Interpretation of Wireline Logs from Cold Turkey Creek North Dakota Using the Program CORRELATOR

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Interpretation of Wireline Logs from Cold Turkey Creek, North Dakota, Using the Program CORRELATOR

R.A. Olea

Abstract

The logs of three wells in the area of southwest Cold Turkey Creek, Bowman County, North Dakota, record a portion of the Mississippian stratigraphic column different from that revealed by surrounding wells.

A computer-assisted interpretation of the wireline logs from this area was made using the program CORRELATOR. Fourteen cross-sections were produced showing five types of results upon which to base conclusions. Analysis of these cross-sections favors salt dissolution as the likely cause of the anomaly.

Introduction

Lee C. Gerhard, Kansas Geological Survey, and Sidney B. Anderson, North Dakota Geological Survey, have studied the Williston Basin for many years (Gerhard and Anderson, 1988; Gerhard *et al.*, 1991). Among the special projects that have resulted from their synoptic work is the correlation of gamma-ray logs of seven wells from the Cold Turkey Creek area of Bowman County, North Dakota. The correlation of these logs has proved to be difficult. Some of the correlations are weak, leading to several feasible alternative interpretations.

CORRELATOR, a computer program for lithostratigraphic modeling based primarily on the interpretation of wireline logs, was developed at the Kansas Geological Survey (Olea, 1988; Olea and Davis, 1989) and has been tested in many situations, successfully establishing valid correlations in all instances. The Cold Turkey Creek problem was first posed by Gerhard three years ago. Five logs were selected for analysis by CORRELATOR with the idea of seeing what the system could contribute to the controversy. The addition of two more wells to the data set and several rounds of reviews between Lawrence, Kansas, and Grand Forks, North Dakota, has led to the conclusions reported in this paper. Although not necessarily final, the interpretation has kept all parties satisfied for several months (spring/summer, 1993).

Methodology

Correlations

Central to any study using CORRELATOR is the generation of as many correlations as possible. The process employs pairs of wells, ideally a pair of digitized wireline logs: one shale log (gamma ray or SP) and one correlation log (typically a high-resolution resistivity log). In the absence of a correlation log—or in the lack of an appropriate correlation log, as we shall see is the case here—the same shale log can be used both as shale and correlation log.

For ease of comparison, we will refer to the well on the left of the display as the reference well and to the one on the right as the matching well. Given an elevation at the reference well, CORRELATOR automatically selects as the correlating elevation that elevation in the matching well which maximizes the weighted correlation coefficient. The weighted correlation coefficient is defined as the product of the Pearsonian correlation coefficient and the normalized shale similarity coefficient (Olea, 1988). The correlation coefficient is sensitive to the matching of the signatures of the correlation logs and the other coefficient is sensitive to the discrepancy in the relative proportions of shale as given by the shale logs.

Figure 1 illustrates the finding of the correlating interval for elevation 4205 ft in well 5920 when the correlation length is set to 50 ft and the search interval in the matching well extends from 3700 to 4700 ft. CORRELATOR first computed the weighted correlation coefficient between the 50-ft interval centered at 4205 ft in well 5920 and an interval of the same length centered at the starting elevation of 3700 ft in well 5910. The result was a first point at the top of the weighted correlation graph at the center of the figure. The comparison was then slid by one digitization interval, or 0.5 ft, to produce a second point in the graph corresponding to the weighted correlation coefficient between the same interval at the reference well and the 50-ft interval

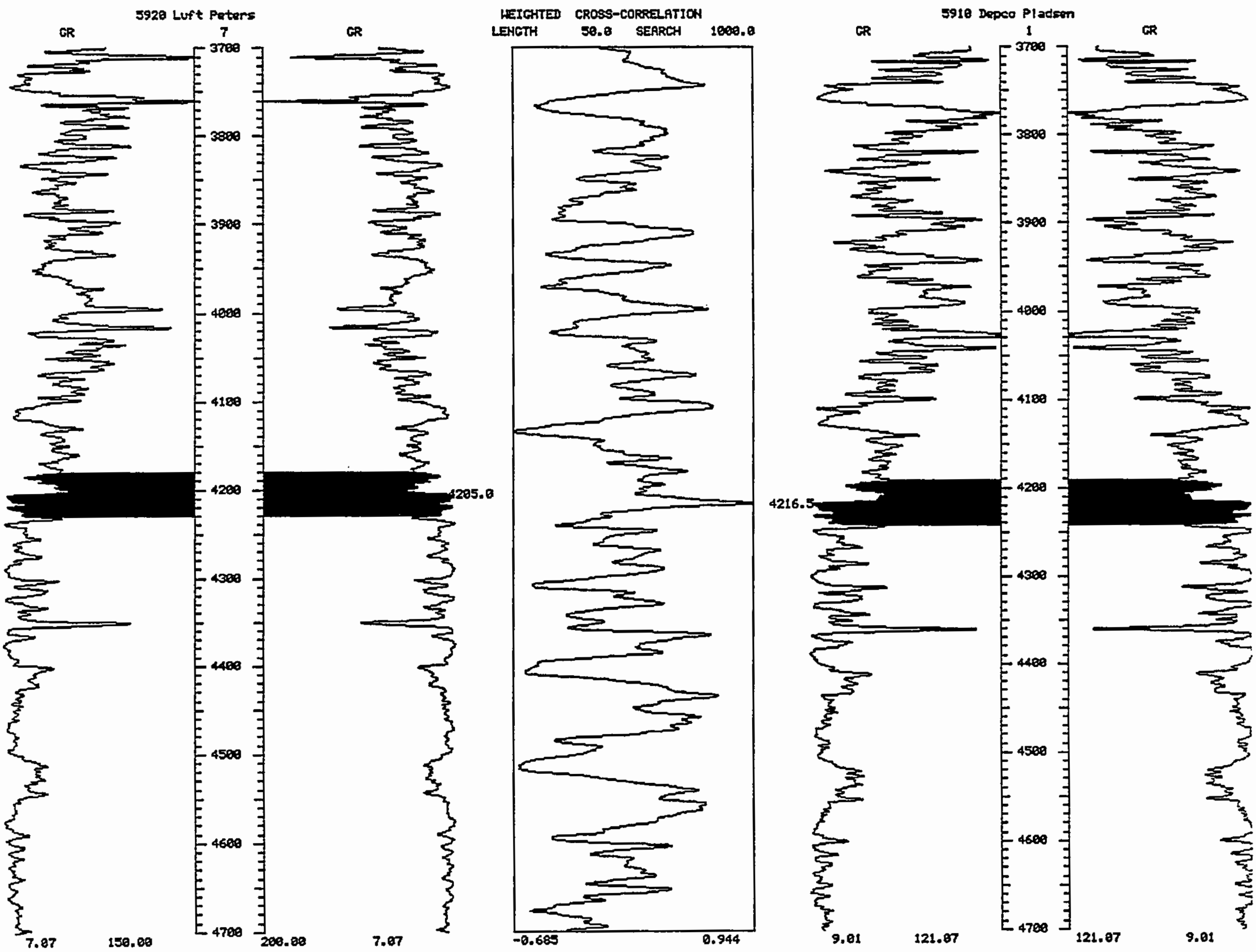

Figure 1. Automatic determination of a correlation.

centered at elevation 3700.5 ft in the matching well. The sliding continued until the end of the search interval was reached at 4700 ft, by which time the 2001-point weighted correlation coefficient graph was ready. Of all matching elevations, the one for 4216.5 ft gave the maximum value for the weighted correlation coefficient, which is interpreted as the correlating elevation for elevation 4205 ft in well 5920.

As may be observed, the selection of correlating elevation depends upon the correlation length and the search interval. Determination of these two parameters is commonly done in two stages. The search interval is really two parameters, either the top and bottom of the search interval in the matching well or a search band defined by the interval's center and width in the matching well.

In a first stage, the top and bottom are set conservatively, the entire digitized interval being the absolute extreme. A good practice is to take a correlation length equal to twice the range of the semivariogram for the correlation log in either well. The semivariogram range is a measure of the average size of the zone of influence. The factor of two is taken because, at this first stage, correlation intervals of longer-than-average length are of interest.

As seen in Figure 2, a cross-plot of the correlating points usually displays a trend that can be modeled with a low-order polynomial, which is the objective of this first stage. In the first stage, only enough correlations are determined to define the polynomial to anchor the expanded interpretation in the next stage. Unless the objective is a completely independent study, the user should make use of all previously available information to establish the anchoring correlations.

The aim of the second stage is to try to produce a correlation for every digitized elevation in the reference well in the shortest possible time. Short processing time presumes narrow search intervals that are derived from the polynomial modeling of the first stage. In the second stage the search interval is defined by its center and width. The center of the search interval in the matching well is equal to the elevation in the reference well offset by the value of the polynomial at the reference elevation. The scattering of the points around the polynomial provides an order of magnitude for the width of the search interval.

Except for the communality that two adjacent correlations may have in correlation length and search length, correlations are found independently of one another. In a final stage, the correlation file must be inspected with

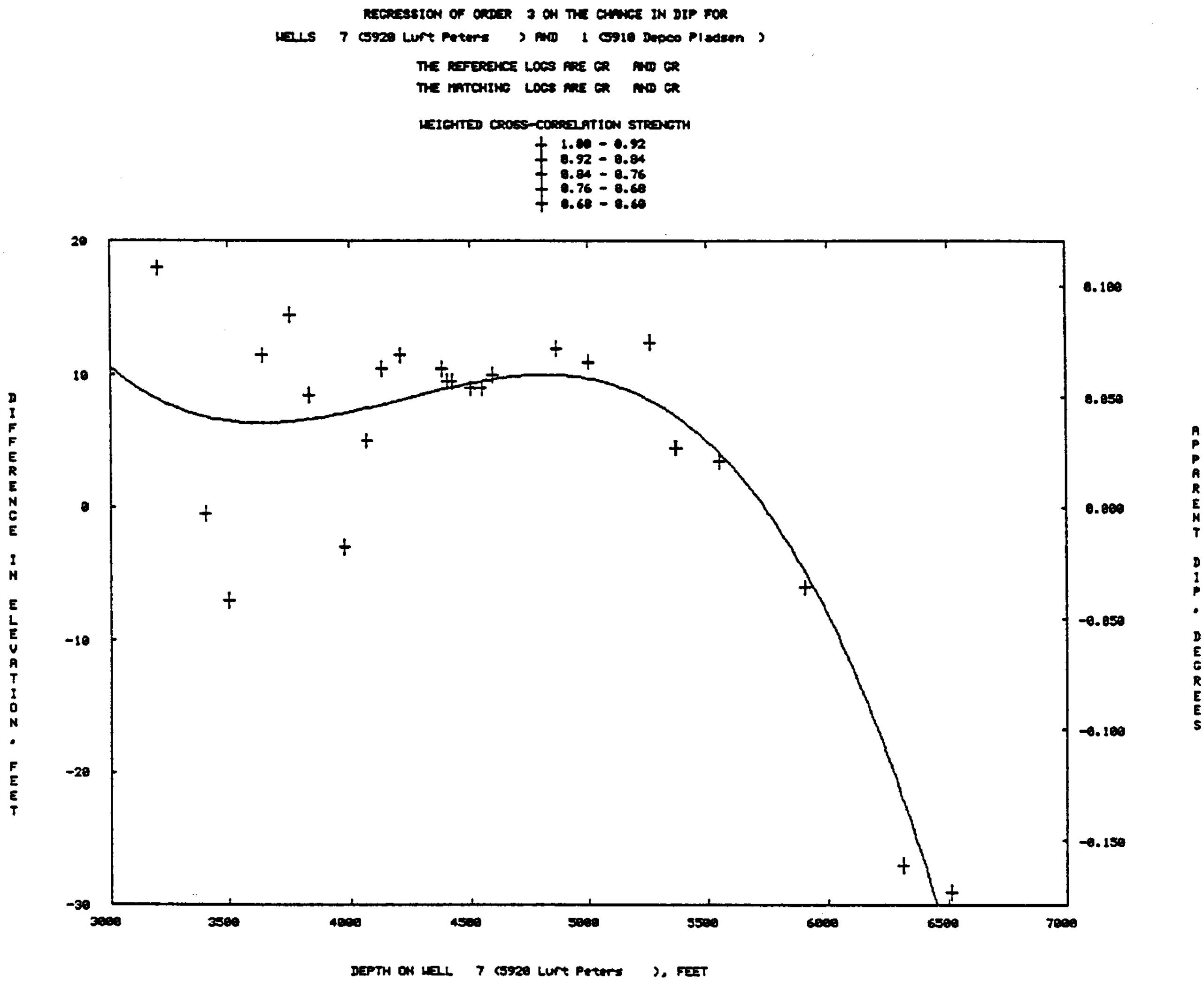

Figure 2. Regression on differences in depth between correlating elevations.

an expert system to assure consistency. The procedure should be repeated for all pairs of wells of interest in the study. All correlations remain on files.

Percent Shale Display

A percent shale display is a display, produced in five colors, of equivalence lines with two important modifications:

1. Faults are added, if any.

2. Instead of coding the equivalence lines with a color denoting strength of the correlation, the lines are colored according to the average percent shale at the correlating elevations.

The percent shale is automatically calculated from the shale log.

Calculation of True Dips

Calculation of true dips resembles the conventional calculation of true dips upon simultaneously running three or more resistivity logs in the same borehole (Schlumberger, 1970; Serra, 1985; Doveton, 1986, chapter 2). CORRELATOR, however, uses the wireline logs run in three different wells.

Three correlating points selected on the same surface—the top of the same sandstone or any lithostratigraphically equivalent feature—completely define a plane characterizing the regional dipping attitude in the area enclosed by the triangle defined by the location of the three wells. Retrieval of lithostratigraphically equivalent points from the correlation files is a trivial operation for CORRELATOR, once those files have been generated. Let $\mathbf{N}$ be a vector perpendicular to the plane defined by points $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$.

$$\mathbf{N} = n_1\mathbf{i} + n_2\mathbf{j} + n_3\mathbf{k} = \mathbf{AB} \times \mathbf{AC}\,.$$

Let (x_1, y_1, z_1), (x_2, y_2, z_2), and (x_3, y_3, z_3) be the coordinates of these three points. Then (Munem and Foulis, 1984, p. 783):

$$\mathbf{AB} \times \mathbf{AC} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \end{vmatrix}\,.$$

The points must not be on a line, which implies that **AB**×**AC** must be different from zero (Munem and Foulis, 1984, p. 794). If $|\mathbf{N}| = S\sqrt{n_1^2 + n_2^2 + n_3^2}$, then the direction cosines of **N** are:

$$\cos(a) = \frac{n_1}{|\mathbf{N}|} \qquad \cos(b) = \frac{n_2}{|\mathbf{N}|} \qquad \cos(c) = \frac{n_3}{|\mathbf{N}|}\,.$$

If the plane **ABC** does not go through the origin, S is equal to the sign of D, the distance from the plane to the origin:

$$D = n_1 x_l + n_2 y_l + n_3 z_l,\ l = 1, 2,\ or\ 3\,.$$

If D is zero, S is equal to the sign of n_3 , or the sign of n_2 if both D and n_3 are zero (Larsen, 1960, p. 214).

The azimuth of a line on a vertical plane is the angle between a horizontal axis and the projection of that line or vertical plane into a horizontal plane. Because **N** and the line of maximum dip define a vertical plane, the azimuth for **N** is the same as the azimuth for the line of maximum dip:

$$azimuth = \arctan \frac{\cos(b)}{\cos(a)}\,.$$

Because the line of maximum slope is perpendicular to **N** and because the vertical Cartesian axis **k** is perpendicular to the horizontal plane, the angle that the line of maximum dip makes with a horizontal plane is equal to the angle that **N** makes with **k**. The convention is that **k** points upwards, but because CORRELATOR assumes that **k** points downwards, the sign must be reversed:

$$dip = \arccos - (\cos(c))\ .$$

Cold Turkey Creek

Data

The study area comprises seven wells in Bowman County, North Dakota. Although there are several wireline logs available per well, L.C. Gerhard and S.B. Anderson considered that logs other than gamma-ray logs were not suited for the study due to their sensitivity to phenomena that are not of interest in this case. Plate 1 displays all gamma-ray logs and the relative location of the wells. The correlation log to the right of each well in this case is the same as the shale logs to the left, denoting that the same log was used to compute both normalized shale differences and correlations coefficients.

Results

Plate 2 displays all correlations found along the traverse shown in the index map. In this representation, each line joins correlating elevations. Most correlation lengths are 25 ft and the search length varies mainly between 20 and 50 ft, depending on the complexity of the geology.

Anchoring correlations were taken at those intervals of easier interpretation, typically outside the Mississippian, preferably for a marker provided by the geologists. Figure 1 illustrates the example of the top of the Charles at well 5920, which according to geologists is the correct correlation (Gerhard and Anderson, personal communication). In case of discrepancy, the marker was discarded as an anchoring correlation. The strategy for finding all correlations at the second stage went from the easiest to the most difficult intervals to interpret—outside the Mississippian first, followed by the lower Mississippian, and ending with the upper Mississippian.

Plate 3 shows persistent correlations. Persistent correlations are those equivalent correlations that can be established for all seven wells in the closed traverse—no gaps are allowed in the lateral tracing.

Plates 4 to 7 display all the lithostratigraphic units. The tracing was started from well 10421 Abraxas Lewton, left column, based on elevations and subdivisions provided by Gerhard and Anderson. CORRELATOR used the correlations in Plate 2 to calculate depths for the rest of the markers. A solid line denotes a lithostratigraphic line joining the same points as an equivalence line. A broken line denotes either interpolation or extrapolation based on neighboring correlations.

Plates 4 to 7 show an ancient depression in well 5459 going from the bottom of the cross-section to the Midale, at which time the center of the depression started moving toward the northwest. The depression reached its maximum relief during deposition of the Big Snowy and not only disappeared completely later on, but was replaced by a positive anomaly shifting southeastward. This depression is the dominant feature in the cross-section. Gerhard and Anderson now favor salt dissolution as the main cause of the culminating episode during the Big Snowy (Gerhard, personal communication), having discarded the possibility of an astrobleme mentioned in the literature for other locations in the basin (Sawatzky, 1975; Gerhard *et al.*, 1991).

Table 1 contains the elevations for all stratigraphic tops. Because the traverse is closed, CORRELATOR can also compute the closure errors, which

Table 1. Lithostratigraphic markers and closure errors.

TRACING STARTED FROM WELL(5) 10421, FIRST COLUMN
THE DATUM IS SEA LEVEL
ALL RESULTS ARE IN FEET

WELLS AND LOGS

	5	6	7	1	2	3	4	5		
	10421	8982	5920	5910	4654	9317	5459	10421	CLOSURE	
	GR-GR	GR-GR	GR-GR	GR-GR	GR-GR	GR-GR	GR-GR	GR-GR	ERROR	TOP
1	3124.0	3139.5	3206.0	3225.5	3144.0	3108.0	3096.5	3124.0		Spearfish
2	3306.0	3306.5	3391.5	3391.0	3317.0	3264.5	3251.0	3306.0		Minnekahta
3	3346.0	3349.0	3428.0	3432.0	3357.5	3304.0	3291.0	3346.0		Opeche
4	3452.0	3413.5	3565.0	3556.0	3476.5	3402.5	3350.0	3452.0		Minnelusa
5	3576.0	3593.5	3630.0	3636.5	3578.0	3522.5	3525.5	3576.0		Dickinson
6	3710.0	3722.0	3752.0	3766.5	3702.0	3644.5	3653.0	3710.0		Medora
7	3925.0	3936.5	3969.5	3969.5	3904.5	3841.5	3854.5	3925.0		Tyler
8	3990.0 I	4006.5 I	4037.0	4042.5	3980.0	3906.5 I	3920.0 I	3989.5	0.5	Otter
9	4019.0	4036.5	4067.0	4071.5	4214.5	3930.0	3957.0	4019.0		Kibbey ss
10	4039.0	4069.5	4098.0	4099.0	4291.0	3978.5	4017.0	4039.0		Kibbey ls
11	4075.0	4100.5	4132.0	4142.0	4341.5	4017.5	4041.5 I	4075.0		Kibbey slt
12	4145.0	4173.0	4204.5	4215.5	4415.5	4119.0	4111.5	4145.0		Charles
13	4334.0	4366.0	4398.5	4408.0	4532.0	4488.5	4500.0	4334.0		Ratcliffe
14	4436.0	4468.0	4500.5	4509.5	4622.0	4613.0	4641.0	4436.0		Midale
15	4483.0	4515.0	4545.5	4554.5	4642.5	4651.5	4674.5	4483.0		Rival
16	4531.0	4562.0	4594.0	4604.0	4677.0	4677.0	4697.5	4530.5	0.5	State "A"
17	4803.0	4832.0	4865.5	4877.5	4883.0	4992.0	5057.0	4803.0		Tilston
18	4932.0	4967.0	4997.5	5008.5	5003.5	5117.0	5172.5	4932.0		Flossie L.
19	5141.0	5174.0 I	5205.5	5207.5	5212.0	5285.0	5320.5	5141.0		U.Whitewat
20	5171.0	5209.0	5238.5	5250.5	5248.5	5307.0	5338.5 I	5171.0		L.Whitewat
21	5196.0	5231.0	5265.0	5277.5	5275.0	5329.5	5358.0	5196.0		U. Virden
22	5230.0	5264.5	5298.5	5307.0	5307.0	5357.0	5385.5	5230.0		L. Virden
23	5281.0	5318.5	5356.0	5361.0	5361.0	5407.0	5428.0	5281.0		Scallion
24	5505.0	5538.5	5574.0	5577.0	5576.0	5604.0	5614.5	5505.0		3 Forks
25	5542.0	5581.0	5616.5	5612.0	5613.0	5640.0	5652.0	5542.0		Birdbear
26	5584.0	5627.0	5660.0	5656.0	5653.0	5680.0	5692.5	5584.0		Duperow
27	5770.0	5813.5	5847.0	5843.5	5839.0	5859.0	5873.5	5770.5	-0.5	Souris R.
28	5851.0	5910.0	5929.0	5919.0	5916.0	5948.5	5952.5 I	5851.0		Interlake
29	6209.0	6253.0	6286.0	6260.5	6270.0	6295.5	6301.5	6209.0		Stonewall
30	6304.0	6350.0	6386.0	6362.0	6367.0	6390.0	6402.5	6304.0		Stony Mtn.
31	6428.0	6473.5	6510.0	6480.5	6492.0	6514.5	6525.0	6428.5	-0.5	Red River

MAXIMUM ABSOLUTE CLOSURE ERROR: 0.5 FEET

AVERAGE ABSOLUTE CLOSURE ERROR: 0.065 FEET in this instance are nearly perfect. Unfortunately, low closure error is a necessary but not sufficient condition to verify correct interpretation.

Plates 8 and 9 display variations in the amount of shale, which are fairly low, especially for the Interlake and the Mississippian units.

Finally Plates 10 to 14 are true dip diagrams. The solid circles denote a dip based on correlations for both pairs of wells, while an open circle indicates a dip based on the actual correlation of one pair of wells and an extrapolation for the other pair.

The diagram for well 5920 is the only one free from the influence of the anomalies around well 5459 and all five unconformities that appear to be associated to sudden changes in dip are well picked. The diagram also shows the intraformational unconformity described for the Interlake (Gerhard and Anderson, 1988, p. 229).

Conclusions and Recommendations

Using CORRELATOR, 14 cross-sections of the area southwest of Cold Turkey Creek, North Dakota, were prepared, as shown in Plates 1–14, based on the lithostratigraphic correlation of seven gamma-ray logs. In those areas to the north away from the anomalies, the interpretation as indicated by the plates confirms the global evolution of the Williston Basin described in the literature.

This study confirms the existence of an anomalous area around wells 4654, 9317, and 5459. The mechanism responsible for the anomaly is still not clear, but the possibility of an astrobleme has been discarded.

The most likely cause of the anomaly is at the moment considered to be salt dissolution. Gerhard and Anderson intend to review drilling cuttings and the old seismic lines before preparing a paper which will present final conclusions.

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