3D borehole geophone orientation study, central Alberta

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ABSTRACT

Geophone orientation azimuths were found analytically from 3D and 2D walkaway VSP data acquired near Lousana, Alberta. The 3D dataset was divided based on source-well azimuth into bins with centers trending 0°-180°, 45°-225°, 90°-270° and 135°-315°; the standard deviation in orientation azimuth was found to be 5.24° using all azimuths, and 1.28°, 0.66°, 1.07° and 2.77° respectively when binned. The 2D dataset consisted of three lines; the standard deviation for this survey was 1.73° for all lines, 1.87° for the east line, 0.71° for the southeast line and 1.81° for the south line. In both cases, the mean angle calculated for each receiver did not appear to have any dependence on source-well azimuth, suggesting flat, isotropic geology near the well. Removal of sources nearer than 300 m (approximately 1/3 of the geophone depth) significantly improved the scatter in the 2D walkaway, but had little effect on the 3D walkaway. Finally, the orientation angles for the 3D walkaway analysis were also calculated using a linear regression analysis of trace hodograms. Results showed that mean angles calculated using this method differed from the analytic method by less than 1° on average, but that the analytic method produced less scatter.

INTRODUCTION

In July 2007, several vertical seismic profile (VSP) surveys were acquired for EnCana, using a vertical well near Lousana, Alberta; these comprise a zero offset VSP, 3 2D walkaway VSP's and a 3D walkaway VSP. One of the issues that must be overcome in any borehole geophone experiment is that the orientation of the receivers is, in general, unknown. Often, it is reasonable to assume that the z, or vertical, component of the geophone is of a known orientation; this orientation is usually along the borehole's trajectory, though certain types of geophones are designed to orient the z-component vertically using a gimballed system. However, since cables used to lower tools down a borehole tend to spin, the orientation of the horizontal components of the geophone is not so well constrained. Thus, a calibration survey must be carried out.

In a study done by Gagliardi and Lawton (2011), the calculation of geophone orientation azimuth showed some dependence on the source-well azimuth. This study will examine the relationship between source-well azimuth and geophone orientation calculations. Additionally, a comparison will be drawn between two different methods of orientation calculations: an analytic method described by DiSiena et al. (1984) and a linear regression of hodograms generated using the data from the horizontal components.

STUDY AREA

Angle calculations were performed on the 2D and 3D walkaway surveys; the 2D walkaway had 10 source locations per line with a maximum offset of 1391 m (Figure 1), while the 3D walkaway consisted of 249 source locations with a maximum offset of 3255 m (Figure 2). Both walkaway surveys used 16 borehole geophones; however, all shot locations in the 2D survey were repeated an additional 3 times using different tool positions, resulting in a total of 64 receiver positions. Both surveys used dynamite as a source. Unfortunately there is some error in the 2D walkaway geometry, as the small differences from source locations of repeated shots were not included in the SEGY headers. An example of a common shot gather from the 3D VSP survey, for the horizontal components of a near-offset shot location, are shown in Figure 3.

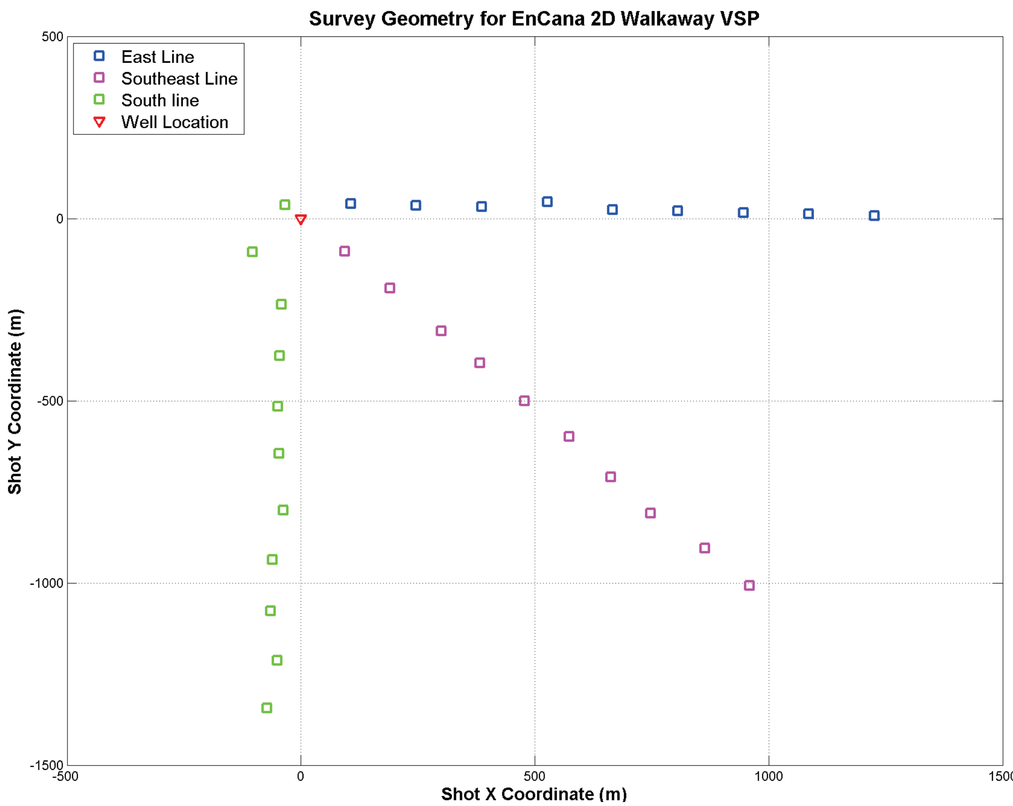

FIG. 1. Surface geometry for the 2D walkaway VSP examined in this study. The well location is shown in red and sources from the east, southeast and south line are shown in blue, magenta and green respectively.

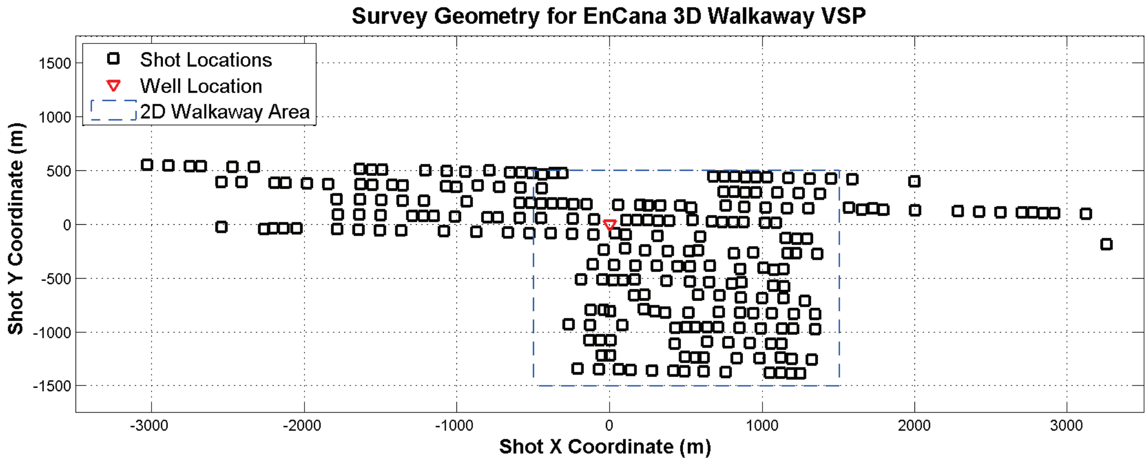

FIG. 2. Surface geometry for the 3D walkaway VSP examined in this study. The well location is shown in red, source locations are shown in black and the 2D walkaway area is shown in blue.

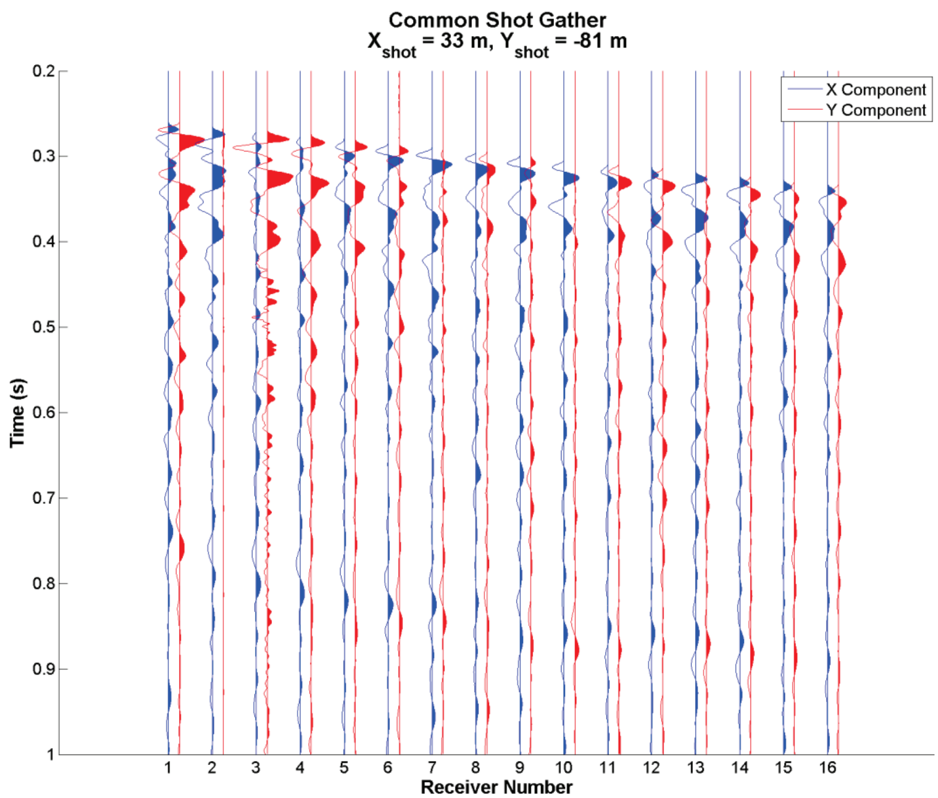

FIG. 3. Raw shot gather from a near offset shot. X-component is shown in blue and y-component is shown in red.

ROTATION METHODS

Analytic

An analytic solution for calculation of geophone rotation angle is given by (DiSiena et al., 1984)

$$\tan 2\theta = \frac{2X \otimes Y}{X \otimes X + Y \otimes Y}, \qquad (1)$$

where $\otimes$ is a zero-lag crosscorrelation operator, X and Y are the windowed horizontal component data and θ is the angle between the x-component and source. For this study, a window of 100 ms was used, beginning at the first break. In the case of a vertical well, this angle can be converted into an azimuth relative to North, ϕ_r, by

$$\phi_r = \phi_s + \theta, \qquad (2)$$

where ϕ_s is the shot azimuth from the well.

Linear regression

In addition to the analytic solution described above, angle calculations were made by crossplotting the windowed x and y samples and calculating the slope of the line of best fit. Figure 4 shows sample hodograms for a far offset shot, along with the calculated lines of best fit.

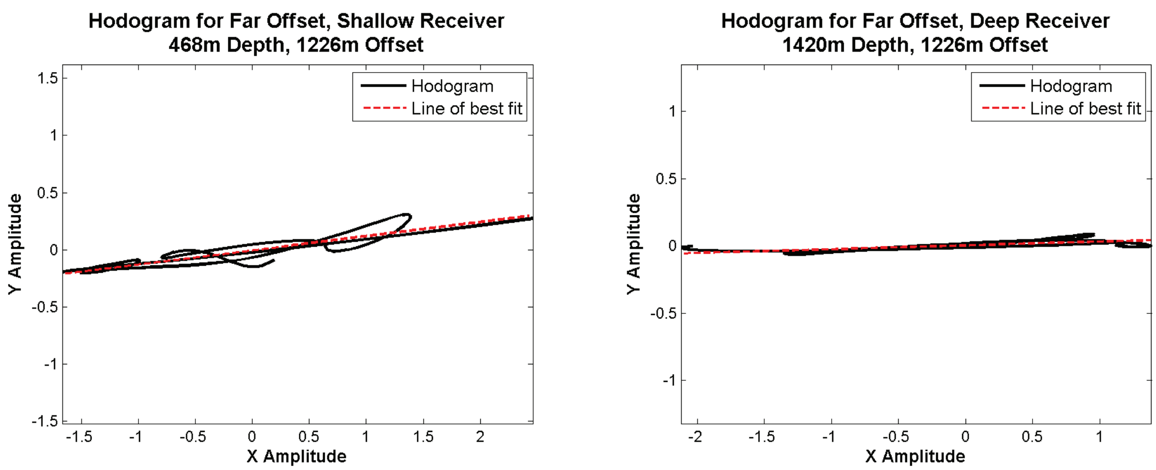

FIG. 4. Examples of hodograms used for linear regression calculations.

Once the line of best fit is calculated, it can be converted into a source-receiver angle using the relationship

$$\text{slope} = \frac{y}{x} = \tan \theta, \qquad (3)$$

which can be converted into an azimuth relative to North using Equation 2.

3D WALKAWAY RESULTS

Orientation calculations

In order to examine consistency of the relationship of geophone orientation and source-well azimuth, that dataset was divided into 4 bins based on the source-well azimuth (Figure 5). Bin centers were lines trending at 0°-180° (Bin 1), 45°-225° (Bin 2), 90°-270° (Bin 3) and 135°-315° (Bin 4) azimuths. It should be noted that, due to the acquisition geometry, there was a large variation in the number of source locations between each bin.

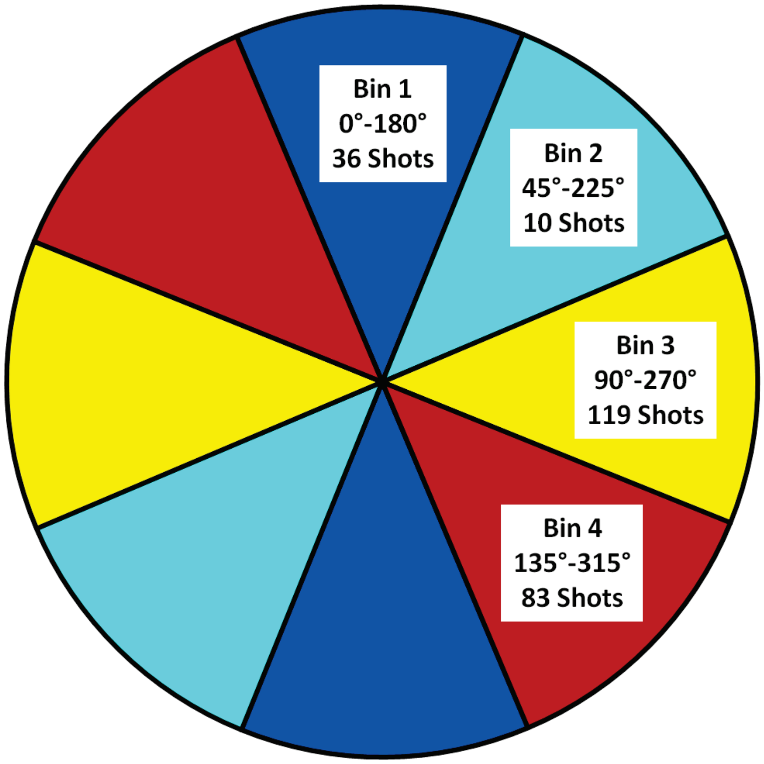

FIG. 5. Binning schematic for 3D walkaway VSP survey.

Figures 6 and 7 show orientation azimuths calculated using the analytic method, plotted against offset; Figures 8 and 9 show histograms of these results. For all receivers, the calculated angles become much less scattered beyond about 300-500 m source-well offset, or about 1/3 of the geophone depth; this agrees with a similar study done by Gagliardi and Lawton (2010). It is difficult to discern any noticeable difference between angles calculated in each of the bins, with the possible exception of Receiver 6; however, the lower number of source locations and more restricted offsets in Bins 1, 2 and 4 is something that must be considered. Finally, the receiver in the second tool position had problems with the y-component, resulting in orientation azimuth calculations that are not useable for this study.

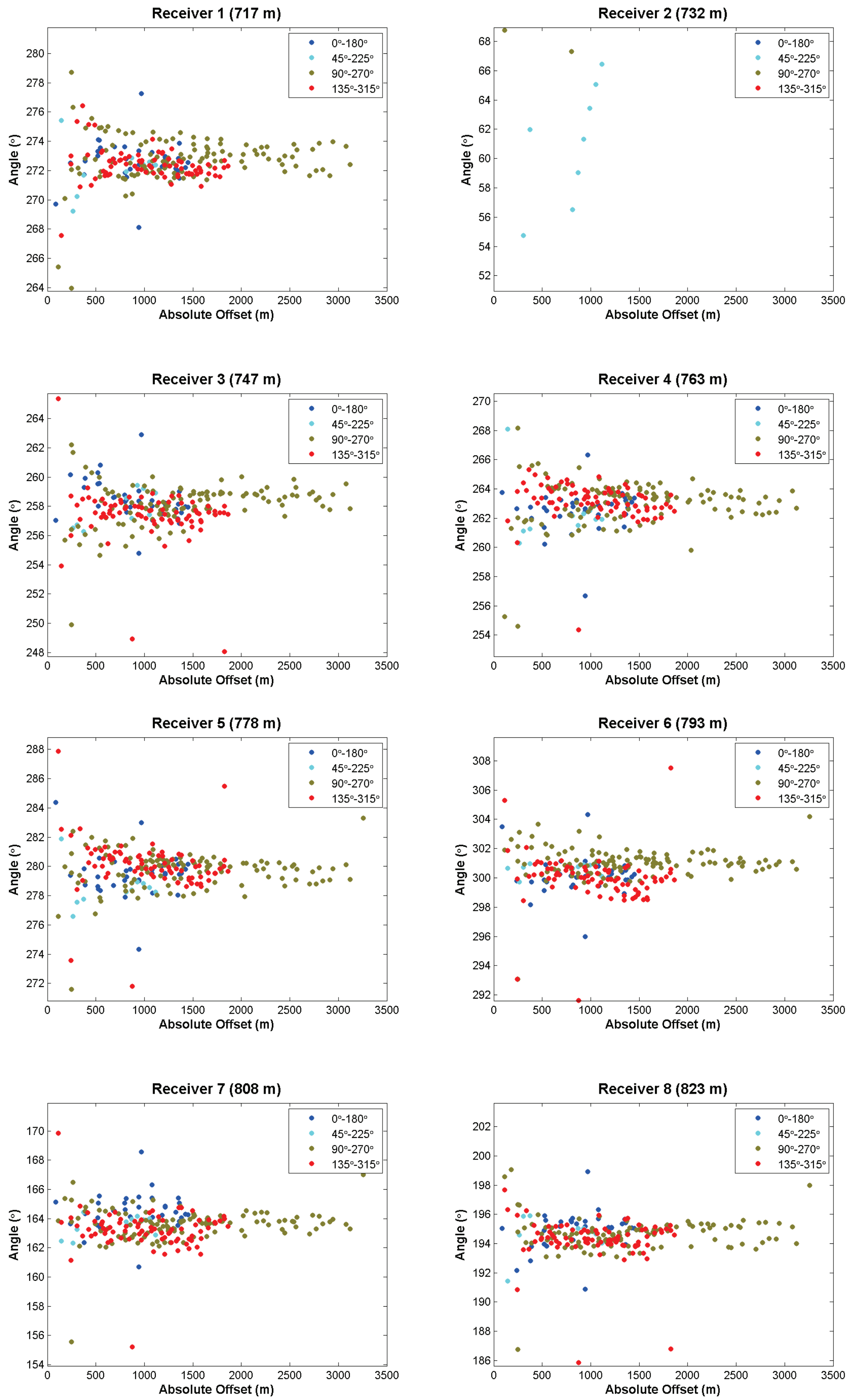

FIG. 6. Geophone orientation azimuths for receivers 1-8, calculated using analytic method, for 3D walkaway colored by bin; 0°-180° is shown in blue, 45°-225° is shown in cyan, 90°-270° is shown in yellow and 135°-315° is shown in red.

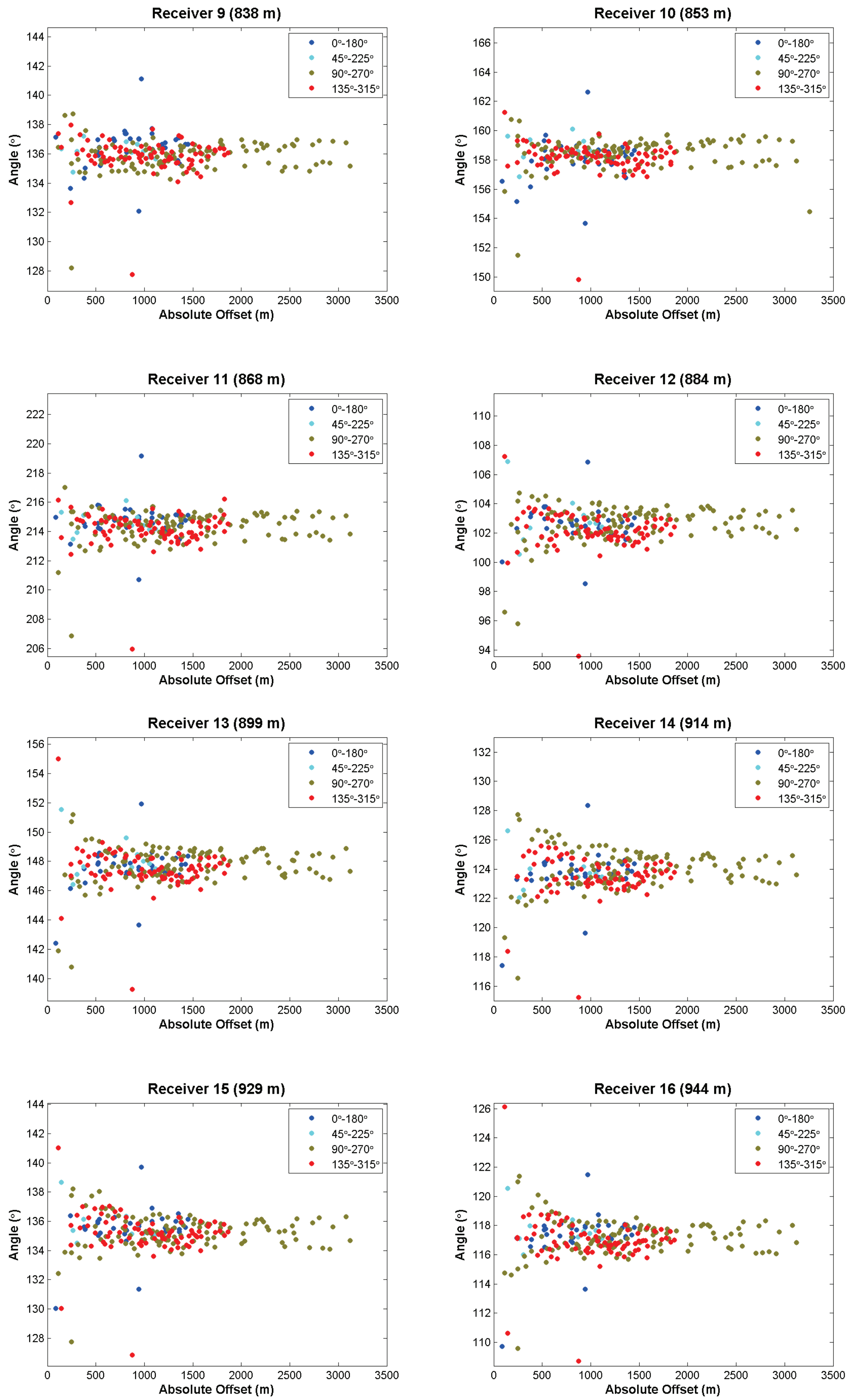

FIG. 7. Geophone orientation azimuths for receivers 9-16, calculated using analytic method, for 3D walkaway colored by bin; 0°-180° is shown in blue, 45°-225° is shown in cyan, 90°-270° is shown in yellow and 135°-315° is shown in red.

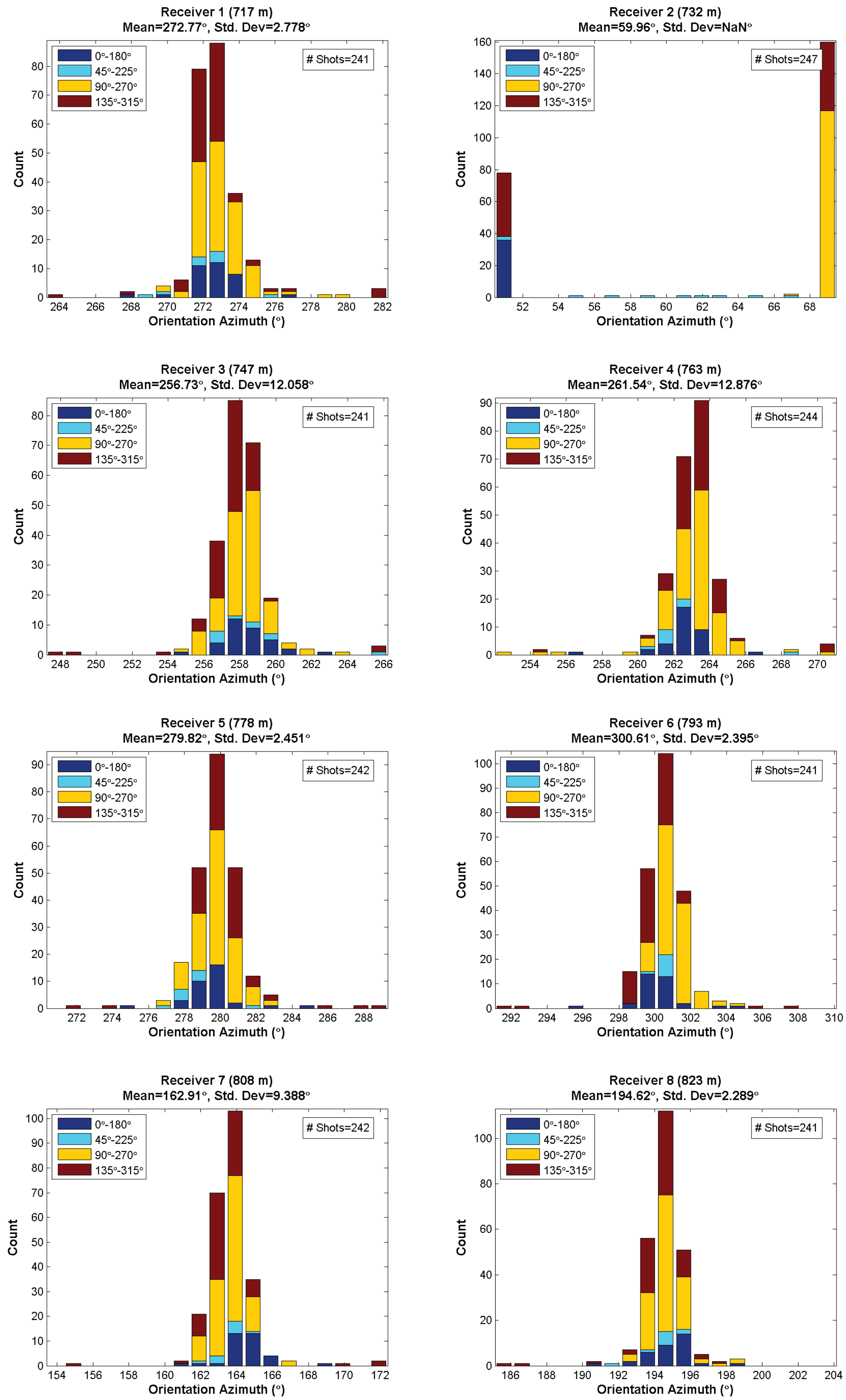

FIG. 8. Histograms of geophone orientation azimuths for receivers 1-8, calculated using analytic method, for 3D walkaway colored by bin; 0°-180° is shown in blue, 45°-225° is shown in cyan, 90°-270° is shown in yellow and 135°-315° is shown in red.

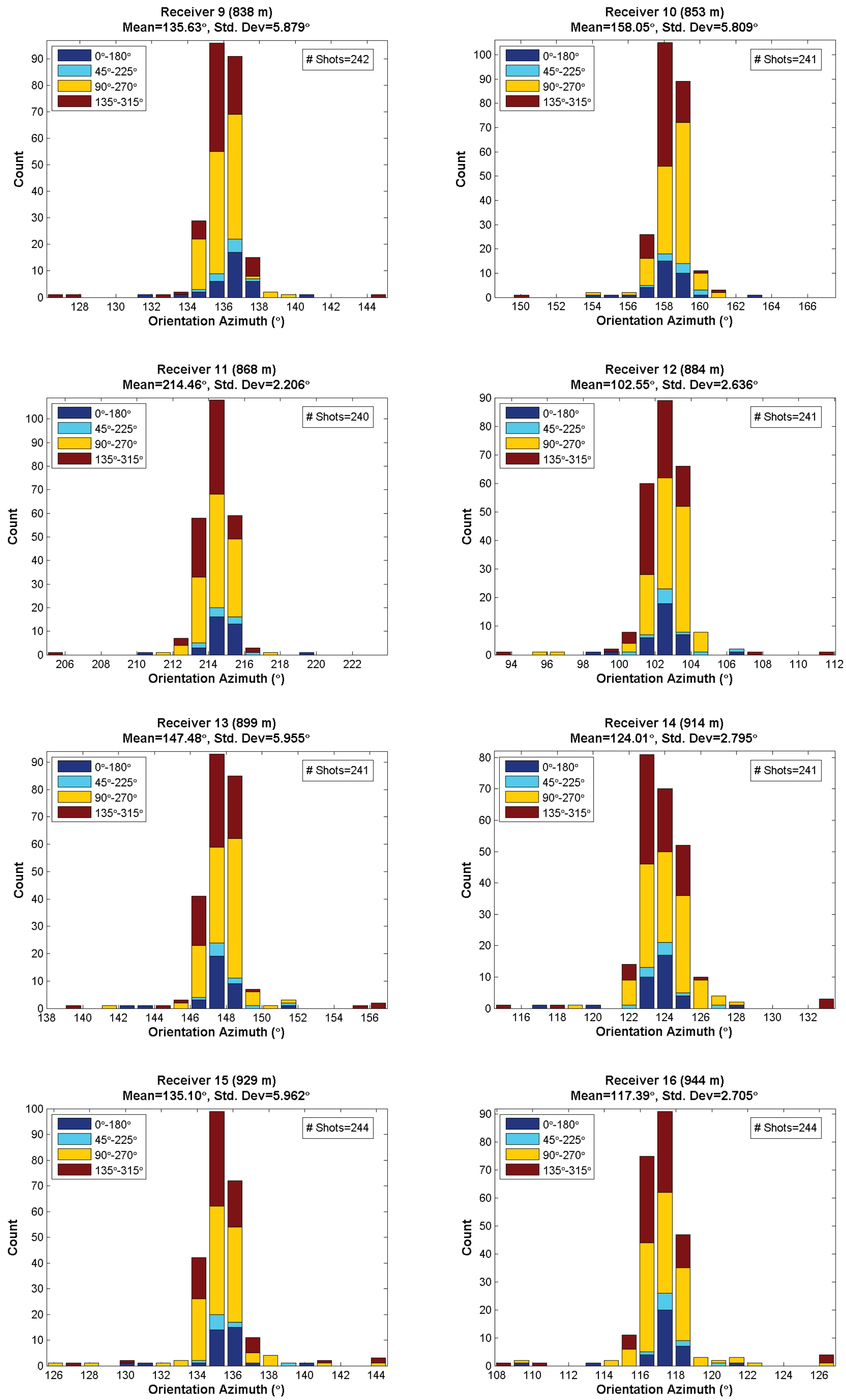

FIG. 9. Histograms of geophone orientation azimuths for receivers 9-16, calculated using analytic method, for 3D walkaway colored by bin; 0°-180° is shown in blue, 45°-225° is shown in cyan, 90°-270° is shown in yellow and 135°-315° is shown in red.

Geophone orientation statistics calculations and method comparison

Figure 10 depicts the standard deviation for the entire set of calculations for the 3D VSP survey, as a function of receiver number. For comparison, Figure 11 shows the standard deviation for each bin, as a function of receiver number. Here, results from both the analytic and linear regression methods are presented. An outlier was judged to be any data point greater than three standard deviations away from the mean. It is important to note that the removal of outliers was done separately for the binned and unbinned calculations; this is apparent through their noticeably different standard deviations.

Tables 1 and 2 show the unbinned orientation azimuth means and standard deviations using all data points, after the removal of outliers, and after excluding near offsets less than 300 m from the well. For both methods, the statistical measures improve after the removal of outliers; however, after the removal of near offsets, there is little further change. Generally, the differences between the analytic and linear regression methods are minimal; these differences can be directly seen in Table 3. Most far-offset angle differences are within 0.5°, and the standard deviations are within 2°, though receiver 11 stands out as having a noticeably higher standard deviation than the other geophones. Ignoring receiver 2, the far-offset standard deviations average to 5.24° using the analytic method and 5.83° using the linear regression method – this suggests that these methods are very comparable, though the analytic method appears slightly more constrained. This final result also shows that there is considerable scatter of orientation azimuth in the unbinned data.

Tables 4 and 5 show the binned orientation azimuth means and standard deviations, after the removal of outliers and near offsets less than 300 m from the well. A comparison of methods using binned statistics (Tables 6 and 7) again shows great similarity, and again the analytic method is shown to have slightly less scatter than the linear regression method. Examining each receiver's mean orientation angle across bins, slight differences can be seen, but none of the differences is greater than 2° and there does not appear to be any consistent trend in the differences. In fact, the maximum mean angle difference is less than 1° for most receivers, despite the large variety in bin sizes. Finally, there are certain receivers (3 and 7) where the unbinned mean angle was outside of the range of the binned mean angles, and others where the unbinned standard deviation is greater than any of the binned standard deviations. These effects are related to the removal of outliers, and are no longer present if the same outliers are removed from both the unbinned and binned datasets.

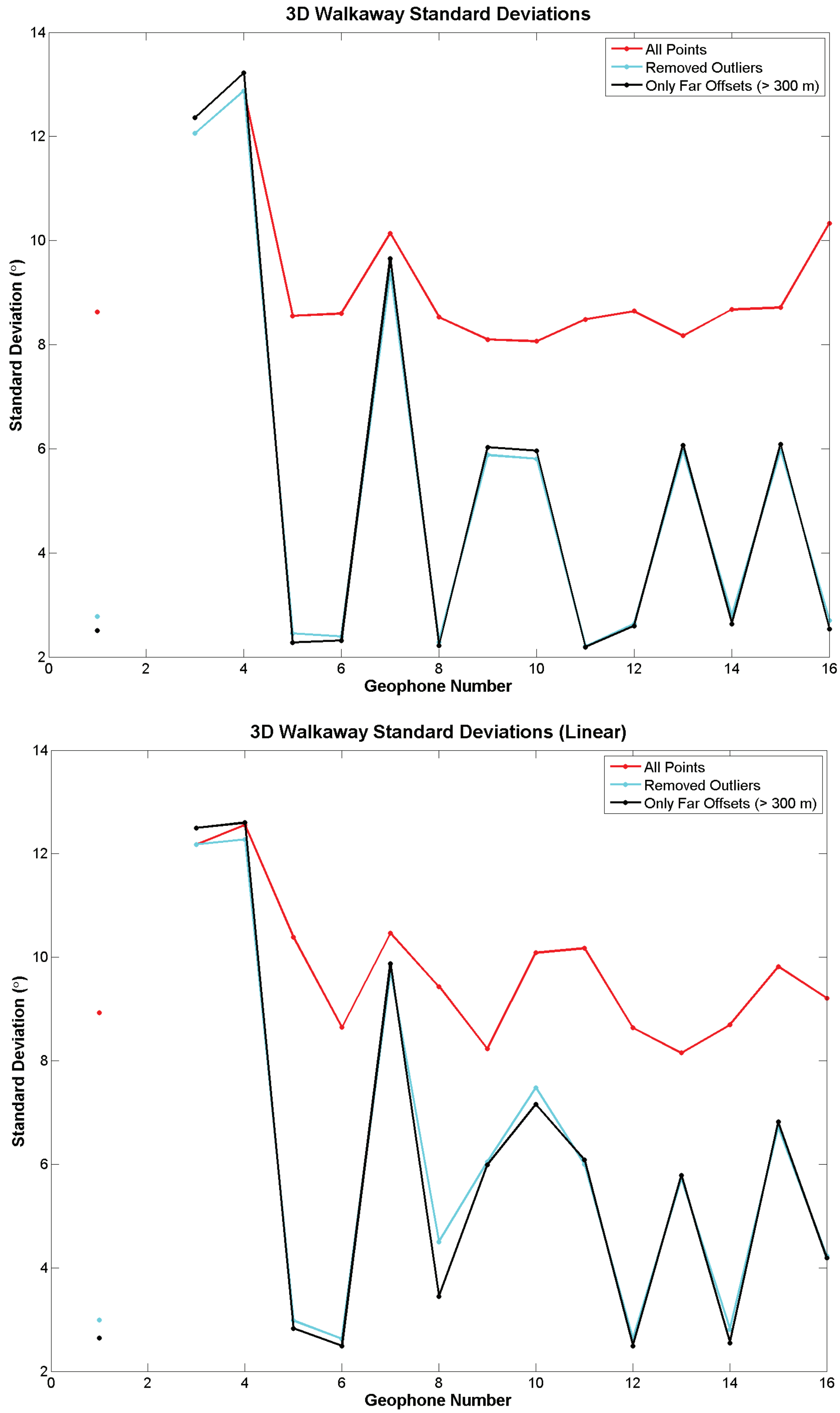

FIG. 10. Orientation azimuth standard deviations for each receiver calculated using the analytic (top) and linear regression (bottom) methods. Red is calculated using all data points, cyan after removal of outliers and black after removal of outliers and near offsets less than 300 m.

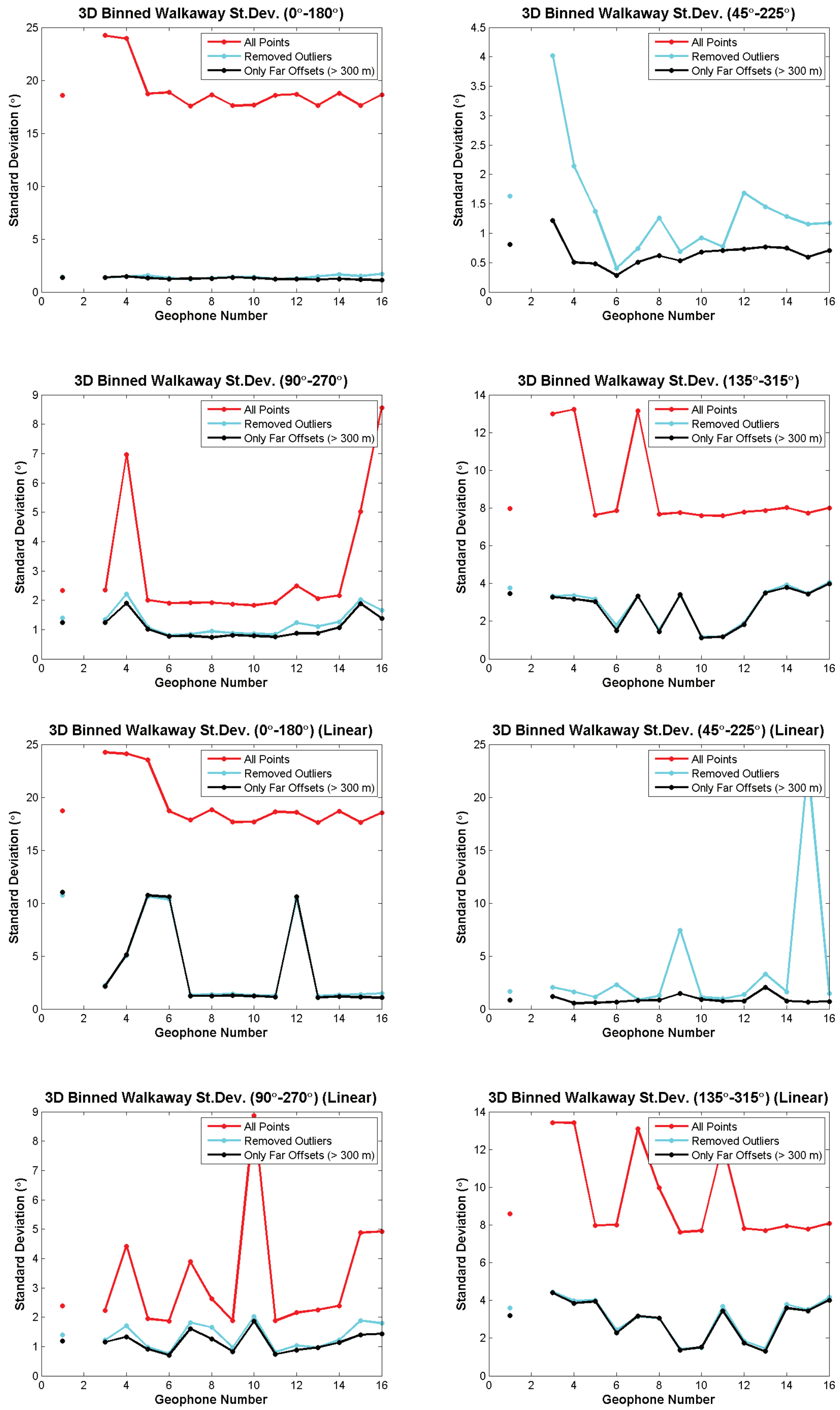

FIG. 11. Orientation azimuth standard deviations for each receiver calculated using the analytic (top 4) and linear regression (bottom 4) methods, using bins. Red is calculated using all data points, cyan after removal of outliers and black after removal of outliers and near offsets less than 300 m.

Table 1. Geophone orientation statistics for 3D azimuth calculations made using the analytic method. All values are in degrees.

	All		Removed Outliers		Far	
Receiver	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
1	273.7	8.63	272.8	2.78	272.8	2.51
2	60.0	57.10	60.0	57.10	60.5	57.45
3	256.7	12.06	256.7	12.06	256.7	12.36
4	261.5	12.88	261.5	12.88	261.5	13.22
5	280.7	8.55	279.8	2.45	279.8	2.28
6	301.5	8.60	300.6	2.39	300.6	2.32
7	163.2	10.14	162.9	9.39	162.9	9.66
8	195.5	8.53	194.6	2.29	194.6	2.22
9	136.1	8.10	135.6	5.88	135.6	6.03
10	158.6	8.06	158.0	5.81	158.1	5.96
11	215.3	8.48	214.5	2.21	214.5	2.19
12	103.4	8.64	102.6	2.64	102.6	2.59
13	148.0	8.17	147.5	5.95	147.5	6.07
14	124.9	8.68	124.0	2.79	124.1	2.63
15	135.8	8.71	135.1	5.96	135.1	6.09
16	118.6	10.33	117.4	2.71	117.4	2.54
Average		9.24		5.21		5.24

Table 2. Geophone orientation statistics for 3D azimuth calculations made using the linear regression method. All values are in degrees.

	All		Removed Outliers		Far	
Receiver	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
1	273.8	8.92	272.7	2.99	272.8	2.64
2	60.2	56.92	60.2	56.92	60.7	57.25
3	256.9	12.18	256.9	12.18	256.9	12.50
4	261.9	12.56	261.7	12.27	261.7	12.60
5	281.3	10.39	280.0	2.98	280.0	2.83
6	301.5	8.64	300.7	2.63	300.7	2.49
7	162.8	10.46	162.6	9.73	162.5	9.87
8	195.2	9.44	194.3	4.50	194.4	3.44
9	135.9	8.23	135.4	6.05	135.6	5.99
10	158.2	10.09	157.5	7.48	157.7	7.16
11	214.9	10.18	214.0	6.00	214.0	6.09
12	103.5	8.64	102.6	2.62	102.7	2.49
13	147.9	8.15	147.2	5.71	147.3	5.78
14	124.8	8.69	123.9	2.81	124.0	2.55
15	135.5	9.82	134.7	6.72	134.8	6.82
16	118.0	9.21	117.1	4.23	117.2	4.19
Average		9.71		5.93		5.83

Table 3. Differences in geophone orientation statistics for 3D azimuth calculations made using the analytic and linear regression methods. Negative numbers indicate that values in the analytic method were smaller than those in the linear regression method; average is calculated using absolute values. All values are in degrees.

	All		Removed Outliers		Far	
Receiver	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
1	-0.09	-0.30	0.03	-0.22	0.01	-0.13
2	-0.20	0.18	-0.20	0.18	-0.21	0.20
3	-0.21	-0.12	-0.21	-0.12	-0.22	-0.14
4	-0.38	0.32	-0.21	0.60	-0.21	0.62
5	-0.56	-1.83	-0.20	-0.53	-0.19	-0.55
6	-0.05	-0.05	-0.05	-0.23	-0.04	-0.18
7	0.36	-0.32	0.36	-0.34	0.37	-0.22
8	0.32	-0.91	0.33	-2.21	0.22	-1.23
9	0.19	-0.13	0.19	-0.17	0.04	0.04
10	0.33	-2.02	0.58	-1.67	0.40	-1.20
11	0.46	-1.69	0.47	-3.79	0.53	-3.90
12	-0.08	0.01	-0.08	0.01	-0.08	0.10
13	0.13	0.02	0.23	0.24	0.24	0.29
14	0.10	-0.02	0.11	-0.01	0.07	0.08
15	0.29	-1.11	0.38	-0.76	0.33	-0.73
16	0.60	1.12	0.24	-1.53	0.27	-1.65
Average	0.27	0.63	0.24	0.79	0.21	0.70

Table 4. Geophone orientation statistics for binned 3D azimuth calculations made using the analytic method. All values are in degrees.

	All		0-180		45-225		90-270		135-315	
Receiver	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
1	272.8	2.51	272.7	1.37	272.0	0.81	272.9	1.23	272.8	3.47
2	60.5	57.45	-3.2	12.02	61.1	4.07	89.6	9.54	47.5	80.43
3	256.7	12.36	258.4	1.38	258.0	1.21	258.2	1.23	257.7	3.28
4	261.5	13.22	262.5	1.48	261.8	0.50	263.1	1.90	263.6	3.18
5	279.8	2.28	279.3	1.32	278.3	0.48	279.8	1.02	280.3	3.02
6	300.6	2.32	300.1	1.24	300.8	0.28	301.0	0.78	299.9	1.51
7	162.9	9.66	164.5	1.27	163.8	0.50	163.6	0.78	163.6	3.34
8	194.6	2.22	195.0	1.28	195.0	0.62	194.6	0.73	194.2	1.45
9	135.6	6.03	136.5	1.39	136.3	0.53	135.9	0.81	135.9	3.42
10	158.1	5.96	158.2	1.34	158.8	0.68	158.5	0.78	158.1	1.12
11	214.5	2.19	214.8	1.22	214.7	0.71	214.4	0.75	214.1	1.16
12	102.6	2.59	102.7	1.22	102.7	0.73	102.8	0.87	102.3	1.83
13	147.5	6.07	147.7	1.19	148.0	0.77	147.8	0.87	147.9	3.50
14	124.1	2.63	123.9	1.24	123.8	0.74	124.1	1.07	124.1	3.79
15	135.1	6.09	135.6	1.18	135.4	0.59	135.3	1.88	135.7	3.45
16	117.4	2.54	117.5	1.13	117.4	0.70	117.4	1.38	117.5	3.98
Average		5.24		1.28		0.66		1.07		2.77

Table 5. Geophone orientation statistics for binned 3D azimuth calculations made using the linear regression method. All values are in degrees.

	All		0-180		45-225		90-270		135-315	
Receiver	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
1	272.8	2.64	275.1	11.05	272.0	0.85	272.8	1.19	272.7	3.19
2	60.7	57.25	-3.2	12.02	61.0	4.06	89.4	9.71	47.2	80.24
3	256.9	12.50	258.3	2.12	258.0	1.16	258.2	1.15	258.3	4.40
4	261.7	12.60	261.1	5.11	262.1	0.54	263.2	1.33	263.9	3.85
5	280.0	2.83	281.9	10.74	278.6	0.59	279.7	0.90	280.6	3.95
6	300.7	2.49	302.4	10.59	300.8	0.65	300.9	0.71	300.0	2.28
7	162.5	9.87	164.6	1.25	164.6	0.80	163.3	1.61	163.3	3.18
8	194.4	3.44	195.0	1.23	195.3	0.82	194.6	1.26	194.4	3.07
9	135.6	5.99	136.7	1.27	135.6	1.44	135.8	0.83	135.6	1.37
10	157.7	7.16	158.3	1.22	160.0	0.89	158.2	1.86	157.8	1.51
11	214.0	6.09	214.8	1.15	214.7	0.73	214.5	0.73	214.2	3.44
12	102.7	2.49	105.1	10.59	102.6	0.75	102.7	0.88	102.2	1.73
13	147.3	5.78	147.9	1.10	147.5	2.06	147.7	0.96	147.4	1.30
14	124.0	2.55	124.1	1.16	123.4	0.76	123.9	1.13	124.0	3.59
15	134.8	6.82	135.9	1.13	134.9	0.67	135.3	1.40	135.6	3.44
16	117.2	4.19	117.7	1.08	117.1	0.72	117.2	1.43	117.5	4.02
Average		5.83		4.05		0.90		1.16		2.96

Table 6. Differences in geophone orientation statistics for binned 3D dataset calculated using the analytic and linear regression methods. Negative numbers indicate that values in the analytic method were smaller than those in the linear regression method; average is calculated using absolute values. All values are in degrees.

	All		0-180		45-225		90-270		135-315	
Receiver	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
1	0.01	-0.13	-2.37	-9.68	0.00	-0.04	0.09	0.04	0.13	0.28
2	-0.21	0.20	-0.01	0.00	0.03	0.02	0.18	-0.16	0.26	0.19
3	-0.22	-0.14	0.15	-0.74	-0.05	0.05	-0.01	0.09	-0.70	-1.13
4	-0.21	0.62	1.39	-3.63	-0.23	-0.04	-0.10	0.57	-0.30	-0.67
5	-0.19	-0.55	-2.61	-9.42	-0.29	-0.11	0.07	0.12	-0.32	-0.92
6	-0.04	-0.18	-2.32	-9.35	-0.06	-0.37	0.13	0.07	-0.09	-0.77
7	0.37	-0.22	-0.12	0.02	-0.82	-0.29	0.27	-0.82	0.38	0.15
8	0.22	-1.23	-0.01	0.05	-0.27	-0.20	0.00	-0.53	-0.13	-1.61
9	0.04	0.04	-0.16	0.12	0.70	-0.92	0.10	-0.02	0.29	2.05
10	0.40	-1.20	-0.07	0.12	-1.21	-0.21	0.29	-1.07	0.23	-0.39
11	0.53	-3.90	-0.03	0.07	-0.07	-0.02	-0.07	0.02	-0.10	-2.28
12	-0.08	0.10	-2.46	-9.37	0.04	-0.02	0.05	-0.01	0.04	0.10
13	0.24	0.29	-0.16	0.09	0.46	-1.29	0.15	-0.09	0.54	2.21
14	0.07	0.08	-0.27	0.08	0.38	-0.02	0.15	-0.06	0.09	0.19
15	0.33	-0.73	-0.25	0.05	0.53	-0.08	0.05	0.48	0.07	0.01
16	0.27	-1.65	-0.25	0.05	0.33	-0.02	0.13	-0.06	0.03	-0.03
Average	**0.21**	**0.70**	**0.79**	**2.68**	**0.34**	**0.23**	**0.11**	**0.26**	**0.23**	**0.81**

Table 7. Average differences in geophone orientation statistics for binned 3D dataset calculated using the analytic and linear regression methods for individual receivers. All values are in degrees.

Receiver	Mean	Std. Dev
1	0.52	2.04
2	0.14	0.12
3	0.22	0.43
4	0.45	1.11
5	0.69	2.22
6	0.53	2.15
7	0.39	0.30
8	0.12	0.72
9	0.26	0.63
10	0.44	0.60
11	0.16	1.26
12	0.53	1.92
13	0.31	0.79
14	0.19	0.09
15	0.25	0.27
16	0.20	0.36

2D WALKAWAY RESULTS

Orientation calculations

Figures 12 – 15 show the results of orientation angle calculations using the analytic method. Each of the three lines is shown in a different colour on these graphs; there were an equal number of data points for all three lines, and they each had a similar offset distribution. Visually, the orientation azimuths show no clear dependence on the orientation of the line chosen, and agreement is quite good between each of the lines. Again, more scatter can be seen in the nearer offsets, and the deeper receiver positions retain this scatter for further offsets; however, as mentioned previously, one must keep in mind that there were header errors in the source locations, and that these will most likely affect the nearer offsets more than the farther offsets. The problems with the y-component of the receiver in the second tool position (i.e. positions 2, 18, 34 and 50) seen in the 3D walkaway are once again apparent here.

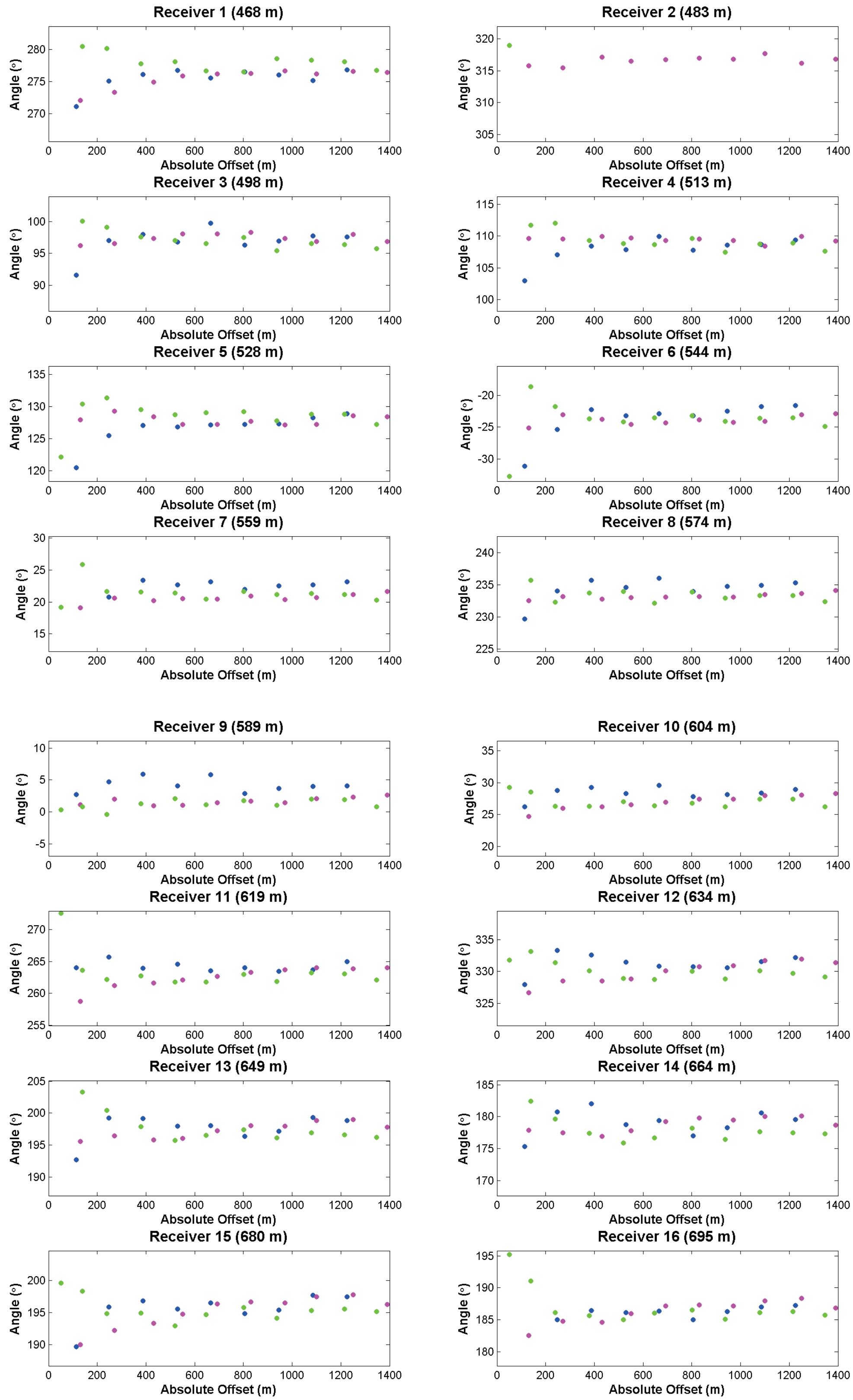

FIG. 12. Geophone orientation azimuths for receiver positions 1-16, calculated using analytic method, for 2D walkaway colored by line; E is shown in blue, SE is shown in magenta and S is shown in green.

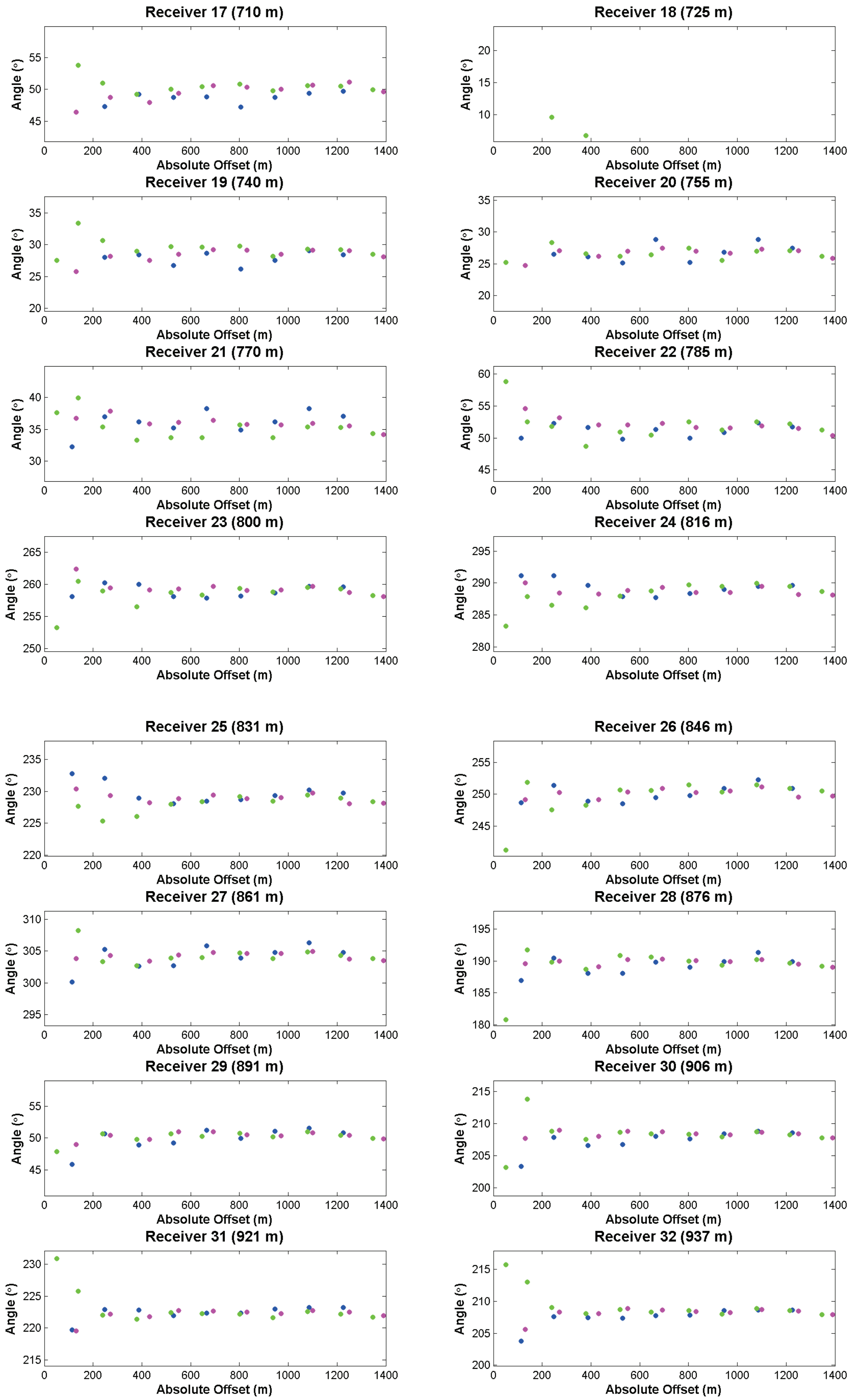

FIG. 13. Geophone orientation azimuths for receiver positions 17-32, calculated using analytic method, for 2D walkaway colored by line; E is shown in blue, SE is shown in magenta and S is shown in green.

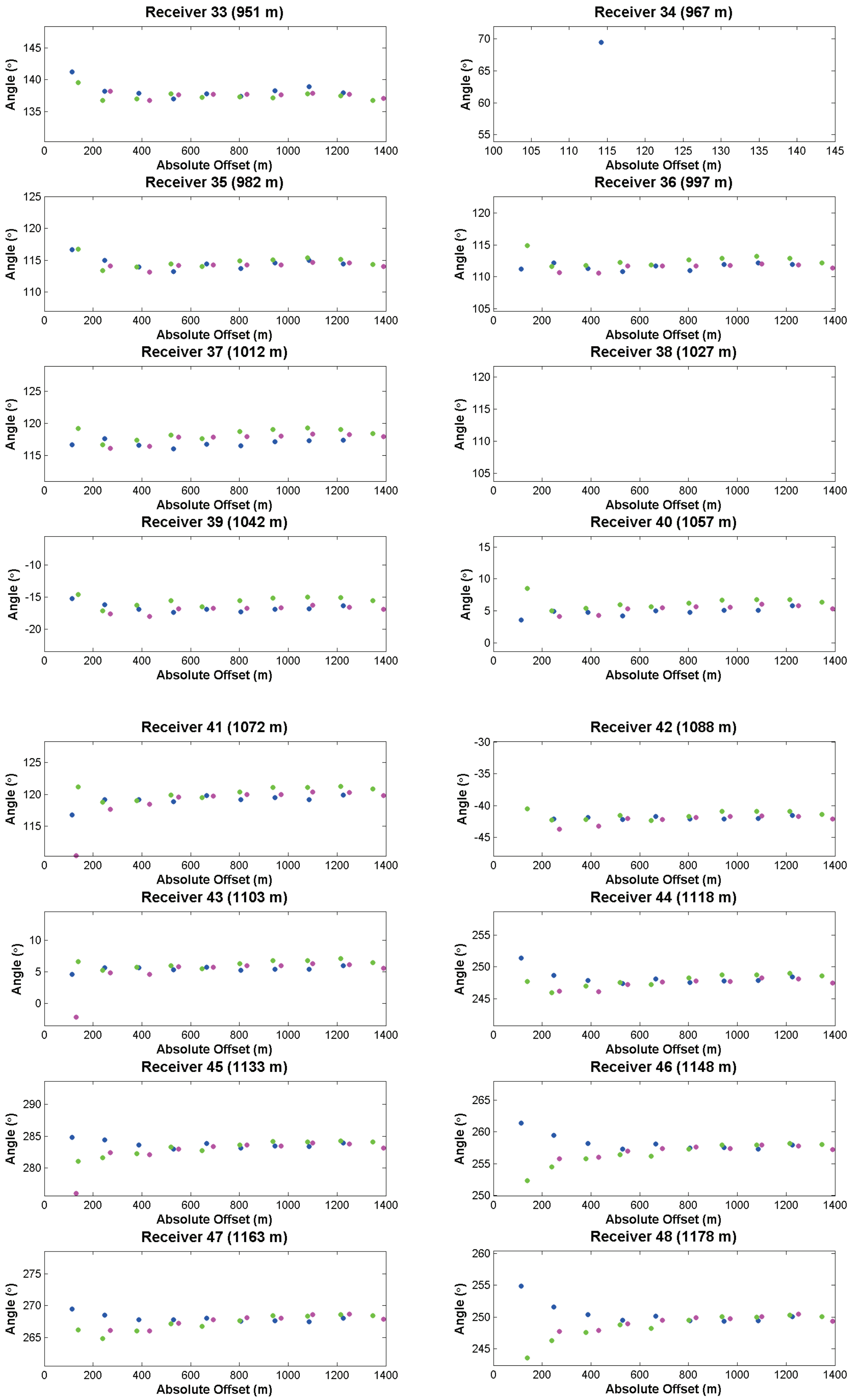

FIG. 14. Geophone orientation azimuths for receiver positions 33-48, calculated using analytic method, for 2D walkaway colored by line; E is shown in blue, SE is shown in magenta and S is shown in green.

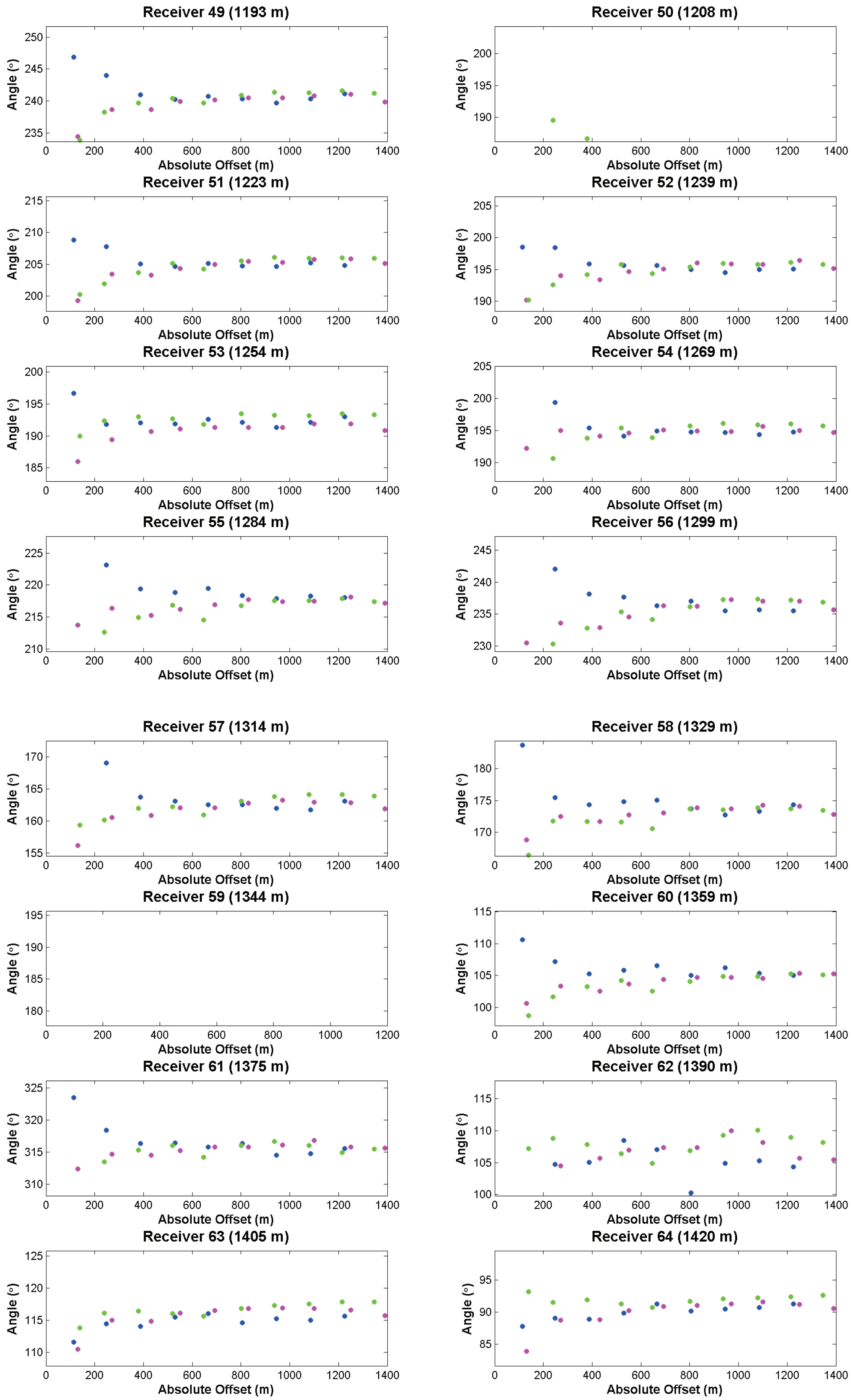

FIG. 15. Geophone orientation azimuths for receiver positions 49-64, calculated using analytic method, for 2D walkaway colored by line; E is shown in blue, SE is shown in magenta and S is shown in green.

Geophone orientation statistics calculations

Tables 8 and 9 show the results of statistical analysis of orientation angles of the 2D dataset when using all data points, after removal of outliers, and after removal of near offsets less than 300 m; here, there is a clear improvement when the near offsets are removed from the analysis. Figure 16, which graphically summarises the standard deviations calculated, emphasises this. Finally, Tables 10 and 11 show the line by line statistics after removal of near offsets; the scatter in all lines is very similar, and while there are small differences in the mean orientation azimuths calculated, no discernible pattern can be found.

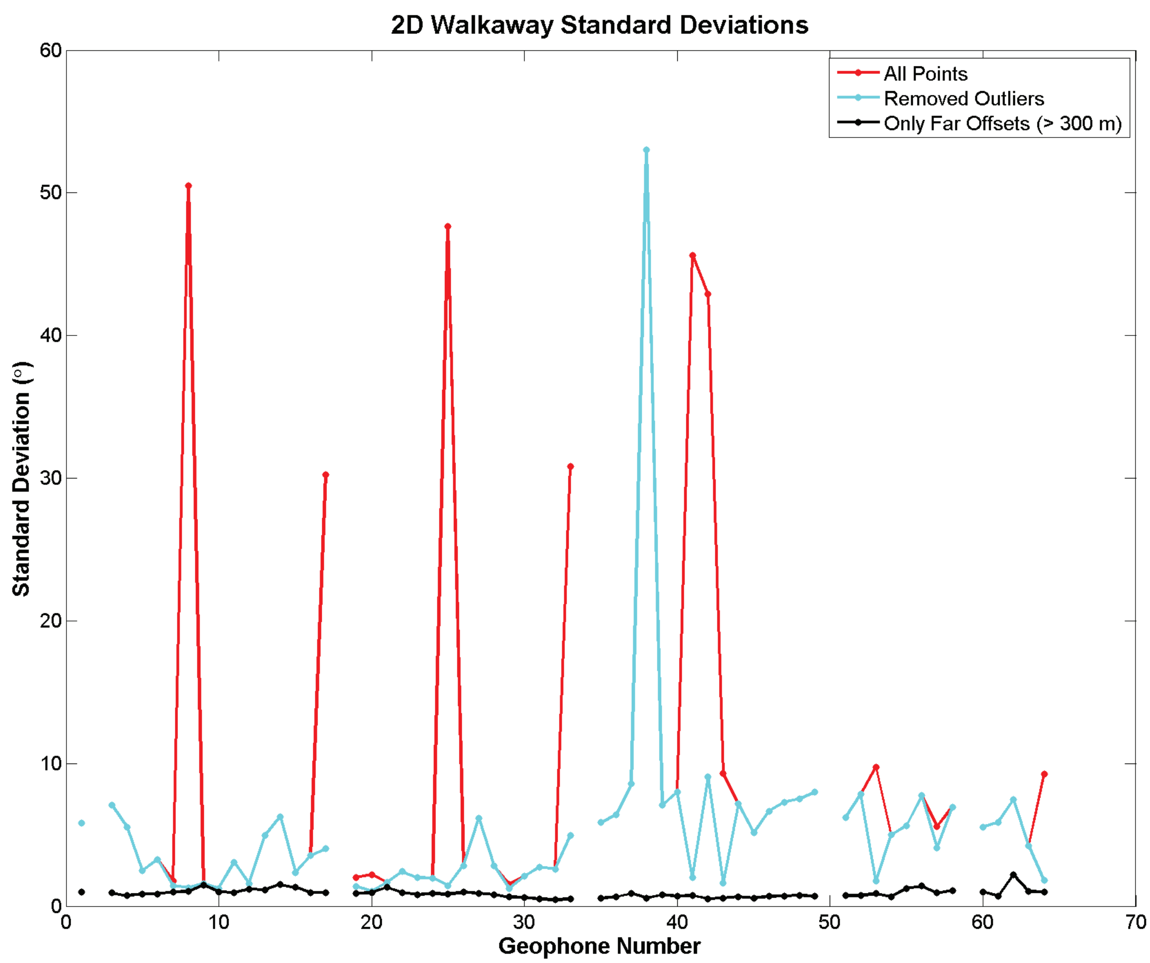

FIG. 16. Orientation standard deviations for each receiver calculated using the analytic method. Red is calculated using all data points, cyan after removal of outliers and black after removal of outliers and near offsets less than 300 m.

Table 8. Geophone orientation statistics for 2D azimuth calculations made using the analytic method for receiver positions 1-32. All values are in degrees.

	All		Removed Outliers		Far	
Receiver	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
1	274.7	5.81	274.7	5.81	276.7	0.97
2	312.9	41.45	312.9	41.45	318.2	40.06
3	94.9	7.10	94.9	7.10	97.2	0.93
4	107.2	5.52	107.2	5.52	108.9	0.75
5	127.3	2.47	127.3	2.47	128.0	0.85
6	-24.4	3.27	-24.4	3.27	-23.4	0.85
7	21.1	1.79	21.3	1.45	21.5	1.00
8	249.6	50.48	233.6	1.30	233.8	1.03
9	2.1	1.57	2.1	1.57	2.4	1.49
10	27.5	1.24	27.5	1.24	27.5	1.00
11	264.0	3.09	264.0	3.09	263.2	0.95
12	330.5	1.59	330.5	1.59	330.4	1.21
13	196.1	4.94	196.1	4.94	197.4	1.14
14	176.6	6.27	176.6	6.27	178.5	1.52
15	195.7	2.37	195.7	2.37	195.7	1.32
16	186.8	3.55	186.8	3.55	186.4	0.95
17	56.2	30.23	50.9	4.02	49.7	0.96
18	14.8	57.35	14.8	57.35	13.0	54.76
19	28.3	2.02	28.6	1.38	28.6	0.91
20	26.6	2.21	26.6	1.05	26.8	0.93
21	35.9	1.66	35.9	1.66	35.5	1.31
22	52.2	2.42	52.2	2.42	51.3	0.96
23	258.5	1.99	258.5	1.99	258.9	0.80
24	288.3	1.97	288.3	1.97	288.7	0.88
25	244.0	47.64	228.9	1.43	228.7	0.84
26	249.4	2.85	249.4	2.85	250.3	0.99
27	302.3	6.16	302.3	6.16	304.2	0.91
28	188.8	2.81	188.8	2.81	189.7	0.81
29	50.2	1.52	50.0	1.24	50.4	0.65
30	207.8	2.08	207.8	2.08	208.2	0.61
31	223.1	2.75	223.1	2.75	222.4	0.49
32	208.9	2.60	208.9	2.60	208.3	0.44

Table 9. Geophone orientation statistics for 2D azimuth calculations made using the analytic method for receiver positions 33-64. All values are in degrees.

	All		Removed Outliers		Far	
Receiver	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
33	144.7	30.81	139.4	4.95	137.6	0.49
34	63.0	60.08	63.0	60.08	74.0	54.77
35	116.0	5.86	116.0	5.86	114.4	0.56
36	113.6	6.41	113.6	6.41	111.9	0.64
37	120.0	8.57	120.0	8.57	117.7	0.89
38	112.7	52.99	112.7	52.99	132.8	0.58
39	-14.5	7.07	-14.5	7.07	-16.4	0.79
40	7.7	8.03	7.7	8.03	5.6	0.72
41	104.9	45.60	119.4	2.00	119.9	0.74
42	-28.2	42.91	-38.9	9.04	-41.8	0.51
43	8.4	9.31	5.5	1.60	5.9	0.56
44	249.8	7.17	249.8	7.17	247.8	0.66
45	284.7	5.17	284.7	5.17	283.5	0.58
46	259.0	6.67	259.0	6.67	257.4	0.70
47	269.5	7.29	269.5	7.29	267.7	0.72
48	251.3	7.52	251.3	7.52	249.5	0.77
49	242.7	7.99	242.7	7.99	240.5	0.70
50	195.2	57.69	195.2	57.69	193.2	55.08
51	206.7	6.20	206.7	6.20	205.1	0.73
52	197.5	7.83	197.5	7.83	195.3	0.74
53	195.0	9.74	191.9	1.76	192.2	0.88
54	196.1	4.99	196.1	4.99	195.0	0.67
55	218.6	5.65	218.6	5.65	217.4	1.26
56	238.2	7.75	238.2	7.75	236.1	1.42
57	164.2	5.58	163.5	4.09	162.7	0.92
58	175.3	6.95	175.3	6.95	173.3	1.09
59	186.7	69.59	186.7	69.59	208.1	51.41
60	106.1	5.53	106.1	5.53	104.7	1.00
61	317.2	5.88	317.2	5.88	315.6	0.71
62	108.8	7.45	108.8	7.45	106.7	2.19
63	116.9	4.22	116.9	4.22	116.2	1.03
64	93.5	9.26	90.6	1.81	91.0	1.00
Average		10.47		6.27		1.73

Table 10. Line by line geophone orientation statistics for 2D azimuth calculations made using the analytic method for receiver positions 1-32. All values are in degrees.

	All		E		SE		S	
Receiver	**Mean**	**Std. Dev**	**Mean**	**Std. Dev**	**Mean**	**Std. Dev**	**Mean**	**Std. Dev**
1	276.7	0.97	276.1	0.62	276.1	0.57	277.6	0.82
2	318.2	40.06	267.0	1.82	316.8	0.45	364.2	1.52
3	97.2	0.93	97.6	1.12	97.6	0.57	96.6	0.75
4	108.9	0.75	108.7	0.76	109.4	0.50	108.7	0.74
5	128.0	0.85	127.5	0.76	127.7	0.63	128.6	0.77
6	-23.4	0.85	-22.5	0.65	-23.9	0.60	-23.9	0.52
7	21.5	1.00	22.8	0.49	20.7	0.46	21.1	0.49
8	233.8	1.03	235.0	0.70	233.3	0.44	233.2	0.69
9	2.4	1.49	4.3	1.10	1.7	0.60	1.5	0.50
10	27.5	1.00	28.6	0.65	27.4	0.74	26.7	0.53
11	263.2	0.95	264.0	0.59	263.2	0.92	262.5	0.61
12	330.4	1.21	331.4	0.77	330.5	1.27	329.4	0.60
13	197.4	1.14	198.1	1.07	197.6	1.19	196.7	0.71
14	178.5	1.52	179.4	1.62	179.0	1.14	177.1	0.75
15	195.7	1.32	196.3	1.11	196.1	1.46	194.8	0.91
16	186.4	0.95	186.4	0.73	186.9	1.16	185.8	0.56
17	49.7	0.96	48.8	0.79	50.0	1.00	50.2	0.50
18	13.0	54.76	88.3	2.08	-43.5	0.48	3.8	1.63
19	28.6	0.91	27.9	1.08	28.6	0.62	29.2	0.57
20	26.8	0.93	26.9	1.52	26.8	0.55	26.6	0.60
21	35.5	1.31	36.6	1.34	35.7	0.65	34.4	0.92
22	51.3	0.96	51.1	0.95	51.6	0.59	51.2	1.27
23	258.9	0.80	258.9	0.88	259.1	0.52	258.6	0.97
24	288.7	0.88	288.8	0.82	288.7	0.52	288.8	1.26
25	228.7	0.84	229.1	0.75	228.8	0.61	228.3	1.03
26	250.3	0.99	250.1	1.31	250.2	0.69	250.5	1.01
27	304.2	0.91	304.4	1.41	304.2	0.61	304.0	0.65
28	189.7	0.81	189.4	1.17	189.8	0.53	189.8	0.73
29	50.4	0.65	50.4	1.05	50.5	0.46	50.4	0.40
30	208.2	0.61	207.8	0.87	208.4	0.38	208.2	0.42
31	222.4	0.49	222.7	0.49	222.4	0.36	222.0	0.42
32	208.3	0.44	208.0	0.56	208.4	0.33	208.4	0.36

Table 11. Line by line geophone orientation statistics for 2D azimuth calculations made using the analytic method for receiver positions 33-64. All values are in degrees.

	All		E		SE		S	
Receiver	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
33	137.6	0.49	137.9	0.60	137.5	0.38	137.3	0.35
34	74.0	54.77	87.5	1.92	131.4	0.98	4.8	1.25
35	114.4	0.56	114.2	0.59	114.2	0.47	114.7	0.54
36	111.9	0.64	111.5	0.52	111.6	0.44	112.5	0.54
37	117.7	0.89	116.8	0.48	117.8	0.59	118.4	0.69
38	132.8	0.58	133.0	0.41	132.5	0.59	133.0	0.63
39	-16.4	0.79	-16.9	0.33	-16.8	0.53	-15.6	0.55
40	5.6	0.72	5.0	0.47	5.5	0.53	6.2	0.55
41	119.9	0.74	119.4	0.36	119.8	0.60	120.4	0.83
42	-41.8	0.51	-41.9	0.22	-42.0	0.51	-41.5	0.58
43	5.9	0.56	5.5	0.26	5.8	0.53	6.3	0.55
44	247.8	0.66	247.9	0.36	247.6	0.67	248.1	0.79
45	283.5	0.58	283.5	0.34	283.3	0.57	283.6	0.76
46	257.4	0.70	257.7	0.39	257.3	0.60	257.2	0.94
47	267.7	0.72	267.7	0.23	267.8	0.83	267.7	0.95
48	249.5	0.77	249.7	0.41	249.5	0.80	249.3	0.99
49	240.5	0.70	240.5	0.49	240.2	0.73	240.8	0.77
50	193.2	55.08	269.1	2.54	136.6	0.49	183.5	1.59
51	205.1	0.73	204.9	0.24	205.0	0.85	205.3	0.89
52	195.3	0.74	195.2	0.49	195.3	0.97	195.4	0.74
53	192.2	0.88	192.2	0.54	191.3	0.42	193.0	0.56
54	195.0	0.67	194.7	0.40	194.8	0.43	195.3	0.93
55	217.4	1.26	218.6	0.63	217.0	0.91	216.7	1.25
56	236.1	1.42	236.5	1.07	235.9	1.50	235.9	1.67
57	162.7	0.92	162.7	0.69	162.4	0.77	163.0	1.19
58	173.3	1.09	174.0	0.82	173.3	0.85	172.8	1.26
59	208.1	51.41	198.4	67.59	223.5	1.04	201.2	63.02
60	104.7	1.00	105.6	0.58	104.4	0.91	104.3	0.96
61	315.6	0.71	315.7	0.79	315.7	0.65	315.6	0.78
62	106.7	2.19	105.0	2.55	107.1	1.54	107.8	1.69
63	116.2	1.03	115.2	0.67	116.3	0.73	116.9	0.86
64	91.0	1.00	90.4	0.85	90.7	0.89	91.9	0.63
Average		1.73		1.87		0.71		1.81

DISCUSSION

The geophone orientation azimuth calculations done in this study, for both the 3D and 2D walkaways, resulted in fairly robust outcomes. The 2D walkaway data showed similar scatter in orientation azimuth when the dataset was examined line by line compared to overall calculations, but the scatter in the 3D walkaway data changed significantly when the data were split into separate bins, though the mean angle calculations resulted in very similar values. This is an interesting effect, and shows that statistical calculations can be very sensitive to the approach used, and must be interpreted carefully. Additionally, the removal of shots from source-well offsets nearer than about 1/3 of the geophone depth had a large effect on the 2D walkaway orientation statistics, while having little effect on the 3D dataset. This is probably due to the low proportion of near offset source locations in the 3D walkaway survey; though not shown in this paper, the removal of near offsets in the binned 3D data did result in a noticeable improvement of the standard deviations.

The results found using the binned (3D walkaway) and line by line (2D walkaway) calculations do not show any clear indication that, in this area, there is an azimuthal dependence of borehole geophone orientation angle calculations. Mean angles calculated in this way are very consistent regardless of the bin or line chosen; differences are generally no larger than the standard deviations involved, nor are there any consistent trends for a particular bin or line. The consistency of the orientation angles can be interpreted to mean that the local geology is likely azimuthally independent, which suggests flat, isotropic layers.

Finally, comparison of the analytic and linear regression angle calculation methods revealed that the two are very similar, though the analytic method gave slightly less scatter in angle. In terms of orientation azimuth, the mean of the two methods rarely differed by greater than 1° and on average, other than the 0°-180° bin, differed by less than 0.5°. The similarity of results through both of these methods gives confidence that each of them can extract accurate information about geophone orientation angle.

CONCLUSIONS

- Geophone orientation angles for the 3D dataset were found using the DiSiena analytic method. The standard deviation was 5.24° using all azimuths, and became 1.28°, 0.66°, 1.07° and 2.77° when the data were binned into centers of 0°-180°, 45°-225°, 90°-270° and 135°-315° respectively.

- Geophone orientation angles for the 3D dataset were also found using a linear regression, or hodogram, method. The standard deviation was 5.83° for all azimuths, and 4.05°, 0.90°, 1.16° and 2.96° for binned data.

- Absolute difference in mean angles between the two methods averaged 0.21° for all azimuths, and 0.79°, 0.34°, 0.11° and 0.23° for binned data.

- Geophone orientation angles for the 2D dataset were found using the analytic method. The standard deviation was 1.73° for all lines, 1.87° for the east line, 0.71° for the southeast line and 1.81° for the south line.

- For both the 3D and the 2D walkaways, the geophone orientation azimuths were not found to have any consistent dependence on source-well azimuth, suggesting flat, isotropic geology near the well.

- Removal of data points nearer than 1/3 of the receiver depth had little effect on the scatter of orientation angles in the unbinned 3D walkaway; it did, however, significantly improve the scatter in the 2D walkaway, improving the standard deviation from 6.27° to 1.73° overall.

- The analytic and linear regression methods of calculating geophone orientation azimuth produced comparable results overall; however, the analytic method was found to consistently give less scatter and thus produced better results.

FUTURE WORK

A similar analysis on a dataset from an area with known anisotropy or structural complexity, such as a Foothills dataset, would provide a better indication of the effect of geology on geophone orientation azimuth calculations. Work examining the effects of first break windowing on the linear regression method would allow for a better comparison of this method with the analytic method. Finally, other methods, such as inversion methods, could be put through a similar analysis and compared with the results of the methods tested in this paper.

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