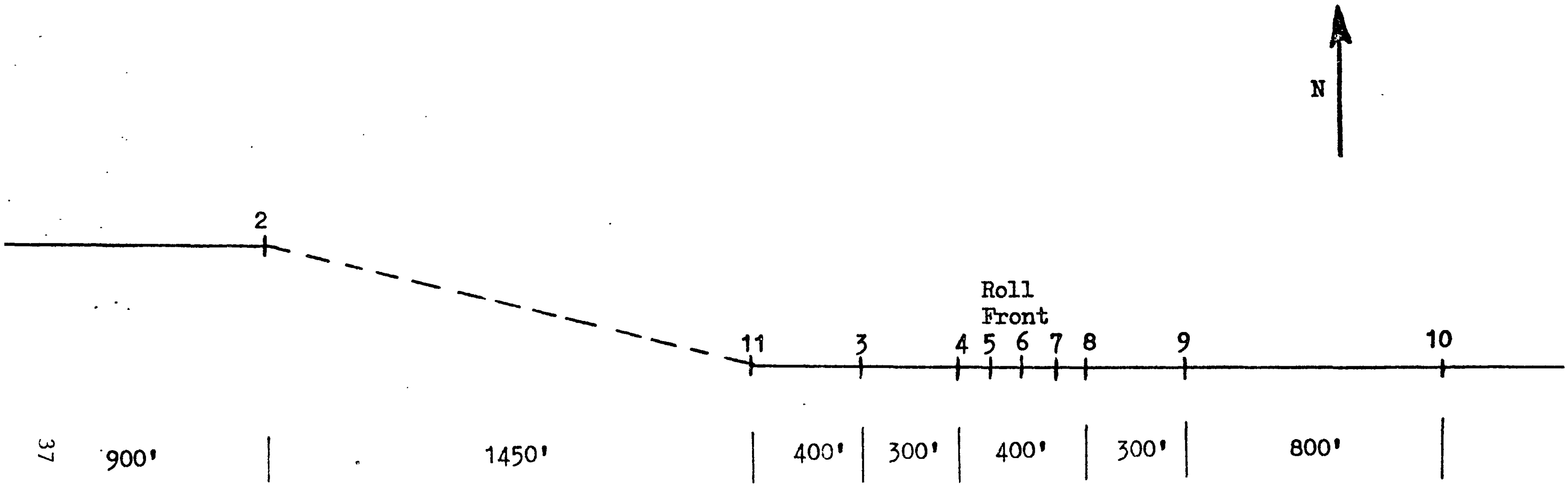
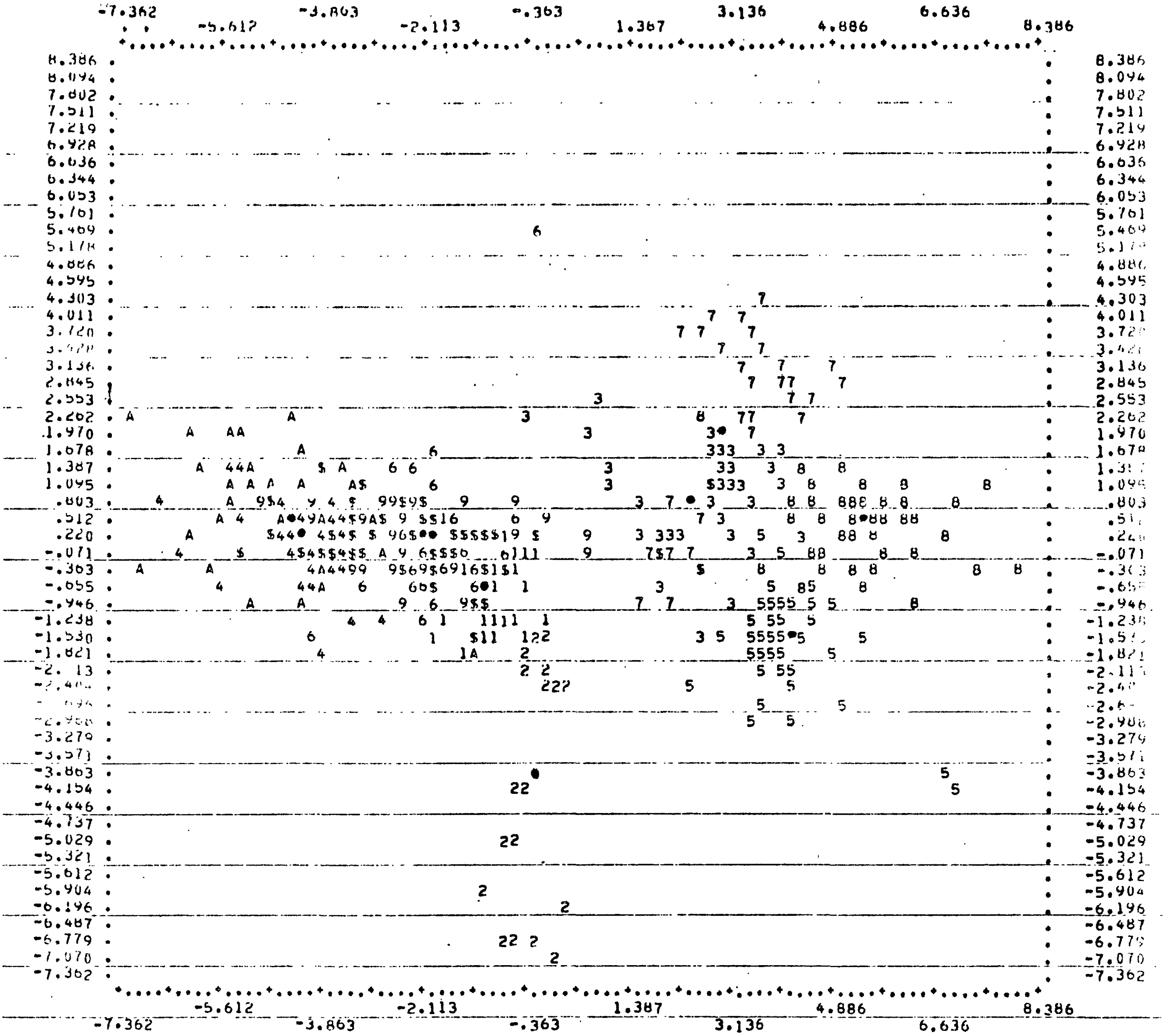
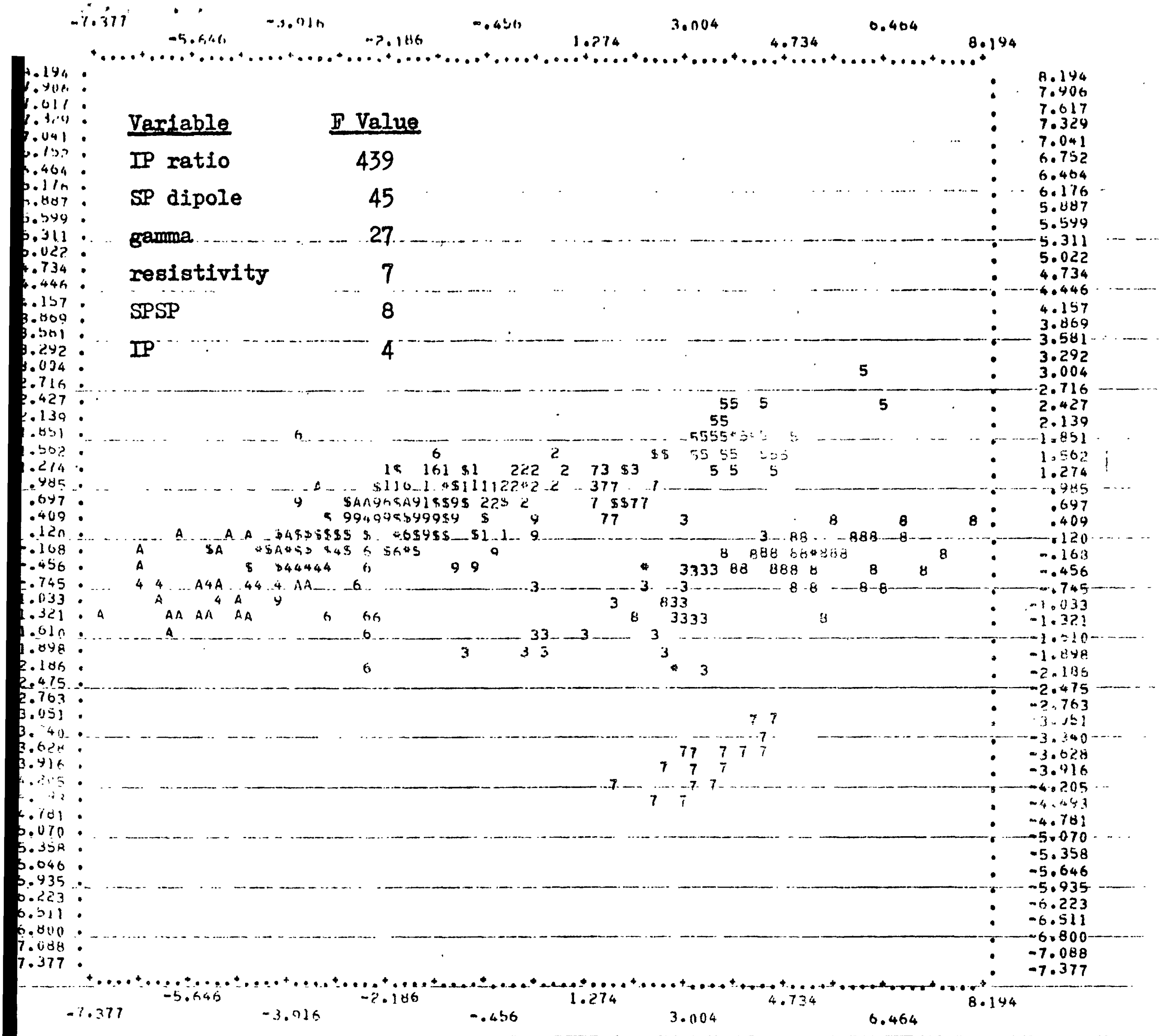


Figure 22 Location of Holes Drilled to Sample the Lamprecht, Texas Roll Front and Surrounding Area. Exact location data withheld.



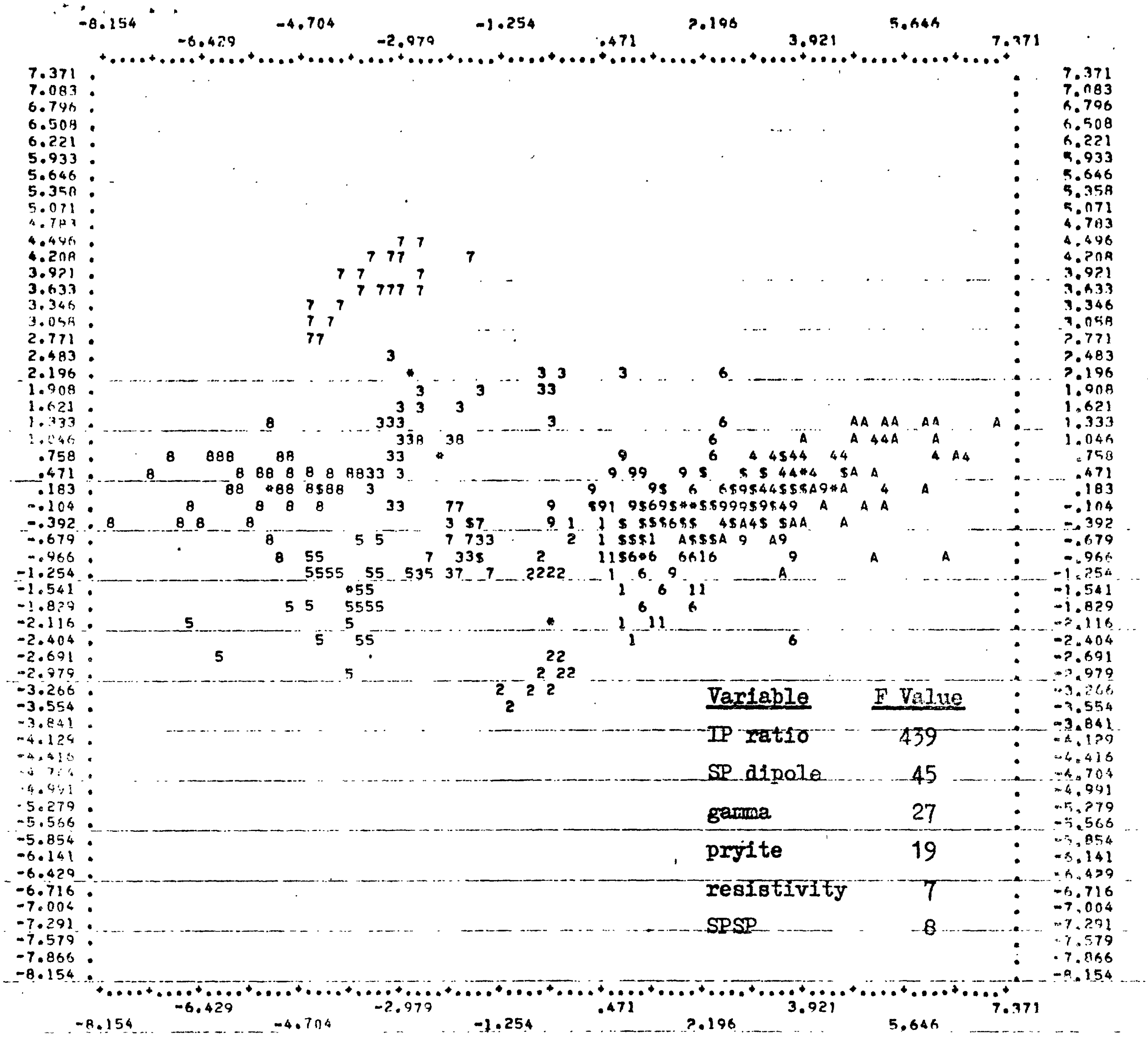
FINISH CARD ENCOUNTERED. JOB TERMINATED

Figure 23 - Hole Discrimination Using all 26 Variables - Lamprecht, Texas. The numbers on this plot correspond to the hole numbers given on Figure 22, except A stands for hole 10 and hole 11 is not included. $ is overprint and * is mean value.



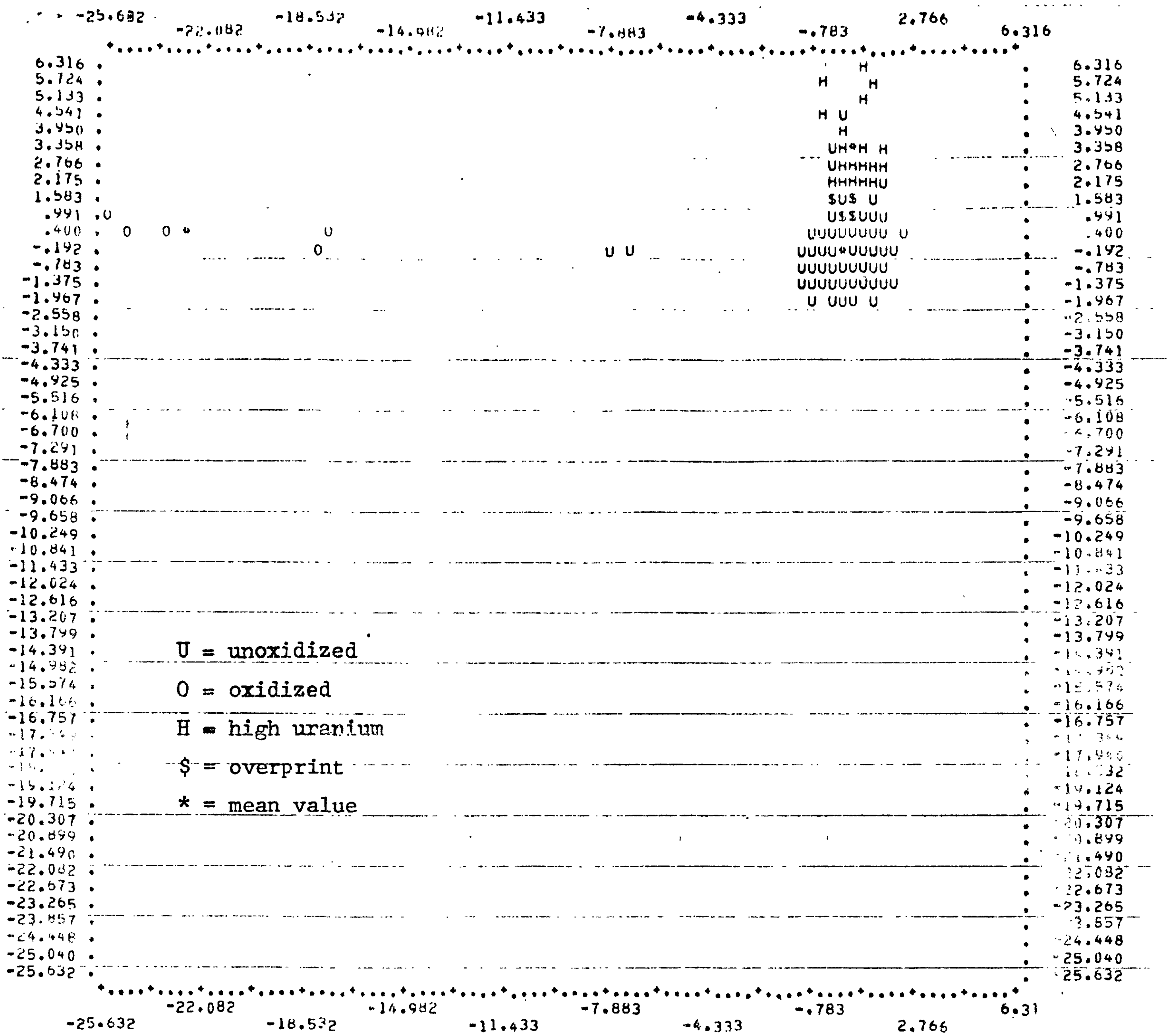
SH CARD ENCOUNTERED. JOB TERMINATED

Figure 24 - Hole Discrimination using only the 6 geophysical variables - Lamprecht, Texas. The numbers on this plot correspond to the hole numbers given on figure 22 except A stands for hole 10, 11 is not included, $ is overprint and * is mean value.



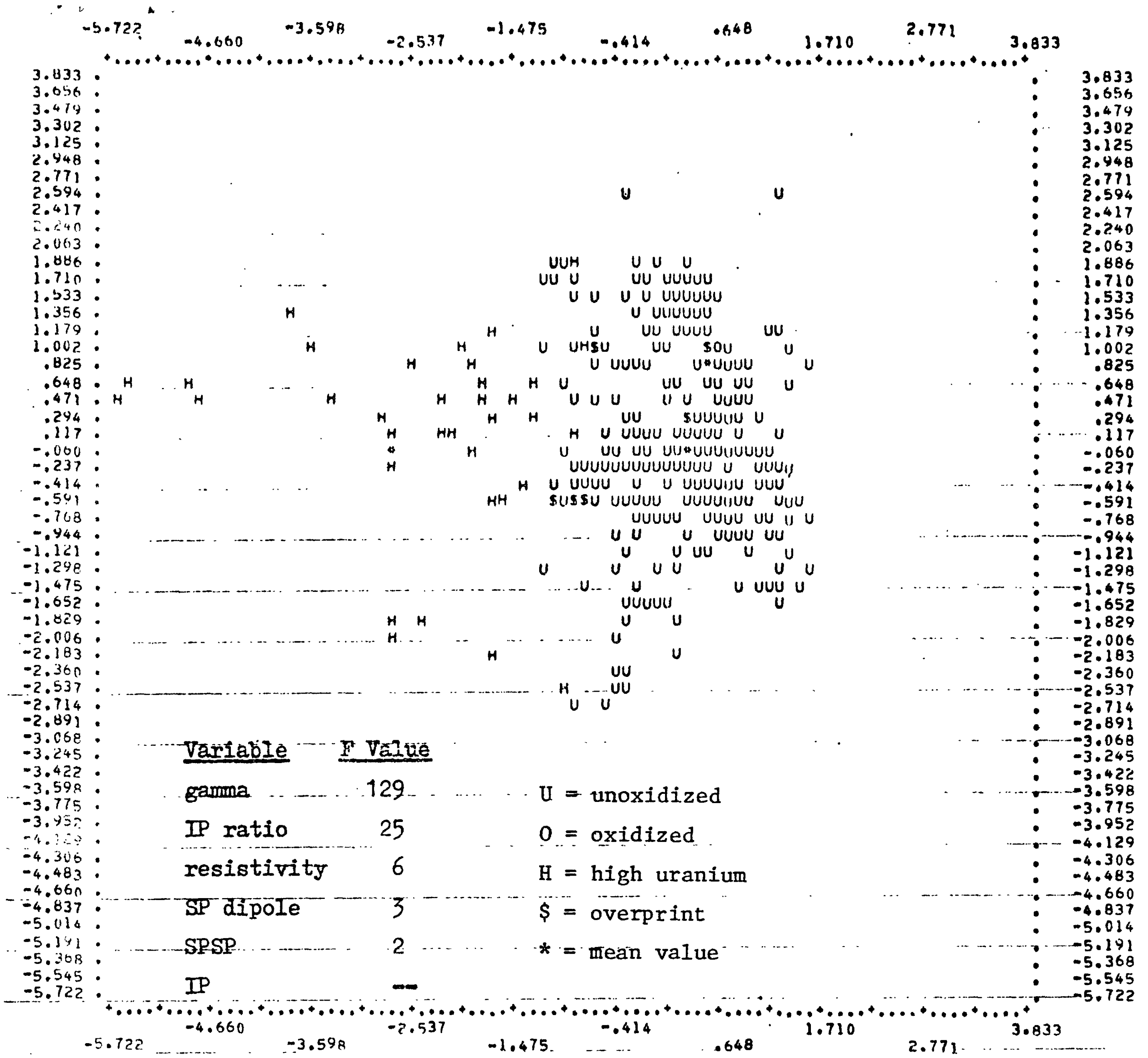
NISH CARD ENCOUNTERED, JOB TERMINATED

Figure 25 - Hole Discrimination using the 5 best geophysical variables and Pyrite - Lamprecht, Texas. The numbers on this plot correspond to the hole numbers given on figure 22 except A stands for hole 10, 11 is not included, $ is for overprint and * is mean value.



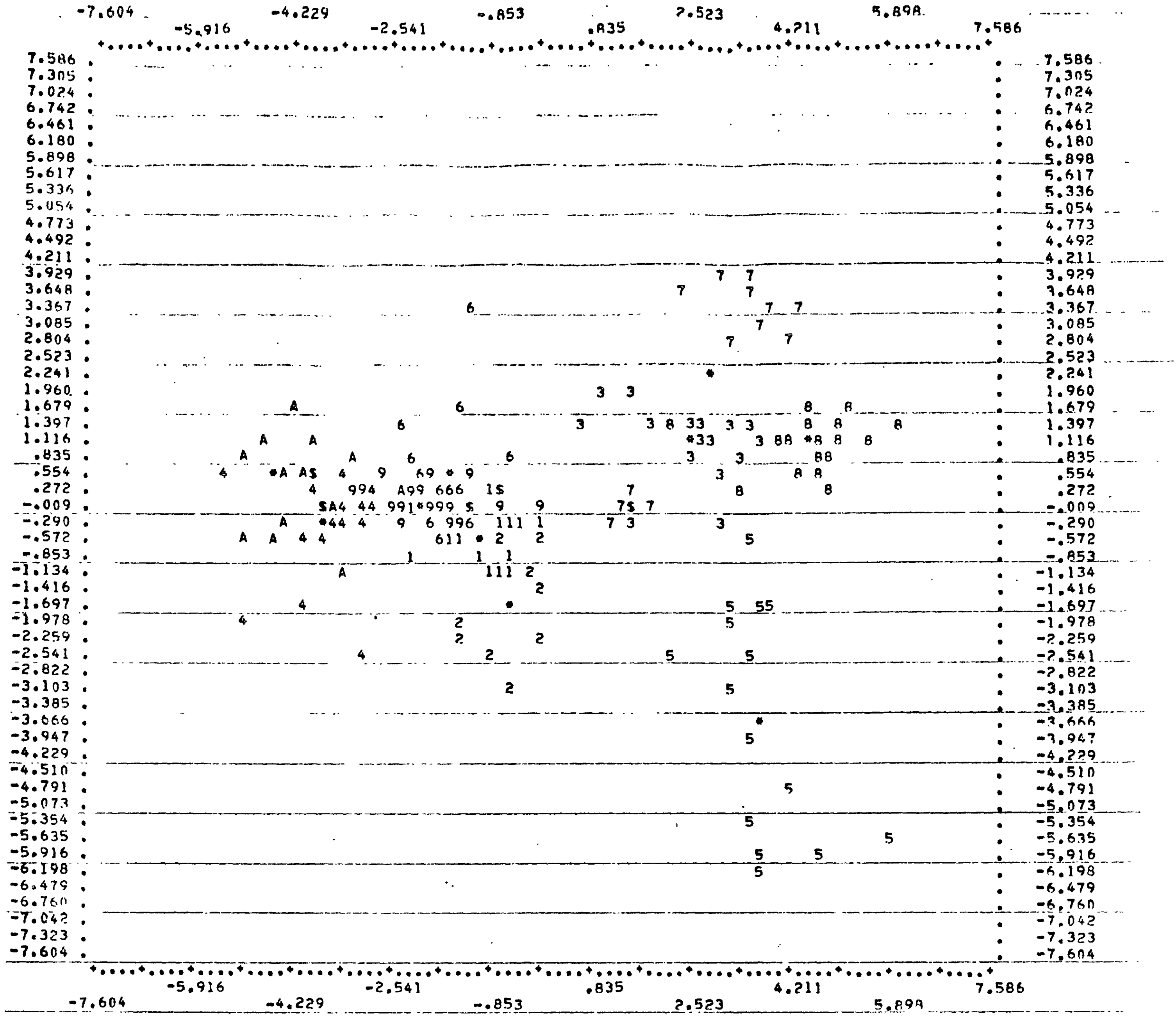
NISH CARD ENCOUNTERED, JOB TERMINATED

Figure 26 - Redox Discrimination using all 26 variables - Lamprecht, Texas.



INISH CARD ENCOUNTERED. JOB TERMINATED

Figure 27 - Redox Discrimination using only the 6 geophysical variables - Lamprecht, Texas.



IISH CARD ENCOUNTERED. JOB TERMINATED

Figure 28.- Hole Discrimination Using all 26 variables - Lamprecht, Texas. These are for data averaged over 3-foot intervals. The numbers on this plot correspond to the hole numbers given on figure 22 except A stands for hole 10, 11 is not included, $ is overprint and * is mean value.

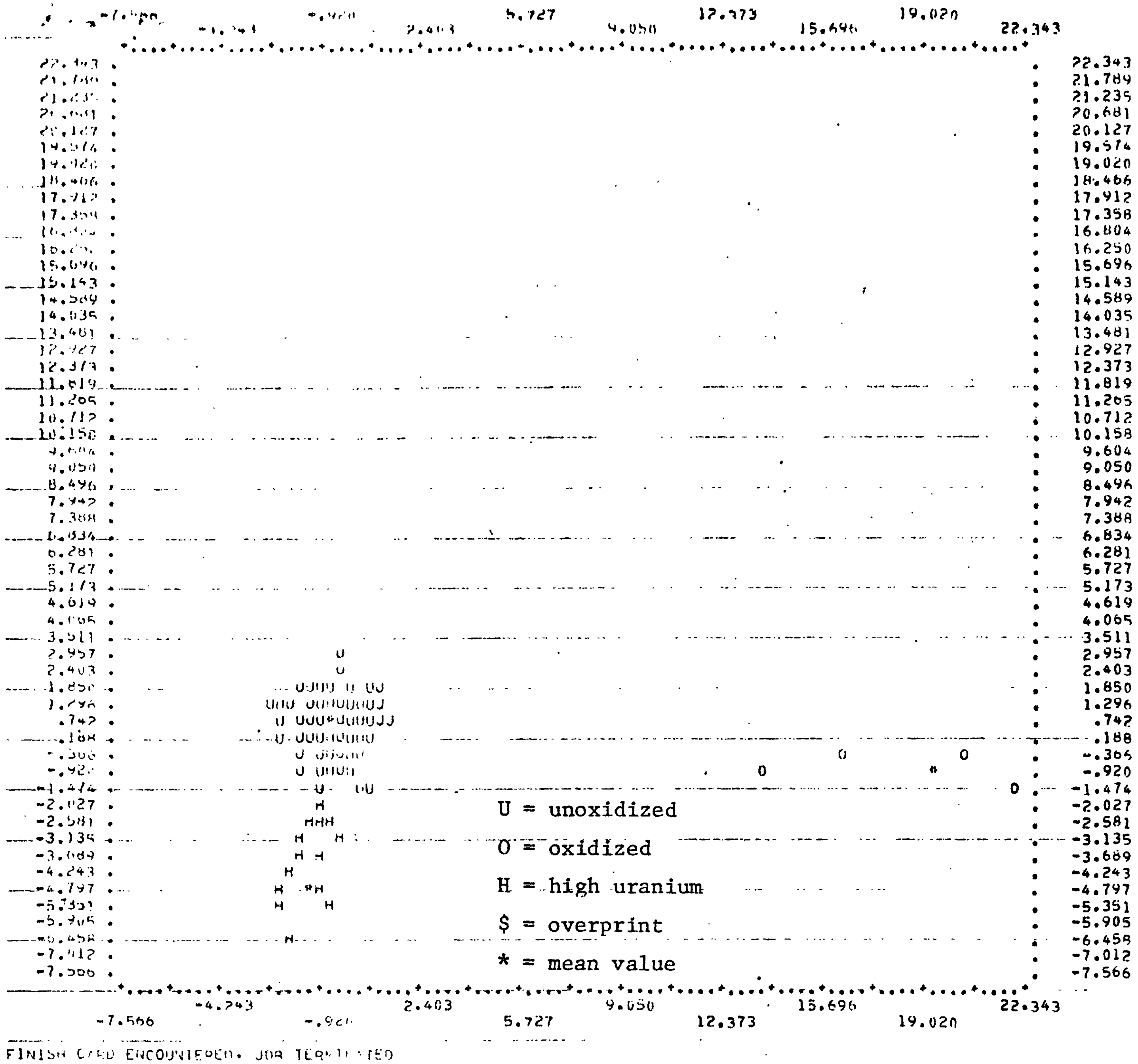


Figure 29 - Redox Discrimination using all 26 variables - Lamprecht, Texas. These are for data averaged over 3-foot intervals.

References

Dixon, W. J., ed., 1974, BMD07M Stepwise discriminant analysis in BMD Biomedical computer programs, Berkley, University of California Press, p. 233-253.

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