Upper Klamath Lake Seismic Results

October, 1999 Airgun and Uniboom Surveys

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Summary

We collected greater than 200 km of seismic reflection data in Upper Klamath Lake for the Oregon Department of Geology and Mineral Industries (DOGAMI) from October 9-15, 1999. We used two independent seismic systems to digitally image subsurface sediment and rock interfaces to help DOGAMI complete a 1:24,000 geologic map of the southern portion of the lake. We successfully imaged the near-surface stratigraphy for earthquake hazards and aquifer characterization studies using both an airgun and a uniboom seismic system. Results suggest that large portions of Upper Klamath Lake contain trapped gas in the lake floor that prevents much of the lake from being seismically imaged. Where trapped gas was not present, high-quality seismic reflection data was obtained. These data show a history of normal faulting in the region that appear to cut the shallowest reflectors, suggesting the region is still active and that seismic reflection methods are a valuable tool for seismic hazards analysis. This report is intended for initial data dissemination and all seismic profiles are presented and processed in a uniform fashion.

Setting

Upper Klamath Lake (UKL), located in southwestern Oregon (Figure 1), lies in an extensional basin at the northwestern edge of the Basin and Range province. The area is dominated by northwest-trending normal faults and the region has been recently seismically active (e.g., Braunmiller et al., 1995; Wiley et al., 1993). Although most of the recent seismic activity has been observed west of Klamath Lake (Braunmiller et al., 1995; Dreger et al., 1995; Wiley et al., 1993), faults in UKL appear to offset the 6.8 ka Mazama tephra (Colman et al., in review), as well as the overlying strata.

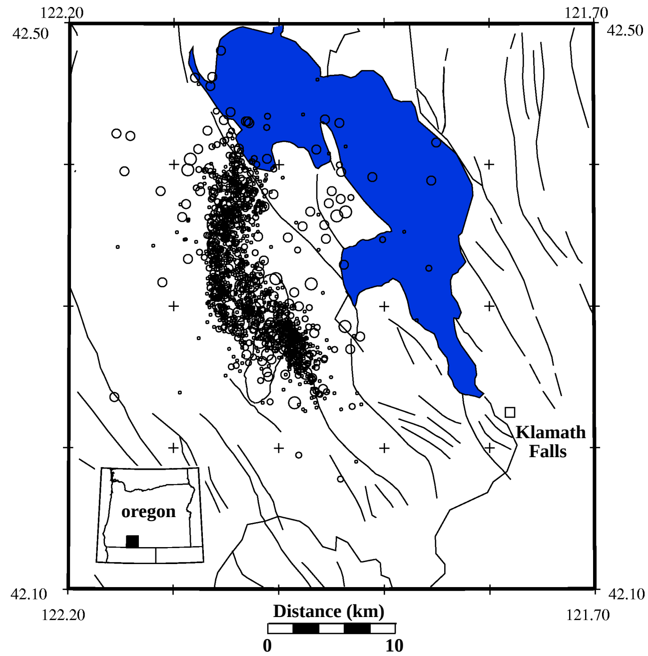


FIGURE 1. Upper Klamath Lake region with selected earthquake epicenters (from 9/20/93-12/03/93) and regional fault boundaries. Figure modified from ftp://ftp.geophys.washington.edu/pub/kfalls/hypos.map2.ps

Below the lake floor, UKL consists of diatomaceous soft sediments overlying Miocene-age diatomite and mudstone, interbedded with basalt flows that likely act as an acoustic basement for our high-resolution seismic studies. Although the soft Quaternary sediments that appear in the lake are often ideal seismic reflectors, a blue-green algal mat dominates the lake floor (Sanville et al., 1974), often collecting gas on the lake floor. This trapped gas creates a strong lake-floor reflection and severely inhibits seismic energy from reaching deeper targets. Colman et al. (in review), map out the regions where 3.5 kHz seismic energy penetrated the lake floor and we used their study to ensure that we collected some high-quality seismic reflection data where the algal mats did not interfere with data analysis. In addition, we also collected seismic data along the entire length and width of UKL (Figures 2-5).

Seismic Data Acquisition

We acquired the seismic reflection data from UKL using a 22-ft U.S. Bureau of Recreation Boston Whaler, and Uniboom^{TM} and air gun seismic sources. Boat speed during acquisition ranged from 1.0-2.0 m/s (2.2-4.4 mph). To attain a high resolution image of the upper hundred meters of the sub water bottom sediments, we recorded the Uniboom seismic source every 0.5 s with a 9-m oil-filled streamer containing 12 equally-spaced elements. The Uniboom seismic source provides approximately 300 joules of energy and has been successfully deployed in nearby water bodies (Pratt et al., in review).

The Uniboom seismic source provided high seismic quality from the upper portion of the lake sediments. To penetrate deeper in the section, we deployed an air gun seismic source and a 12-channel single-element solid-state hydrophone string. The air gun seismic source came equipped with 3, 5, and 10 cu in chambers, equivalent to 4000, 6800, and 13500 joules of energy (McQuillin and others, 1979). With larger air chambers, increased energy and depth of penetration should result (chamber size is proportional to the output energy), but with a decrease in production rates (decreased spatial sampling) and perhaps lower resolution. We tested all air gun chamber sizes in UKL, and opted for the 5 cu in. chamber for production. Since we could not operate both seismic systems simultaneously, we selected the 5 cu in. chamber to balance penetration depth and signal frequencies.

Each seismic source was integrated with a digital recording seismograph. We recorded the single-channel Uniboom seismic data with the MUDSEIS recording system (in-house USGS system) that integrated Global Positioning System (GPS) readings into the seismic headers to accurately record the real-time boat position. We recorded the 12-channel airgun data with a Geometrics RX-60 seismograph at 0.25 ms sample rate and one second recording window.

Seismic Data Processing

Uniboom

The Uniboom seismic data consist of single channel records that require no geometry information to obtain a stack. Processing consisted of a true amplitude recovery and a predictive deconvolution operator to attenuate water bottom multiples. We acquired Uniboom data every 0.5 s, resulting in 0.75-1.0 m spacing between shots.

Airgun

We experimented with 3, 5, and 10 cu in air gun chambers to optimize the seismic source signature and production rate while acquiring seismic data on UKL. In production, we settled on a 5 cu in air gun pressured to 1900-2000 psi. We recorded nominally every 4 seconds between shots approximately 3 knots (1.5 m/s) resulting in a shot spacing of roughly 6 m. Common mid-point (CMP) spacing is 1/2 the receiver spacing (1.5 m), and the CMP fold (redundancy of subsurface coverage) is 3. Due to the uncertainty in position of the source and streamer due to drift, and the GPS positions, we placed each CMP into 6.0 m bins, or 12-fold data.

General processing of the airgun seismic data consisted of:

1. SEG-Y Input - Read raw seismic data into ProMAX
2. Trace Header Math - Define each receiver position w/ respect to the shot position (3.0 m+chan*3.0 m)
3. Trace Header Math - Define each mid-point position to CDP=INT(FFID-CHAN/2)
4. Band pass filter (50-1000)
5. Inline Sort - Sort data into CDP space
6. NMO - correct for velocity moveout (1500 m/s)
7. CDP Stack - Stack each CDP position
8. Applied predictive decon operator
9. True amplitude recovery account for spherical divergence attenuation

10.Time-depth conversion (1500 m/s)

11.Stack Display

* Note: The data have not been migrated.

Upper Klamath Lake South - Buck Island to Klamath Falls

In this section, we present the seismic images and a brief summary of the data from the southern portion of UKL, between Klamath Falls and Buck Island (Figure 2).

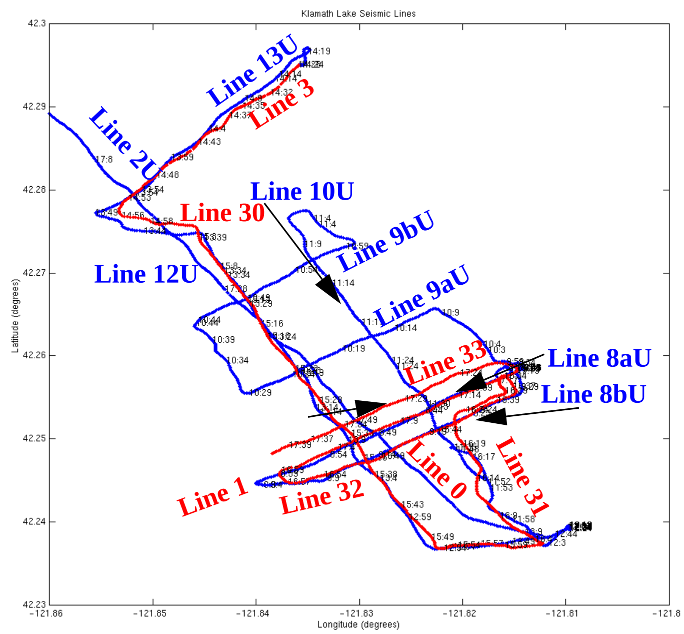


FIGURE 2. Seismic Profiles south of Buck Island in Upper Klamath Lake. Lines represent both 5 cu in air gun profiles and Uniboom profiles (U).

We recorded redundant profiles in this portion of UKL to compare the signature of the Uniboom with the air gun seismic sources. The comparison shows that the uniboom data record higher frequencies (greater than 1000 Hz), therefore greater resolution, but the seismic energy cannot penetrate as deep as the air gun source (energy up to 1000 Hz). The stratigraphy and structural style of the region is clear on many profiles in the region, particularly Uniboom profiles 8b (E-W), 12a (N-S), and 10a (N-S) and air gun profiles 32 (E-W), 30b (N-S), 0c (N-S) and 0d (N-S). It is particularly striking how the geology and data quality vary with minor changes in position (e.g., Uniboom lines 8a and 8b). The variability in data quality may be largely due to trapped gas, but also the small-scale sub-basin style features observed within UKL also contributes to this variation in data quality.

Uniboom Profiles

East-West Profiles (south-north)

Uniboom Line 8b - **JD 285, 16:01 - 16:29**

Uniboom Line 8a - **JD 285, 15:34 - 16:01**

Uniboom Line 9a - **JD 285, 17:10-17:29**

Uniboom Line 9b - **JD285, 17:43-18:01**

Uniboom Line 13 - **JD 285, 20:49-21:16**

North-South Profiles (west-east)

Uniboom Line 12a - **JD 285, 12:50-13:20**

Uniboom Line 12b - **JD 285, 13:20-13:48**

Uniboom Line 2b - **JD 282, 17:10-17:39**

Uniboom Line 2c - **JD 282, 17:40-18:09**

Uniboom Line 10a - **JD 285, 18:01-18:31**

Uniboom Line 10b - **JD 285, 18:32-19:01. Lost power on Line 10b at 18:39-18:47**

Airgun Profiles

East-West Profiles (south-north)

Line 32 - **JD 285, 16:38-16:57**

Line 1 - **JD 285, 17:00-17:20**

Line 33 - **JD 285, 17:20-17:41**

Line 3 - **JD 285, 14:26-14:56**

North-South Profiles (west-east)

Line 30a - **JD 285, 14:59-15:28**

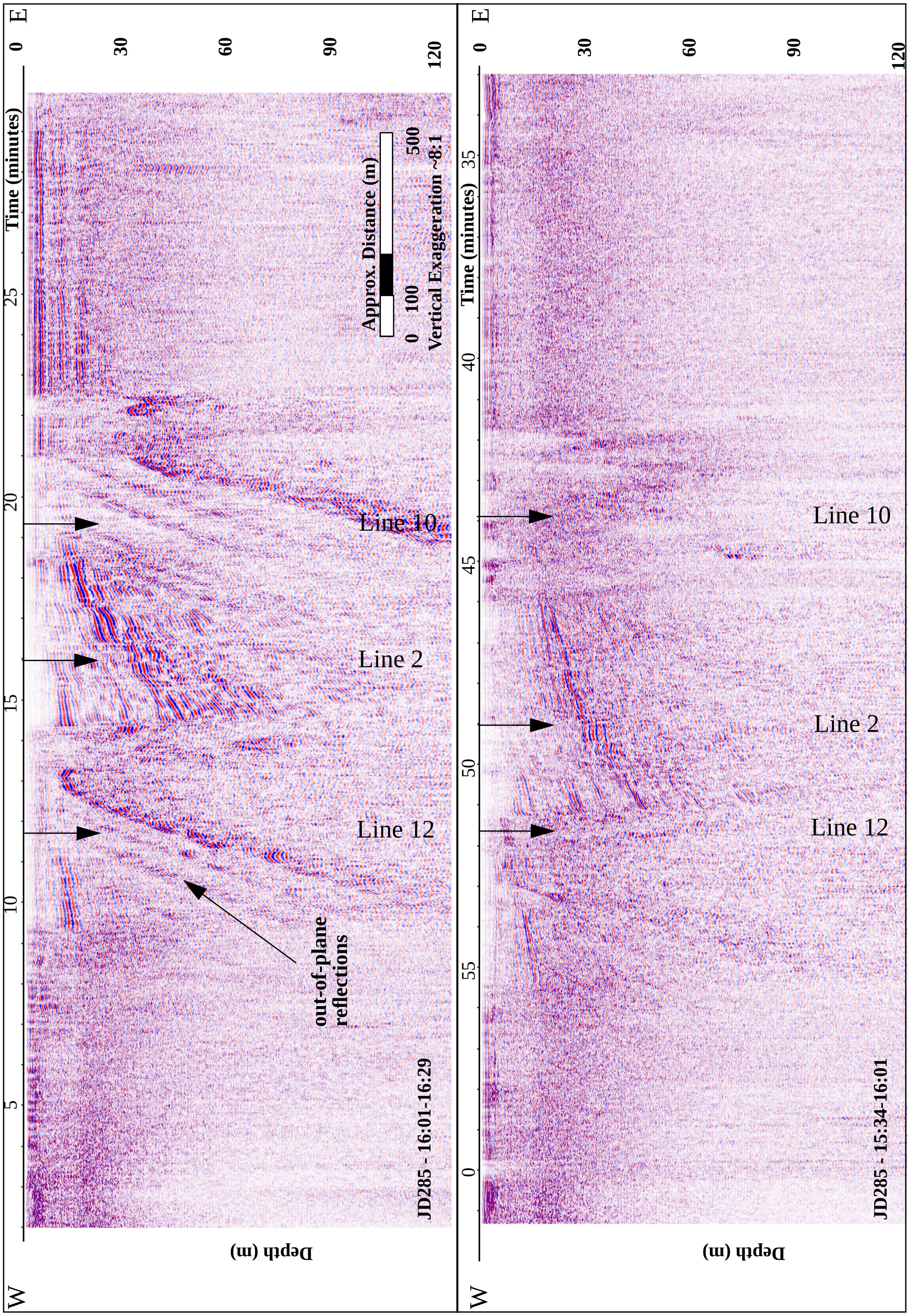
Line 30b - **JD 285, 15:28-15:50**

Line 0c - south of Buck Island - **JD 287, 17:22-17:52**

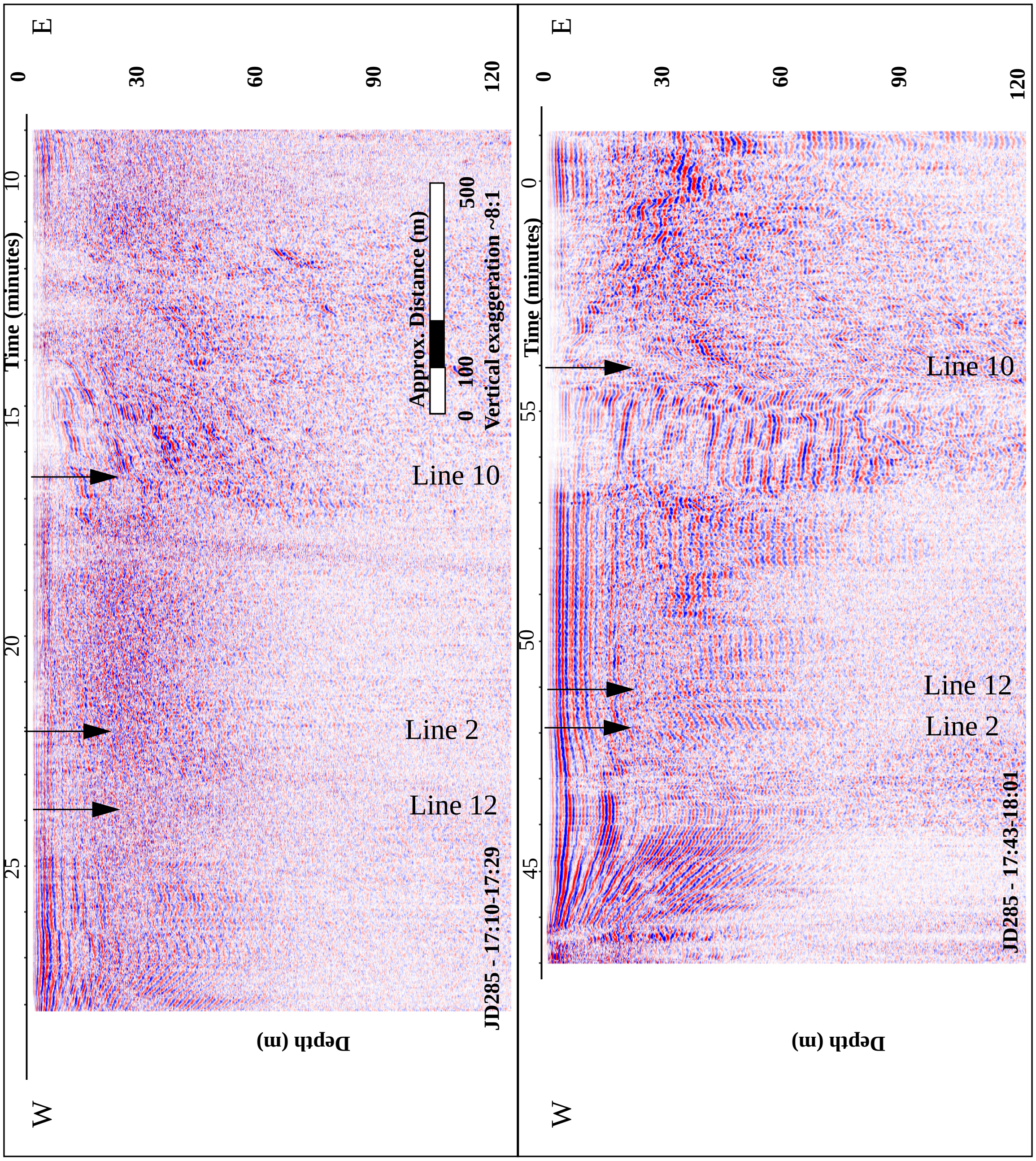
Line 0d - **JD 287 - 17:52-18:18**

Line 31 - **JD 285, 16:05-16:25**

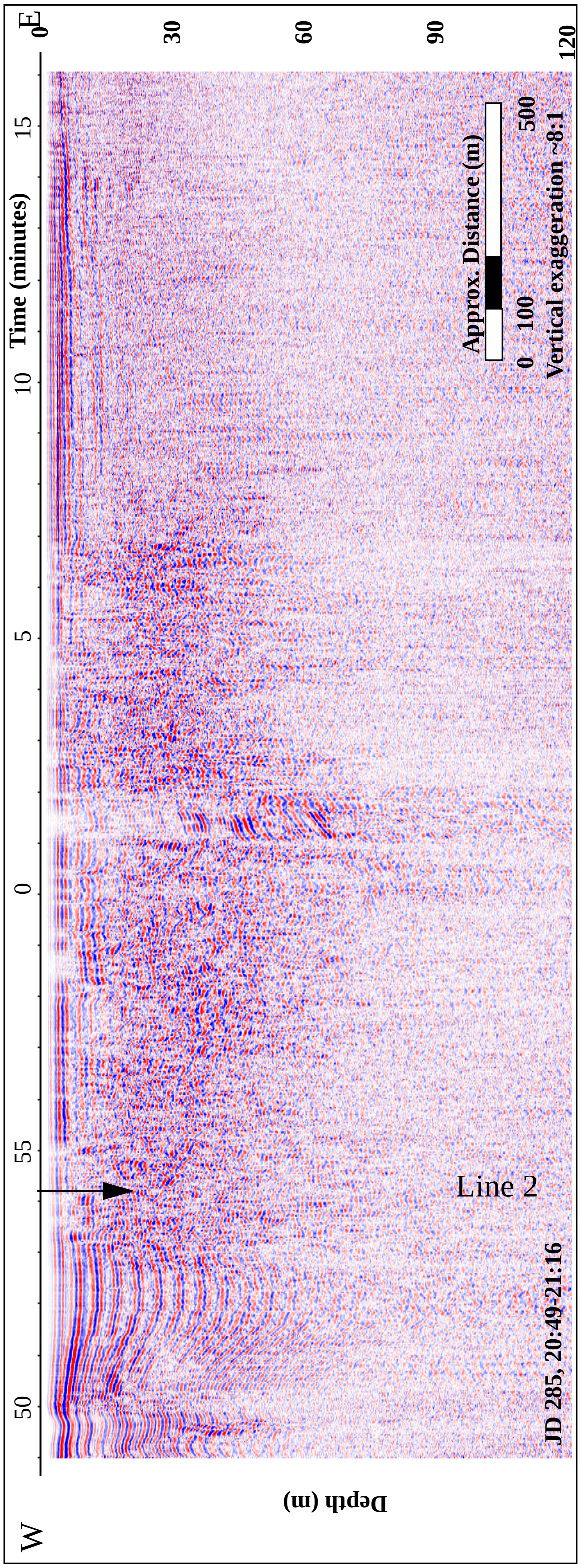
Uniboom Line 8b **Uniboom Line 8a**



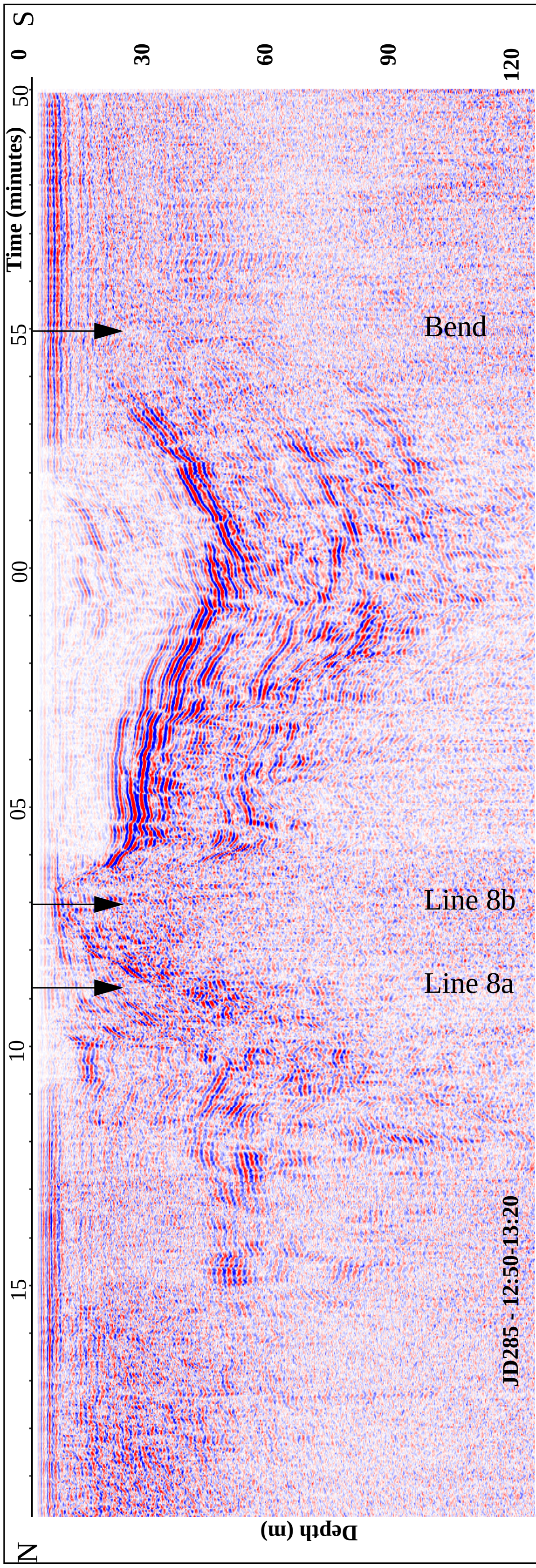
Uniboom Line 9a **Uniboom Line 9b**



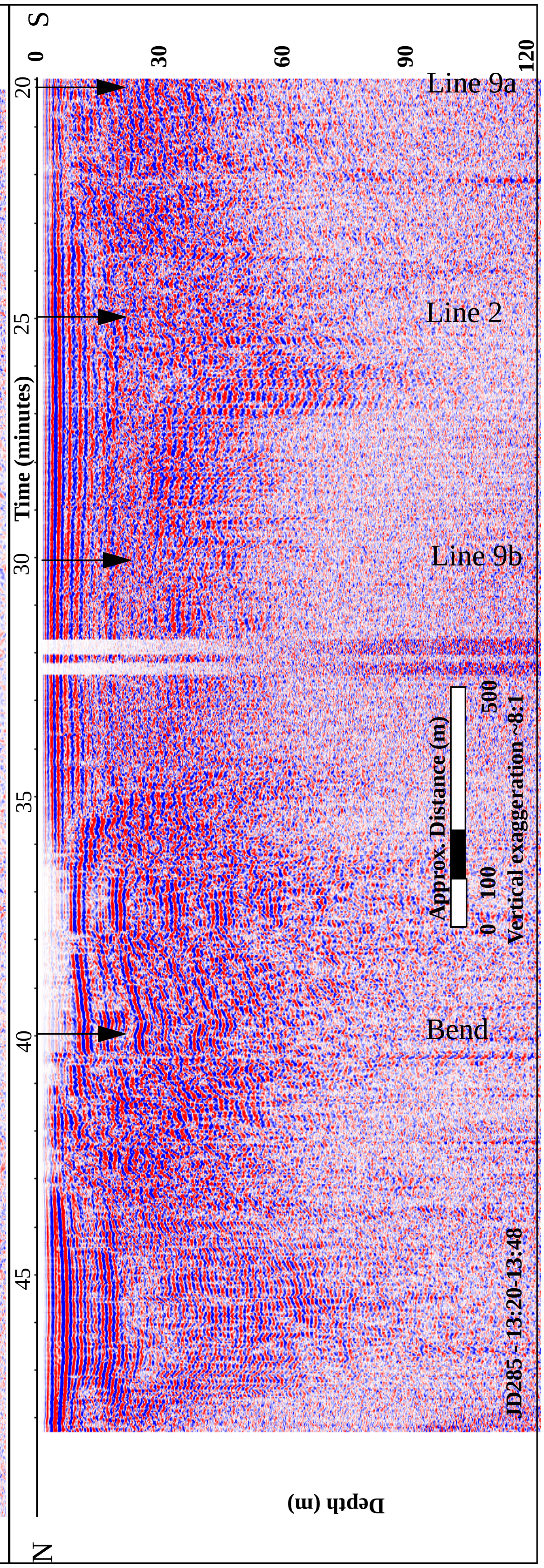
Uniboom Line 13



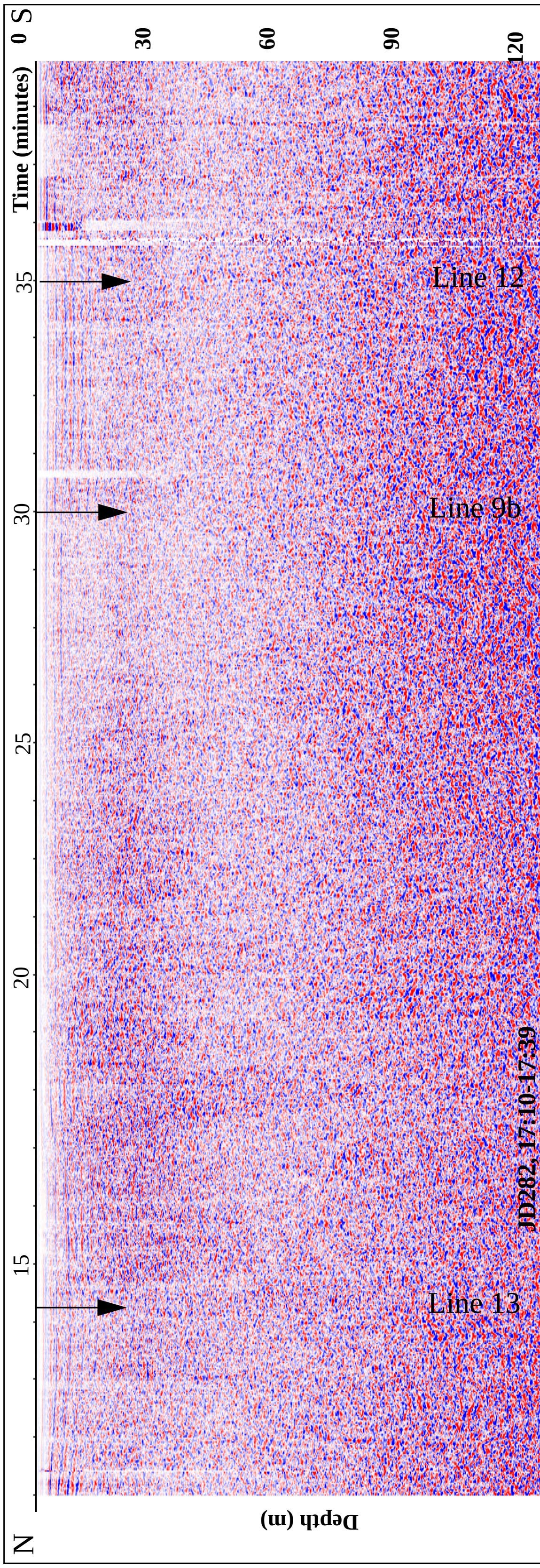
Uniboom Line 12a



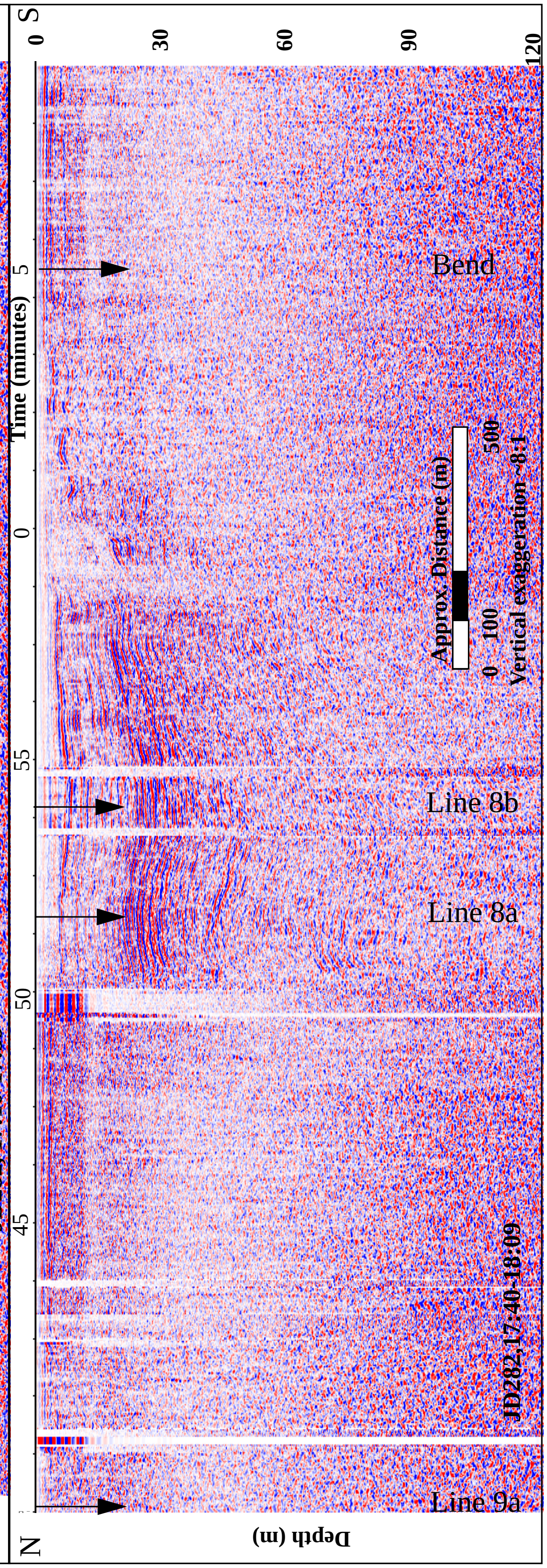
Uniboom Line 12b



Uniboom Line 2b

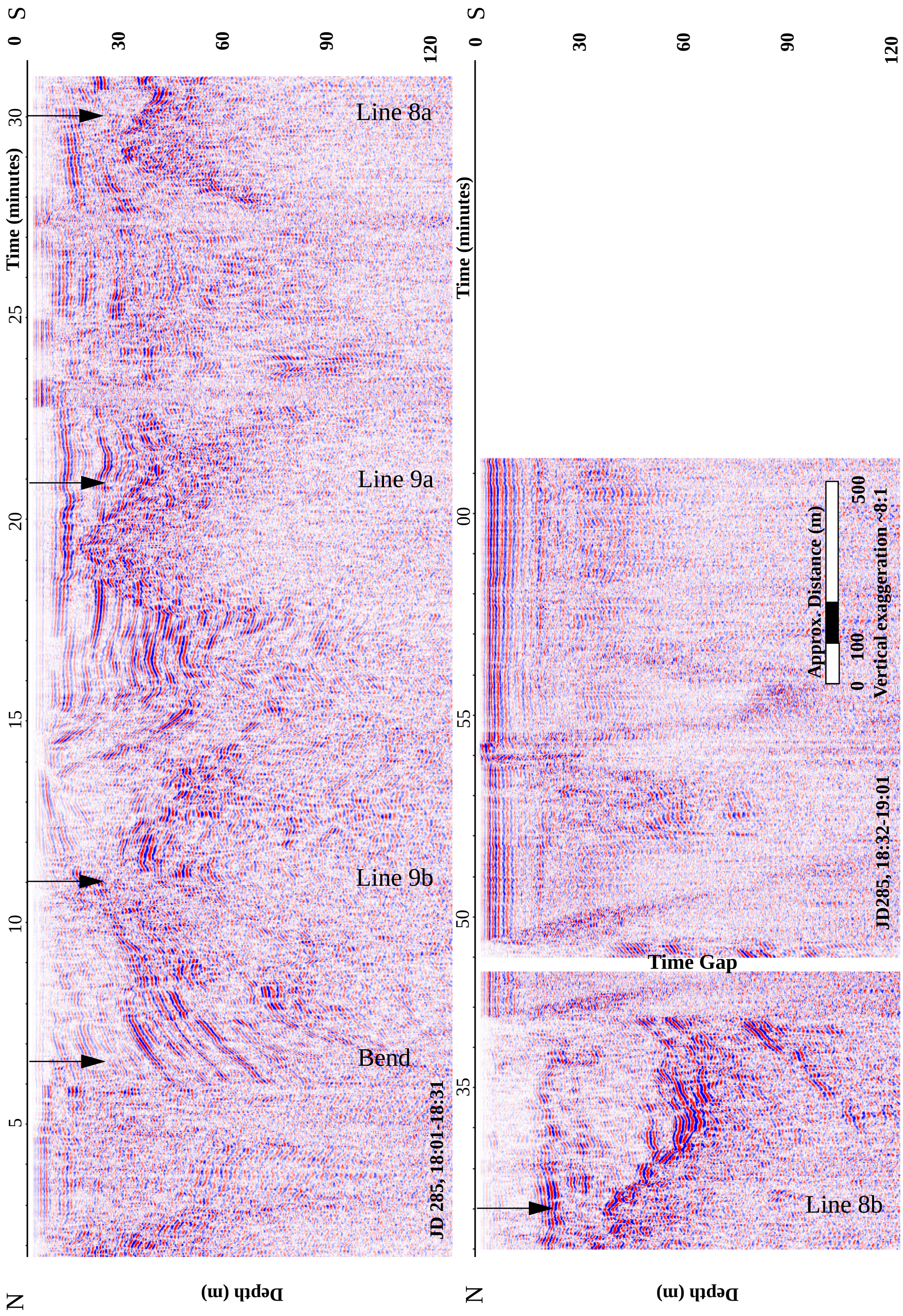


Uniboom Line 2c

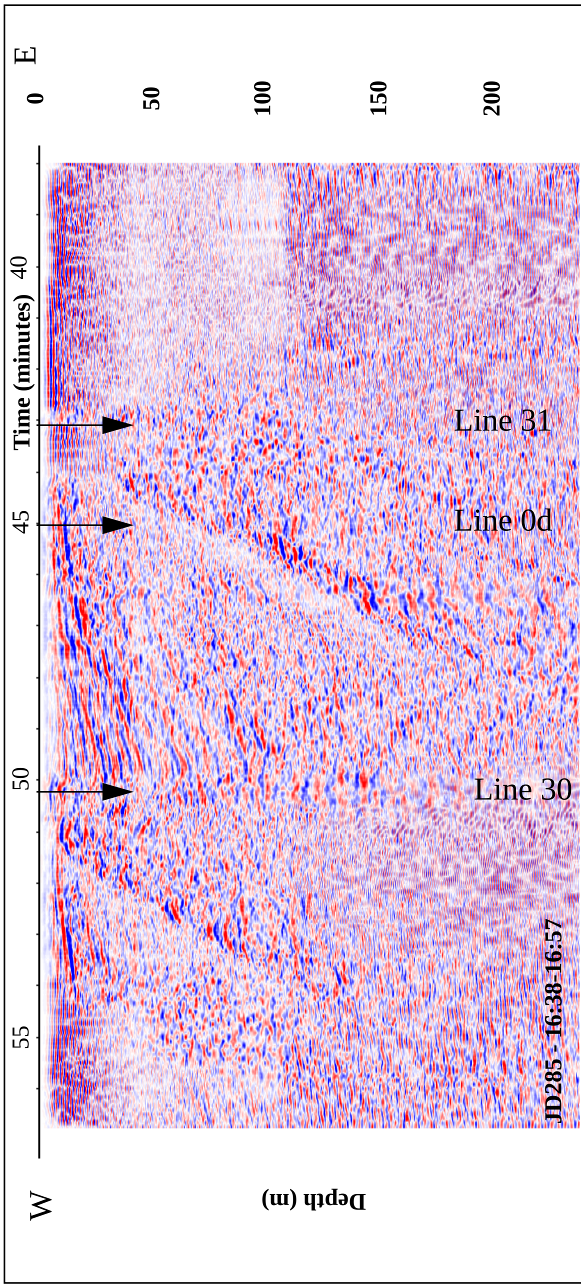


Uniboom Line 10a

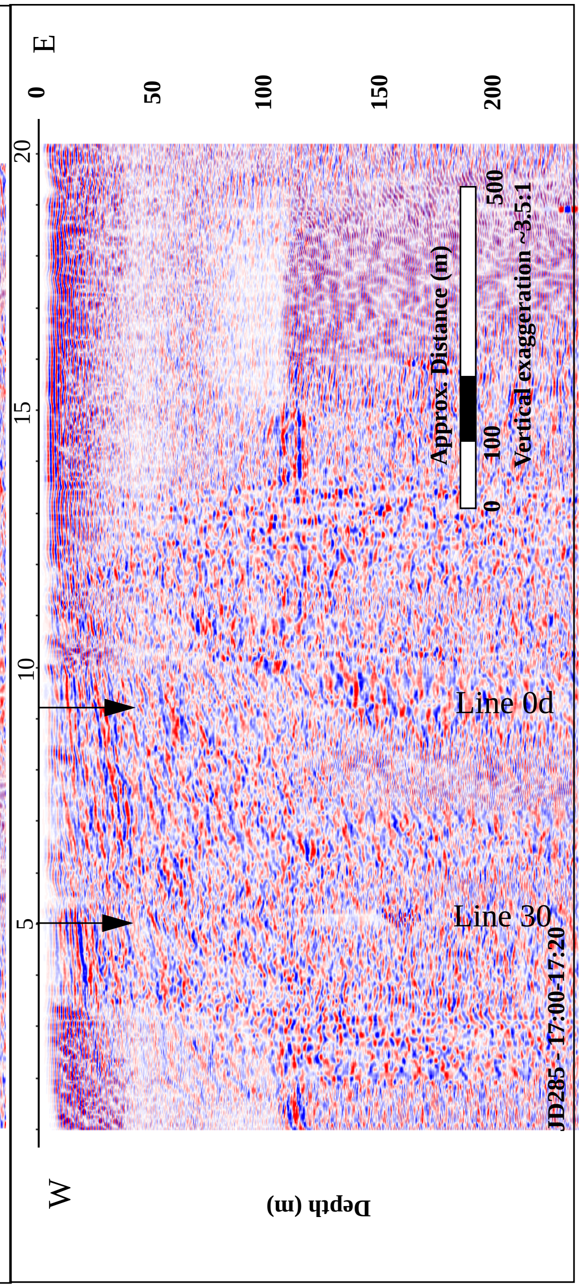
Uniboom Line 10b



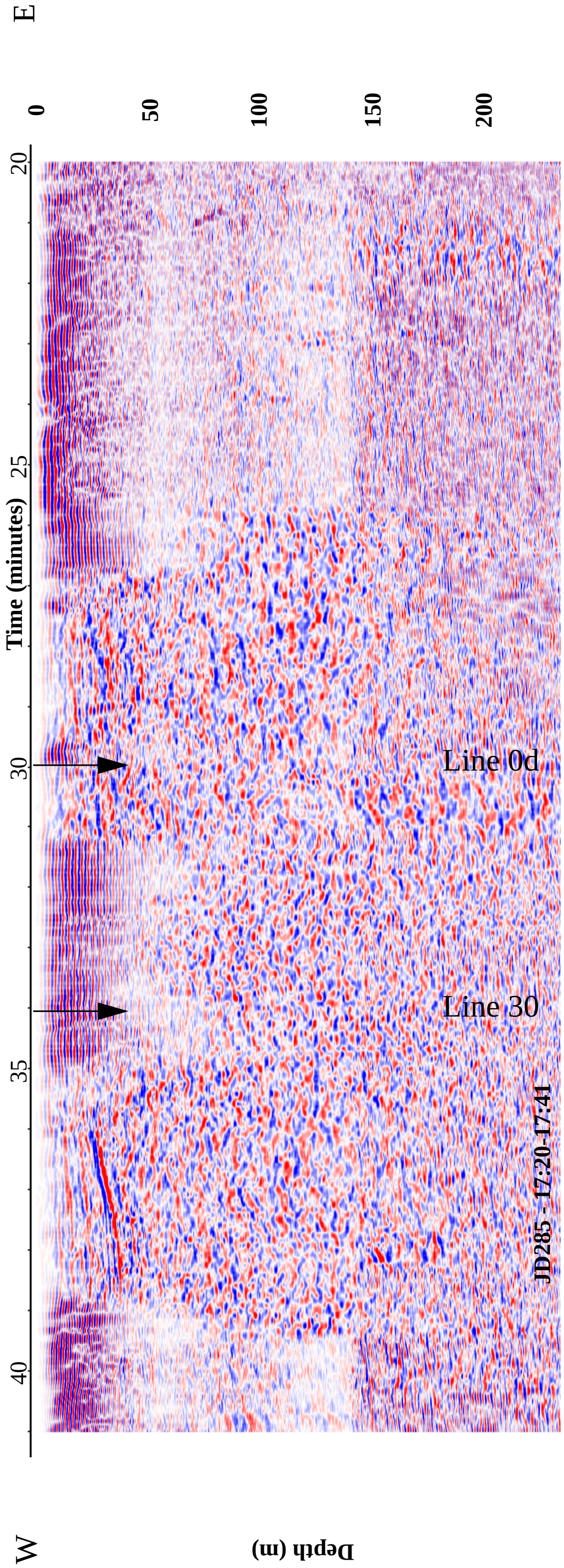
Airgun Line 32



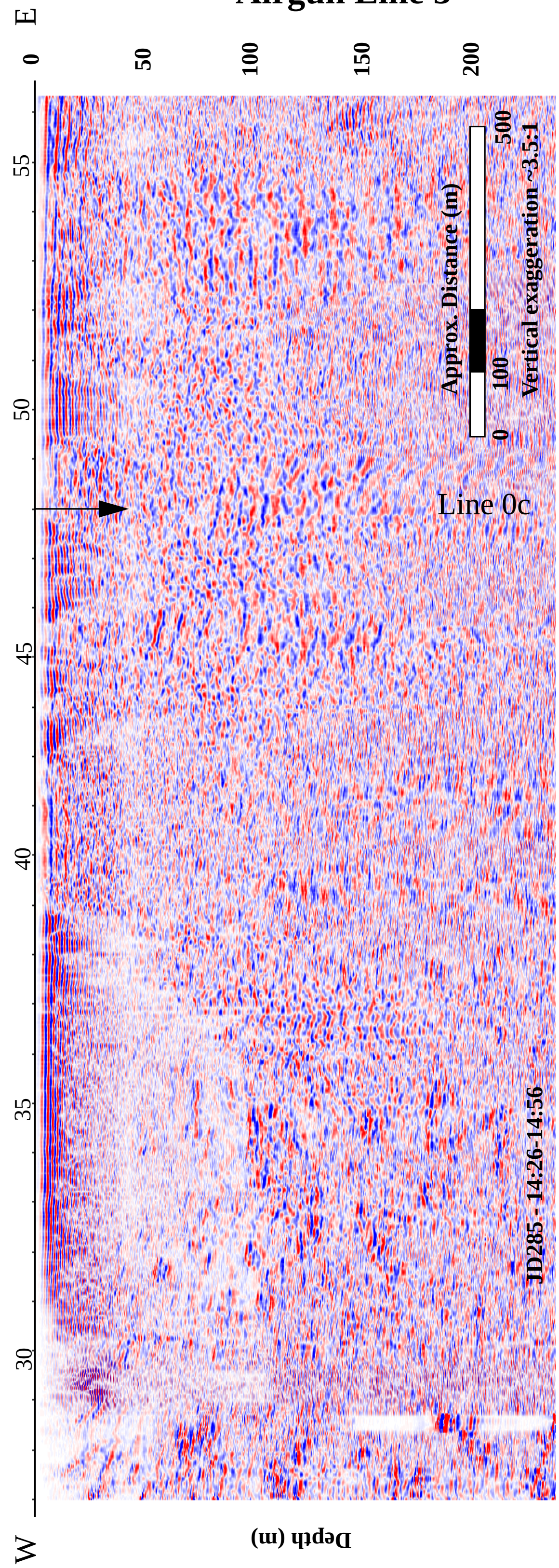
Airgun Line 1



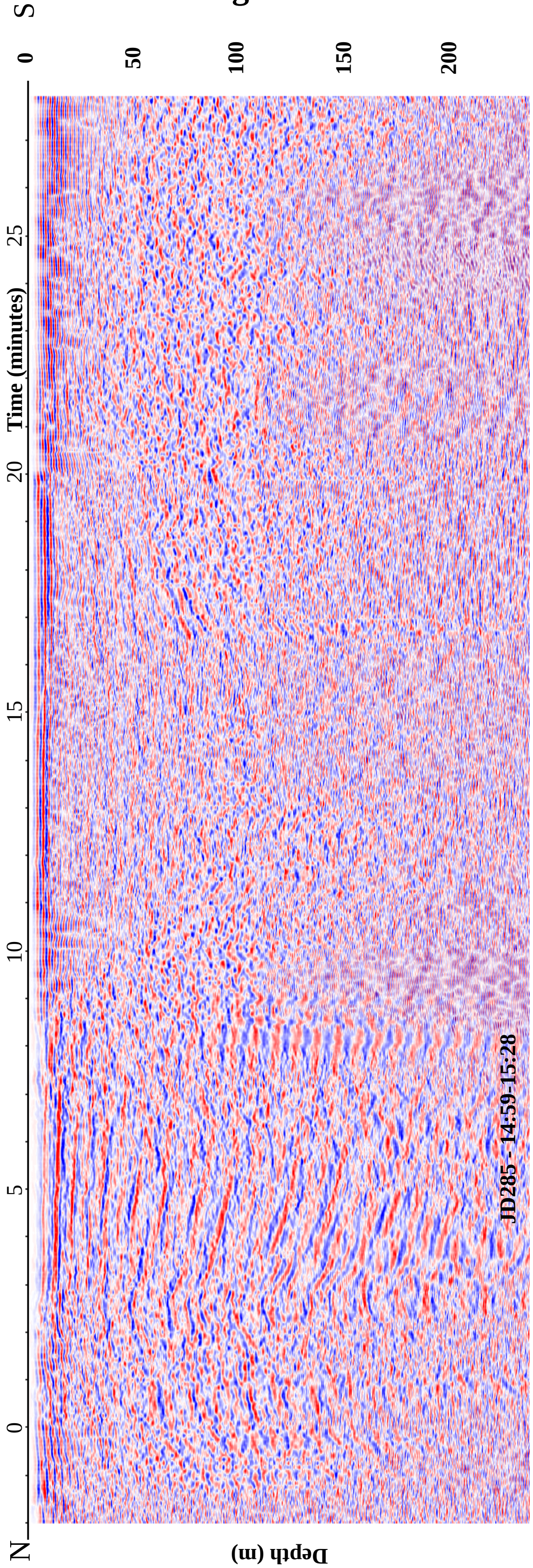
Airgun Line 33



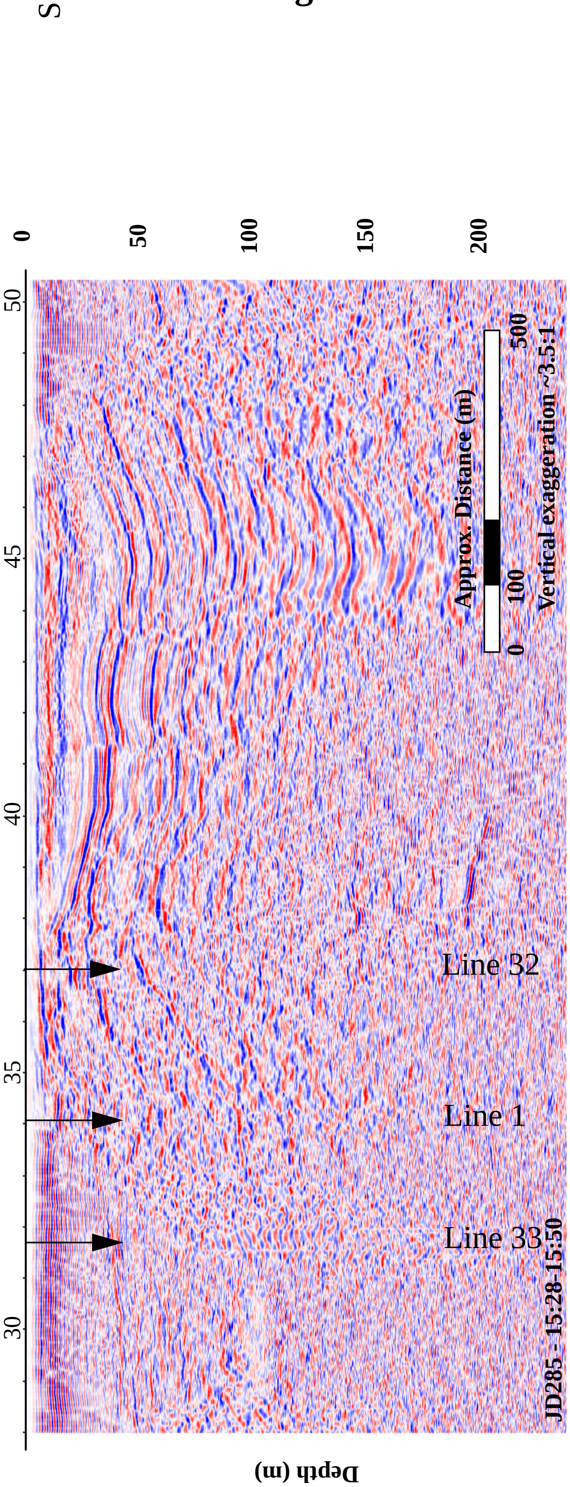
Airgun Line 3



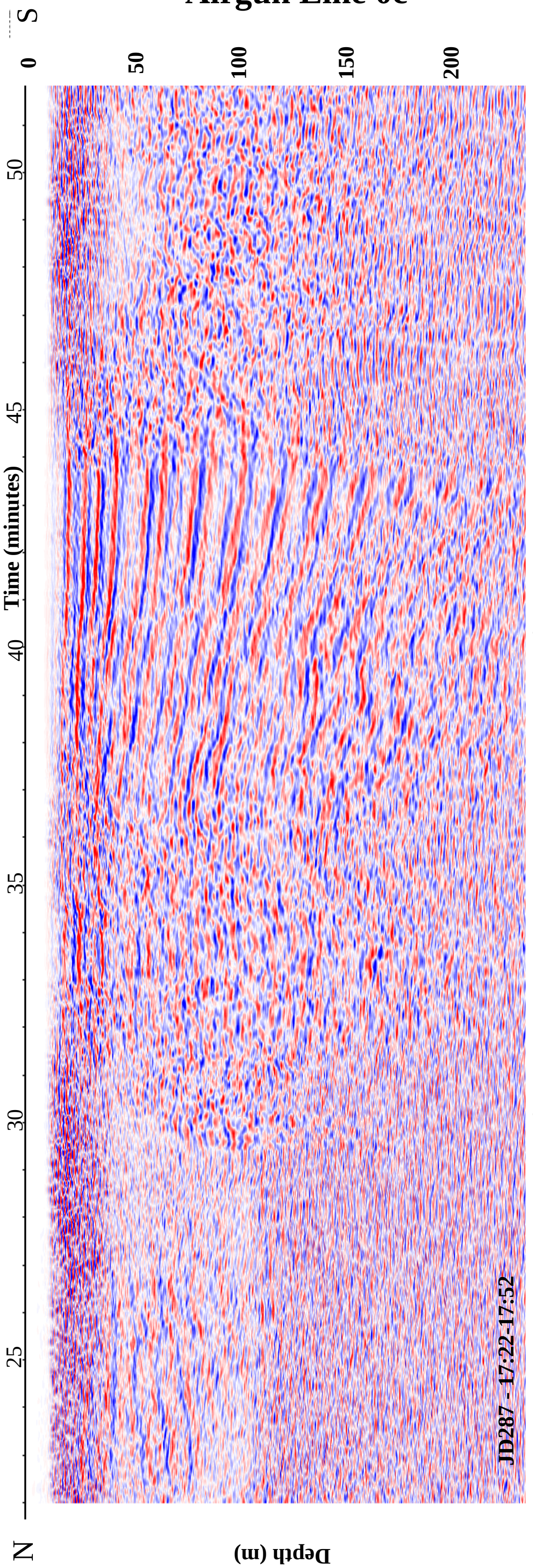
Airgun Line 30a



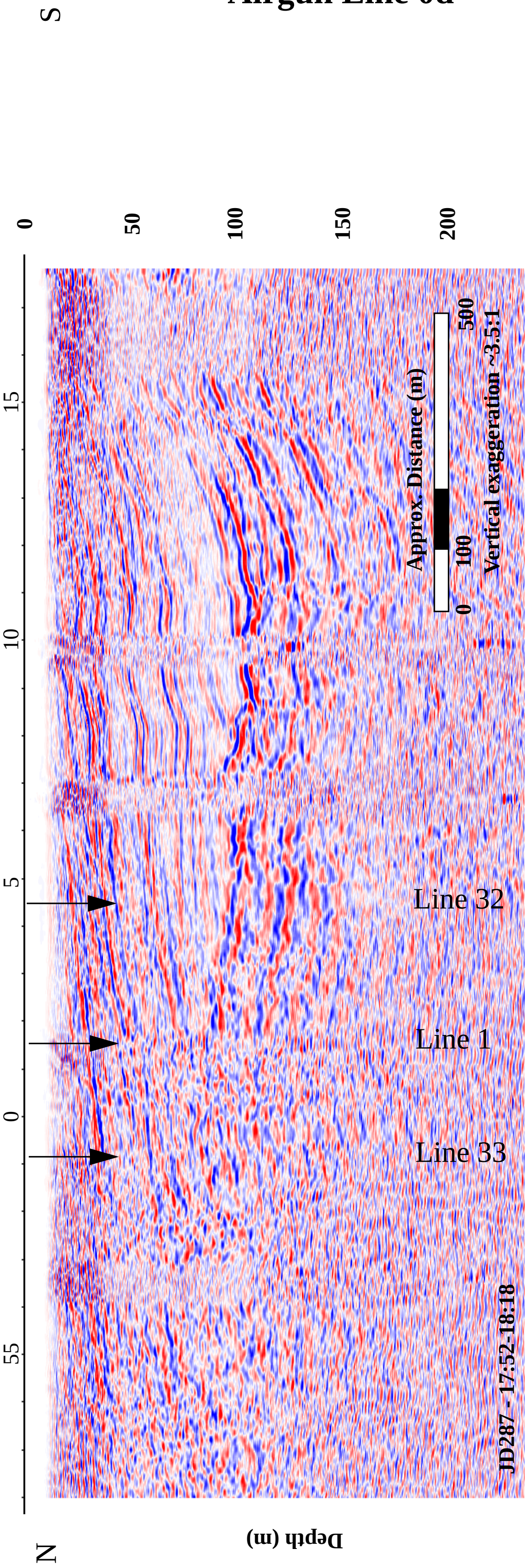
Airgun Line 30b



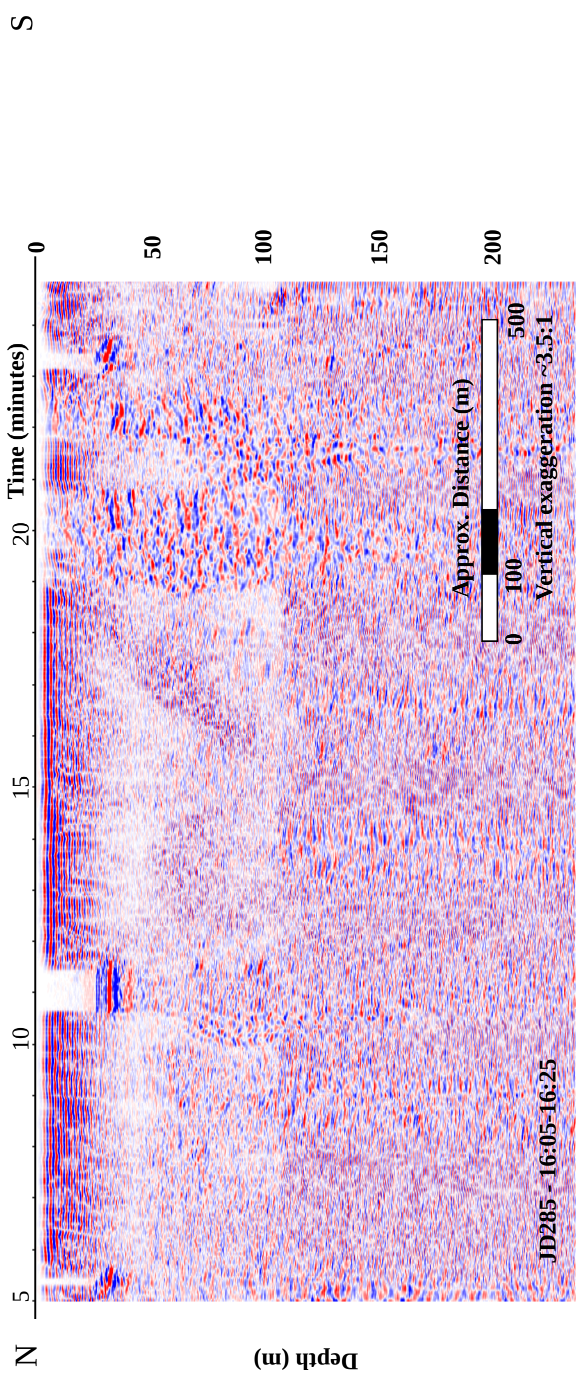
Airgun Line 0c



Airgun Line 0d

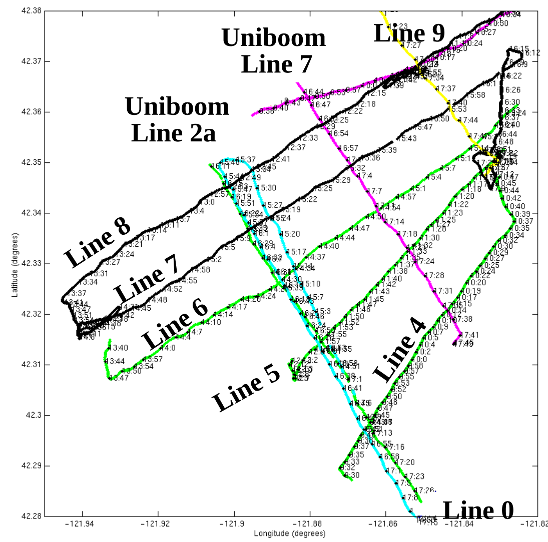


Airgun Line 31



Upper Klamath Lake - Buck Island north to Squaw Point

In this section, we present the seismic images and a brief summary of the data from Buck Island to Squaw Point (Figure 3).



Mostly airgun seismic profiles were acquired in this section of the lake. Line 8 represents the only profile that was acquired with both a 5 cu in and 10 cu in air gun chambers. Results suggest that the 10 cu in gun provides better quality data where trapped gas may be present.

Airgun Profiles

East-West Profiles (south-north)

Line 4 - **(A) JD287 - 09:32-09:59, (B) JD287 - 09:59-10:28, (C) JD287 - 10:28-10:37**

Line 5 - **(B) JD287 - 11:08-11:37, (A) JD287 - 11:37-12:06**

Line 6 - **(A) JD287 - 13:37-14:06, (B) JD287 - 16:59-17:19 (C) JD287 - 14:50-15:20, (D) JD287 - 15:20-15:28**

Line 7 - **(A) JD284 - 14:38-15:08, (B) JD284 - 15:09-15:40, (C) JD284 - 15:42-16:10**

Line 8 - **(A) JD284 - 13:09-13:38, (B) JD284 - 12:07-13_07, (C) JD284 - 10:25-11:37**

North-South Profiles (east-west)

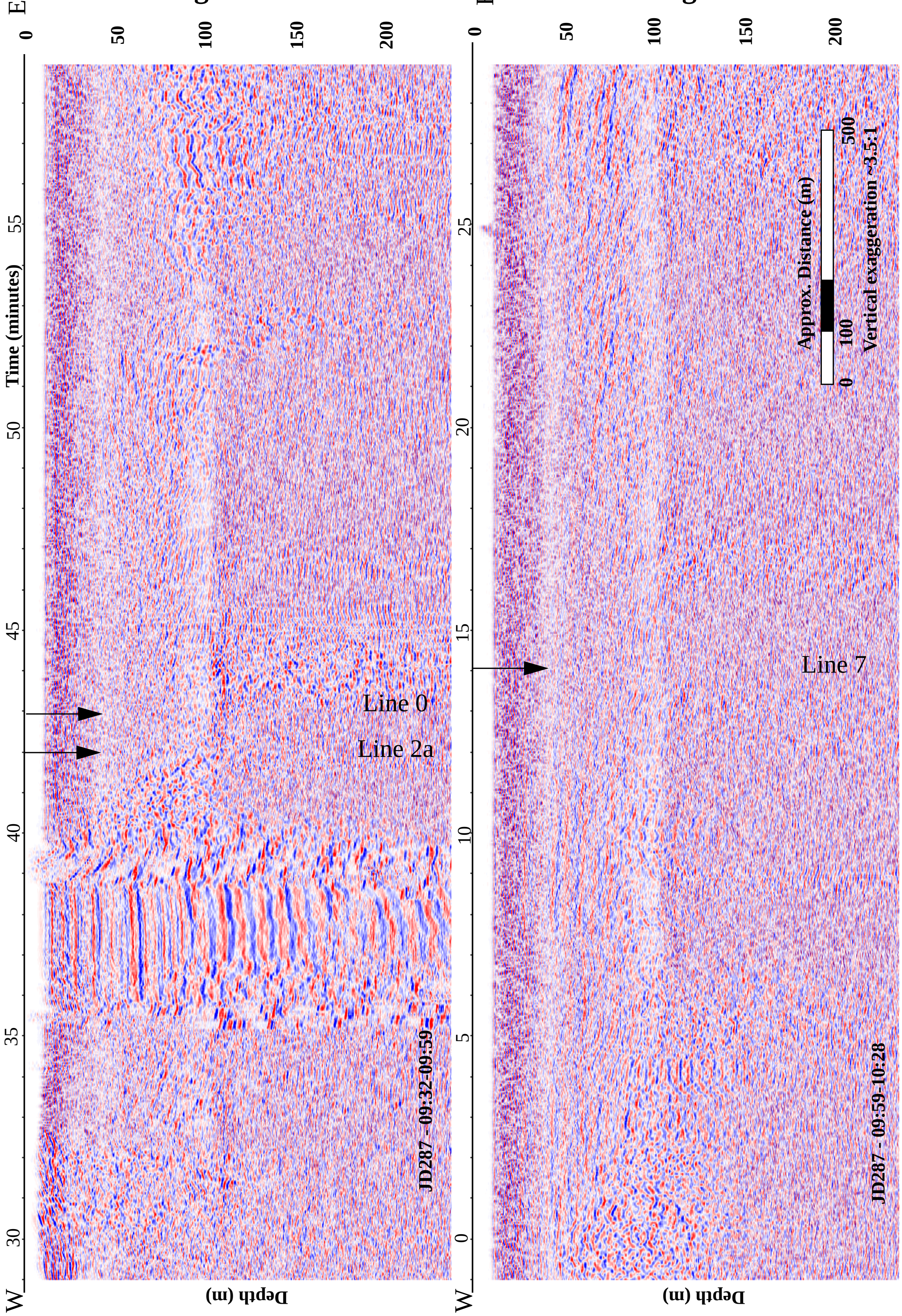
Line 0 - **(A) JD287 - 16:22-16:52, (B) JD2857 - 16:52-17:18**

Line 9 - south of Squaw Point - **(G) JD286 - 17:15-17:40, (H) JD2857 - 17:39-17:55**

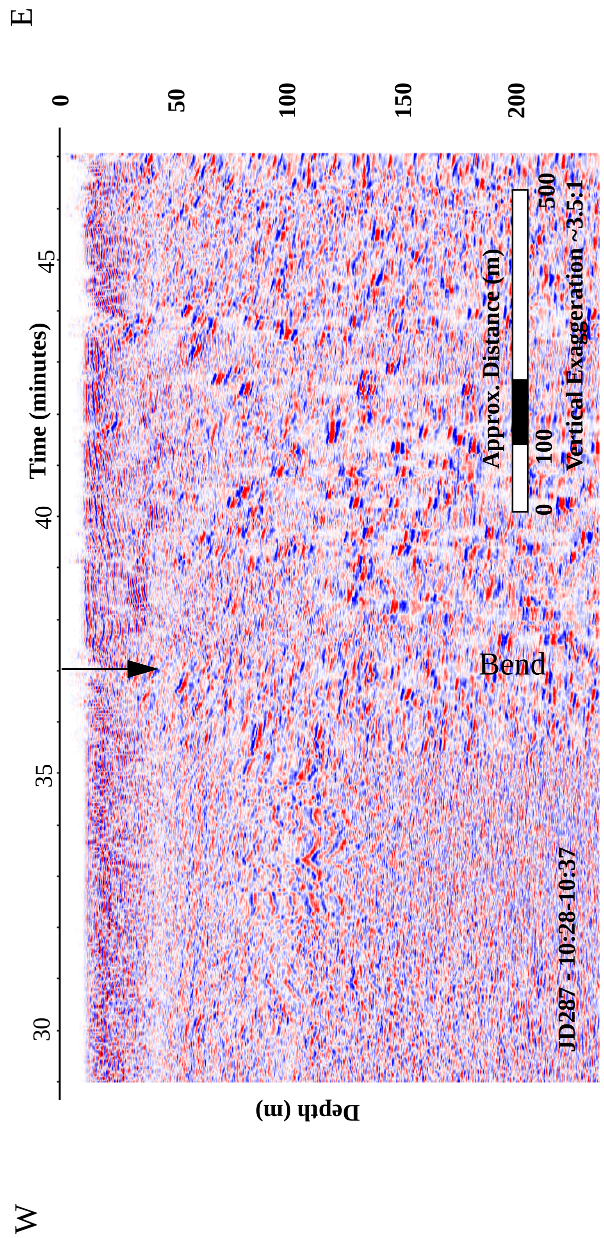
Additional Data

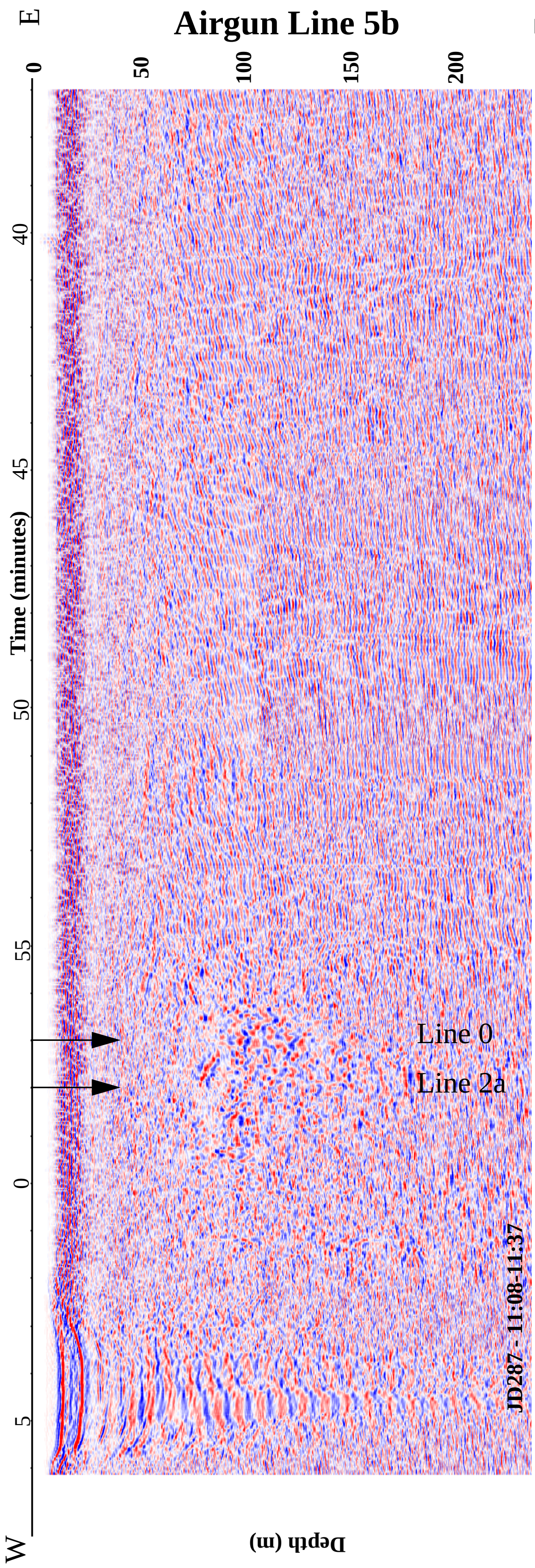
10 cu in Airgun Line 8 - **(X) JD283 - 09;29-09:59, (Y) JD283 - 09:59-10:26**

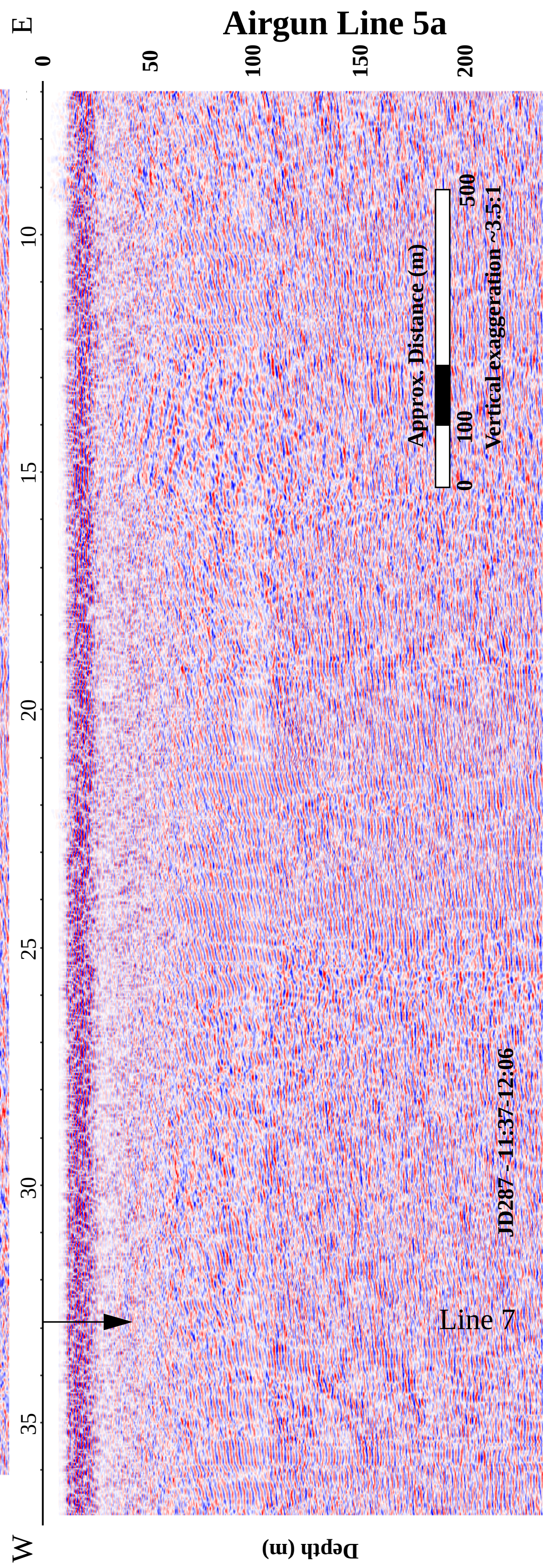
Airgun Line 4a **Airgun Line 4b**

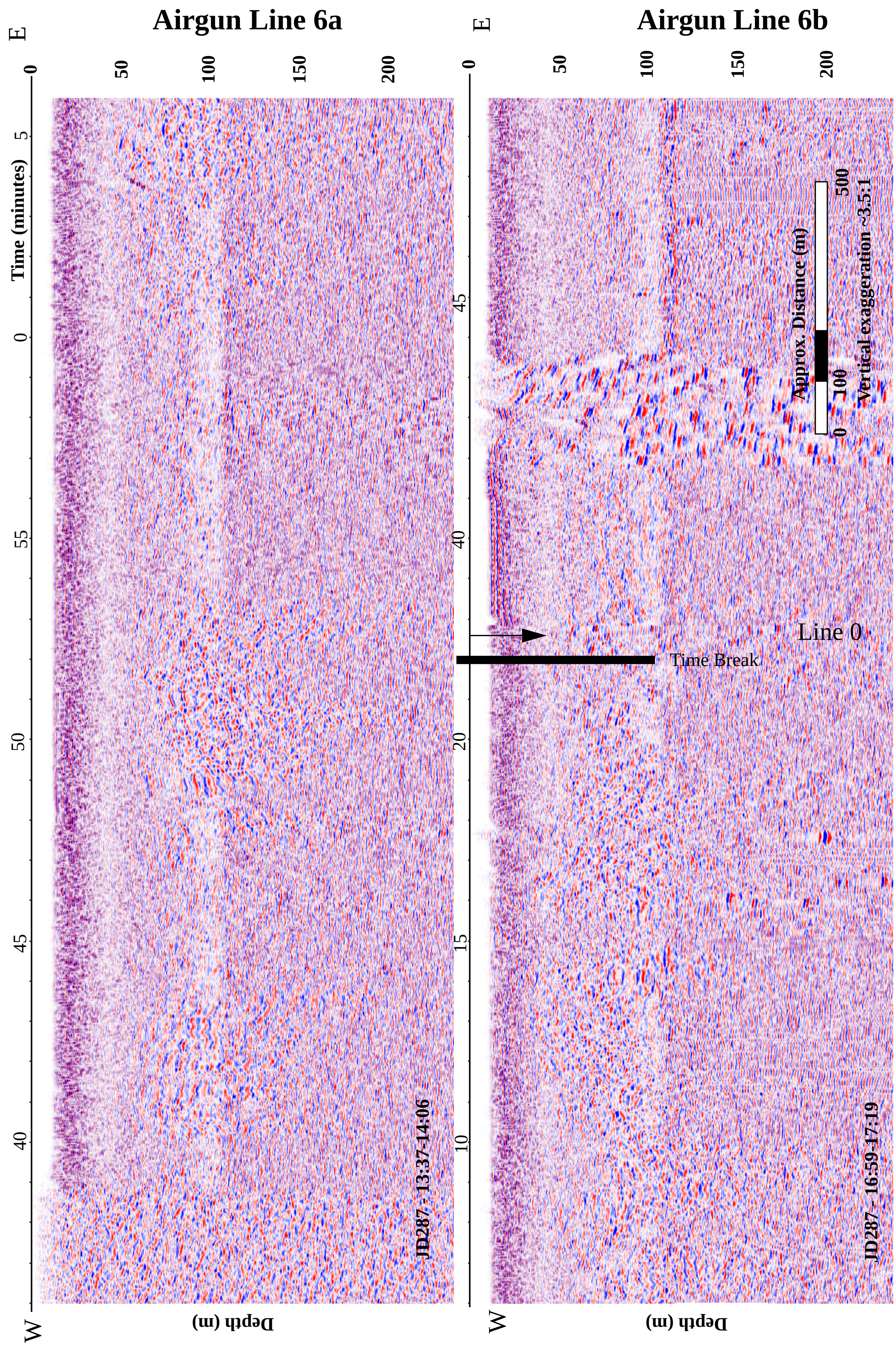


Airgun Line 4c



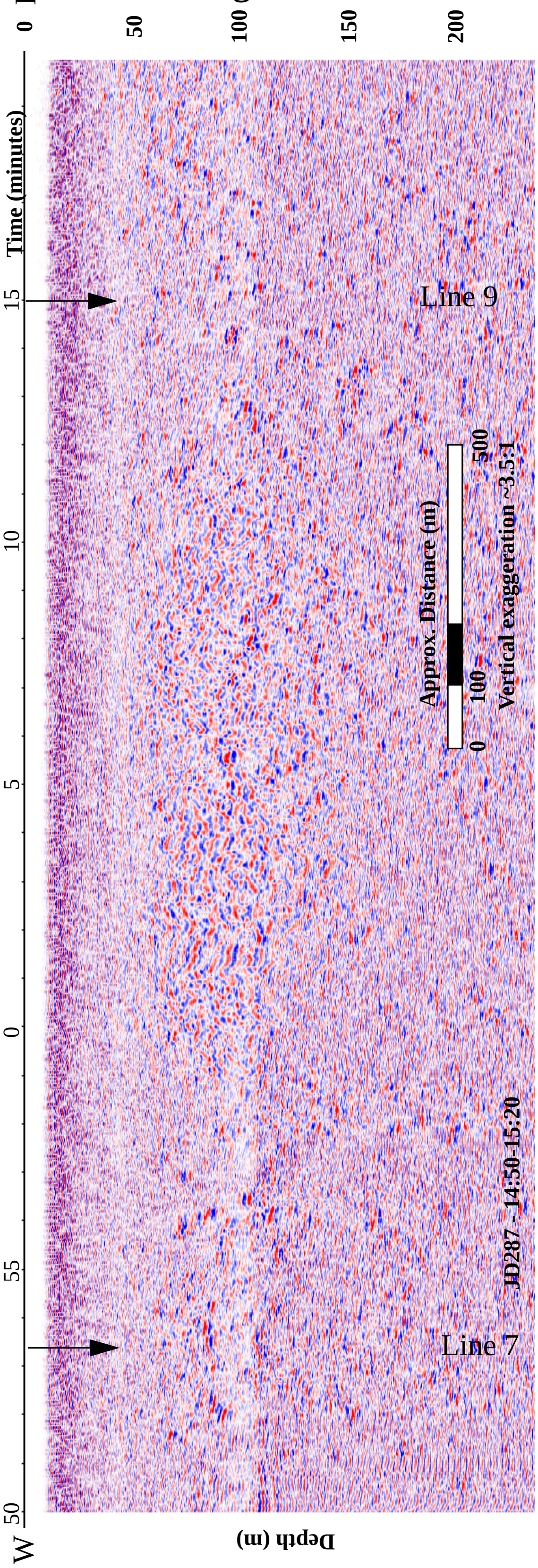

Airgun Line 5b
E
W
0
50
100
150
200
Depth (m)
Time (minutes)
40
45
50
55
0
5
Line 0
Line 2a
JD287 - 11:08-11:37


Airgun Line 5a
E
W
0
50
100
150
200
Depth (m)
10
15
20
25
30
35
Approx. Distance (m)
0
100
500
Vertical exaggeration ~3.5:1
JD287 - 11:37-12:06
Line 7

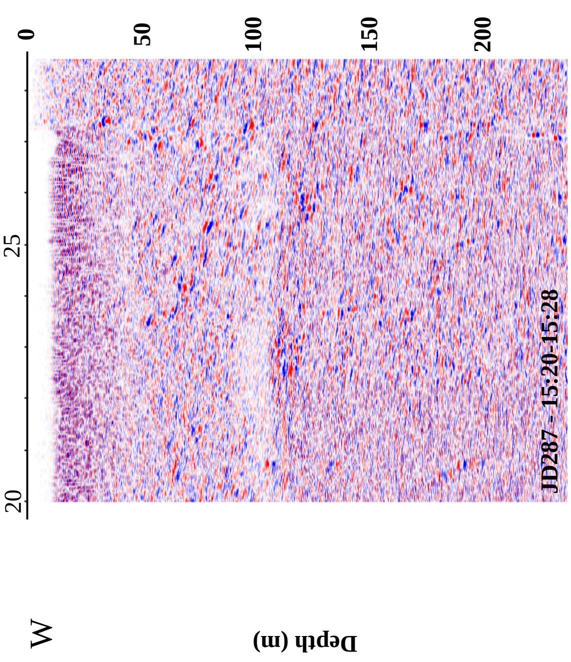


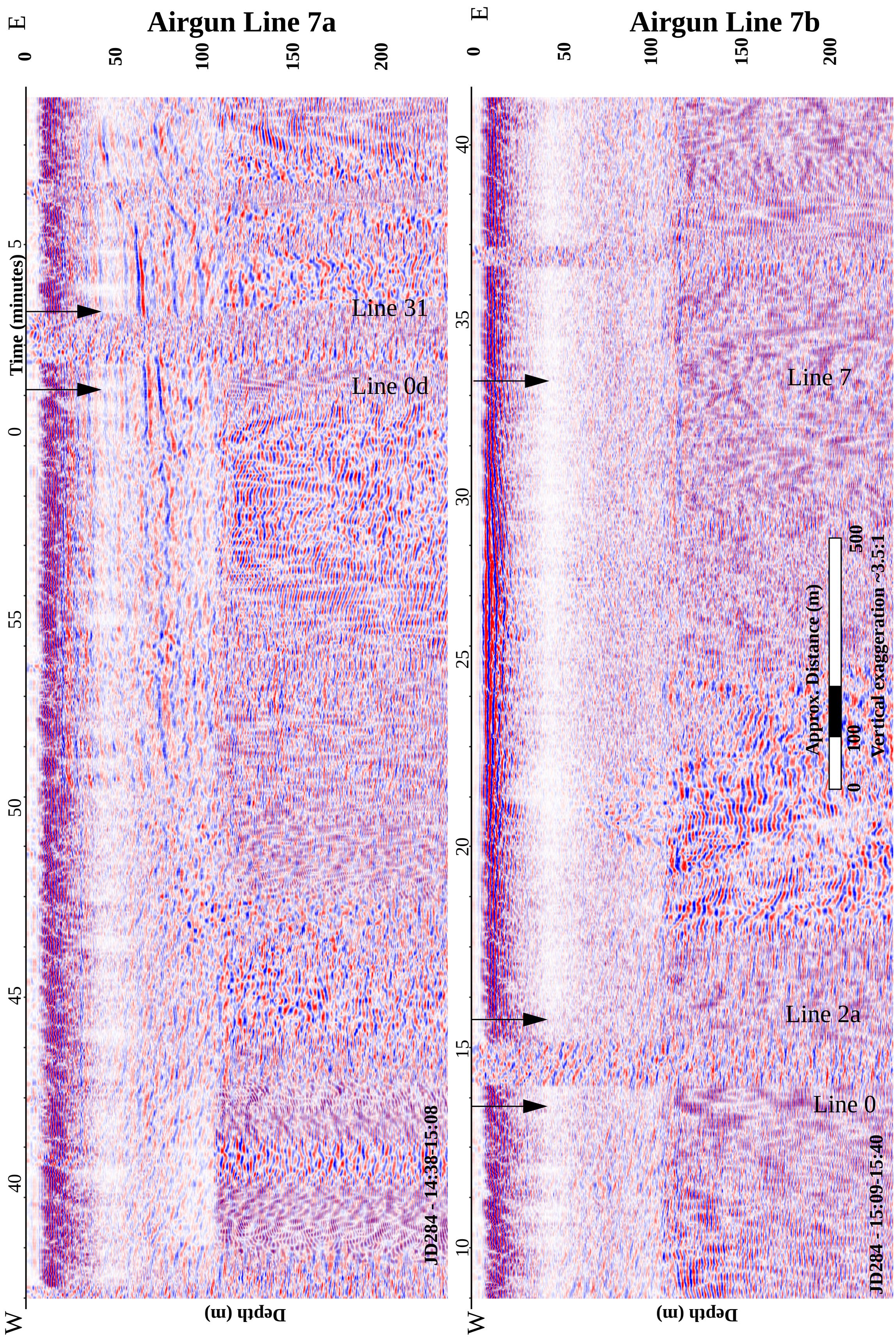
Airgun Line 6a
Airgun Line 6b
E
W
Time (minutes)
Depth (m)
Time Break
Line 0
JD287 - 13:37-14:06
JD287 - 16:59-17:19
Approx. Distance (m)
Vertical exaggeration ~3.5:1

Airgun Line 6c

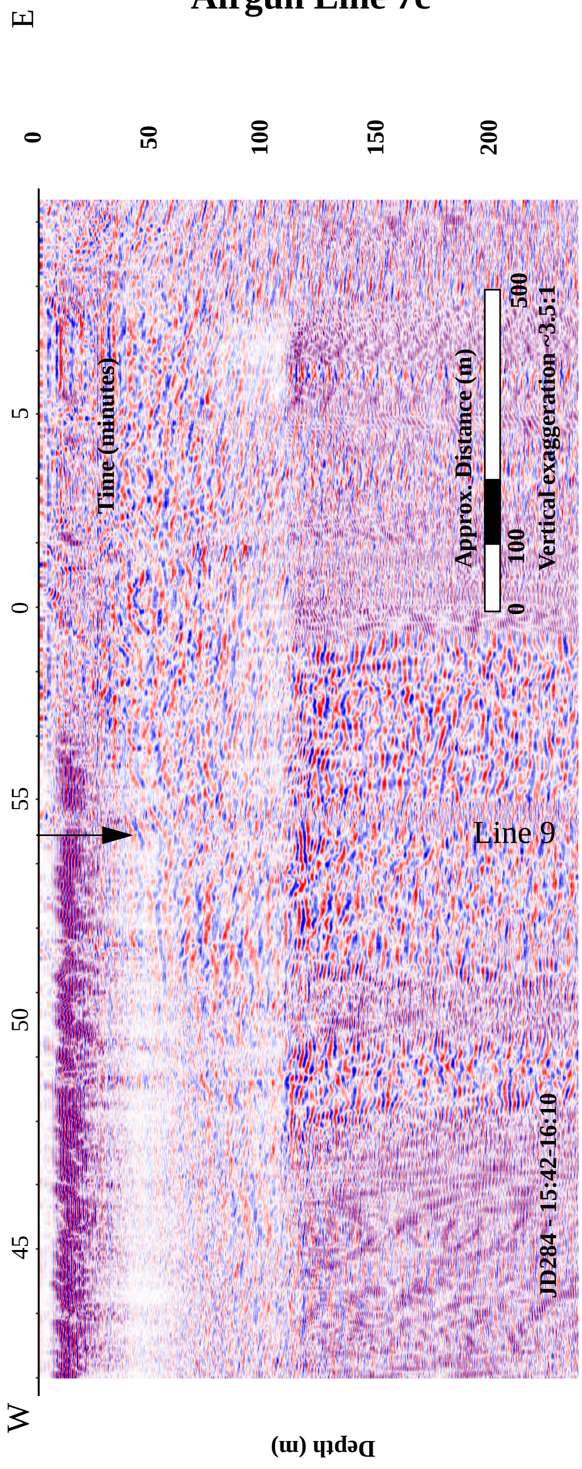


Airgun Line 6d

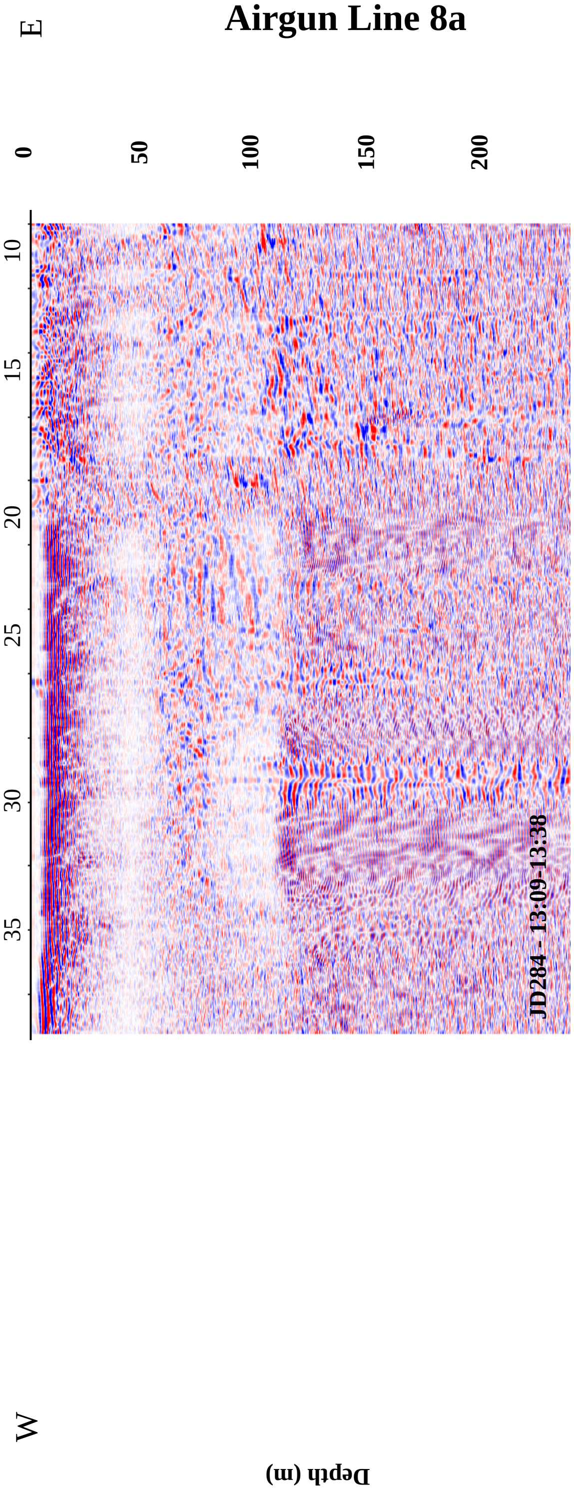



Airgun Line 7a
Airgun Line 7b
E
W
Depth (m)
Time (minutes)
Line 31
Line 0d
Line 7
Line 2a
Line 0
JD284 - 14:38-15:08
JD284 - 15:09-15:40
Approx. Distance (m)
Vertical exaggeration ~3.5:1

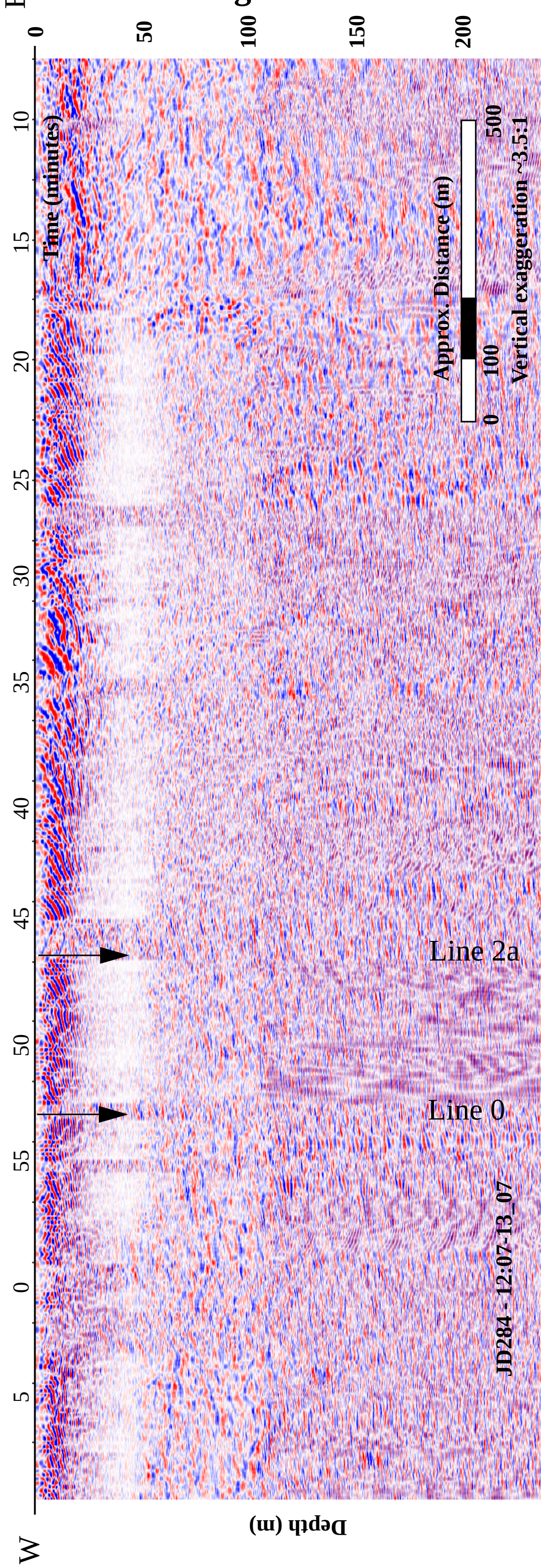
Airgun Line 7c



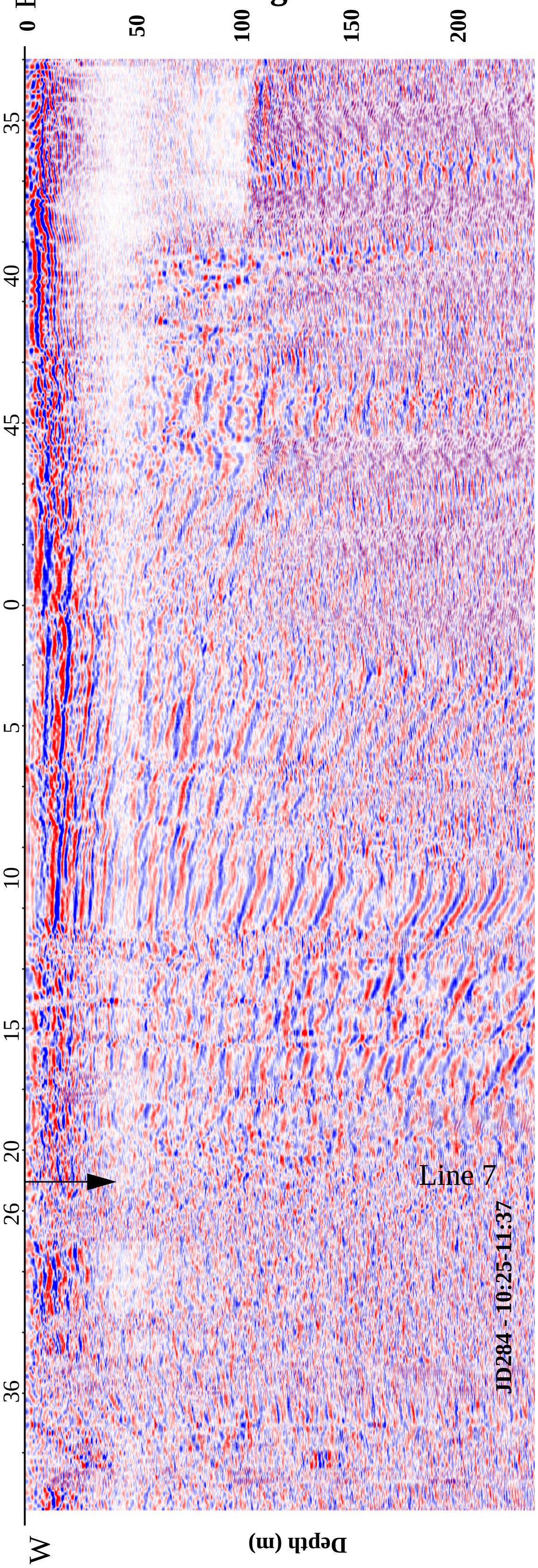
Airgun Line 8a



Airgun Line 8b

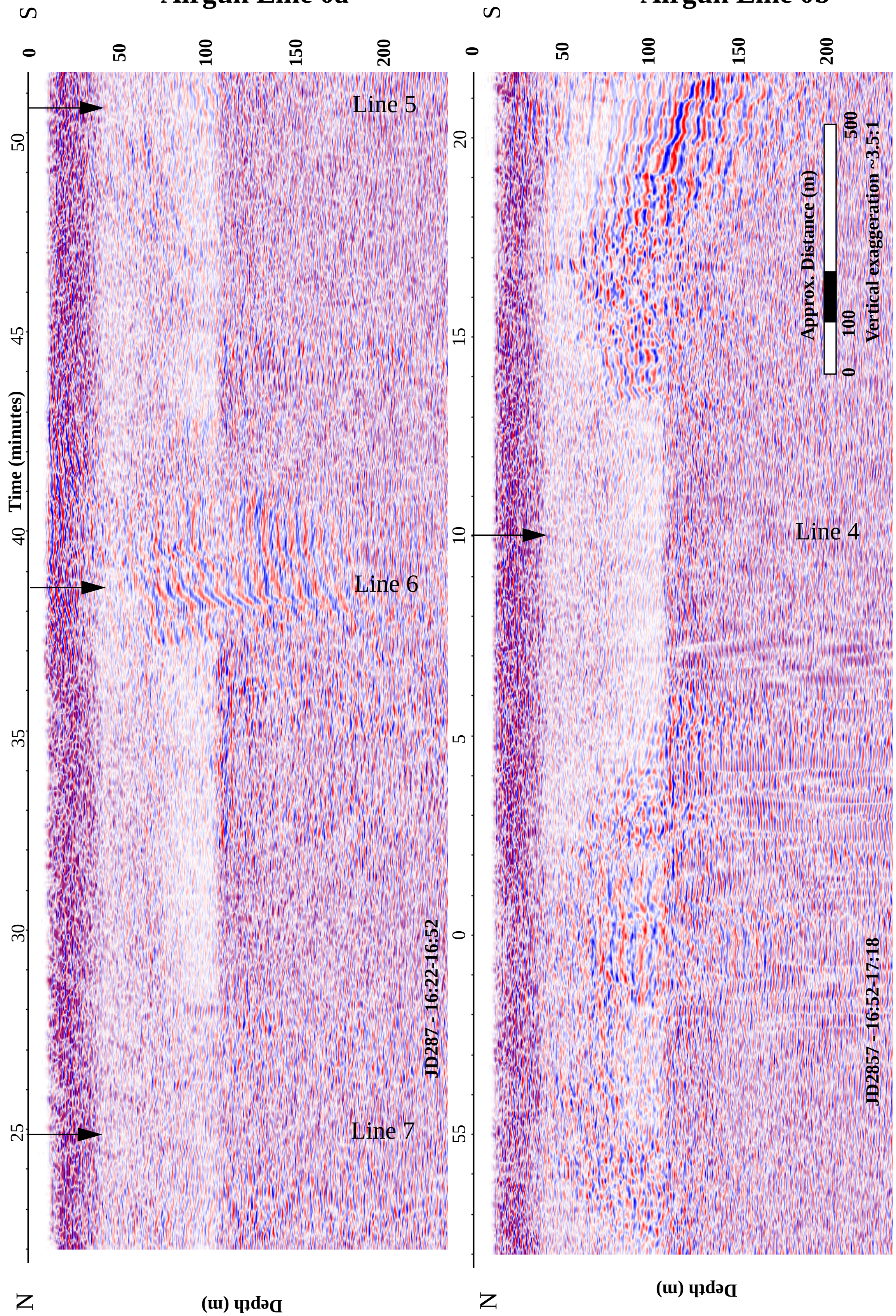


Airgun Line 8c

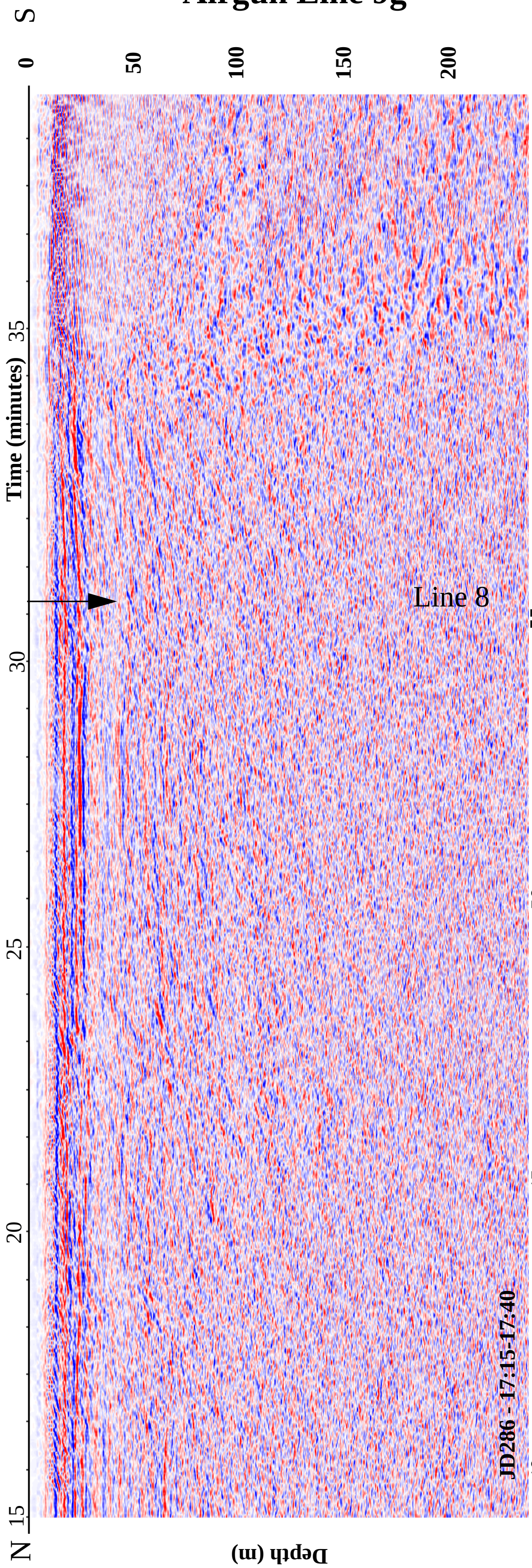


Airgun Line 0a

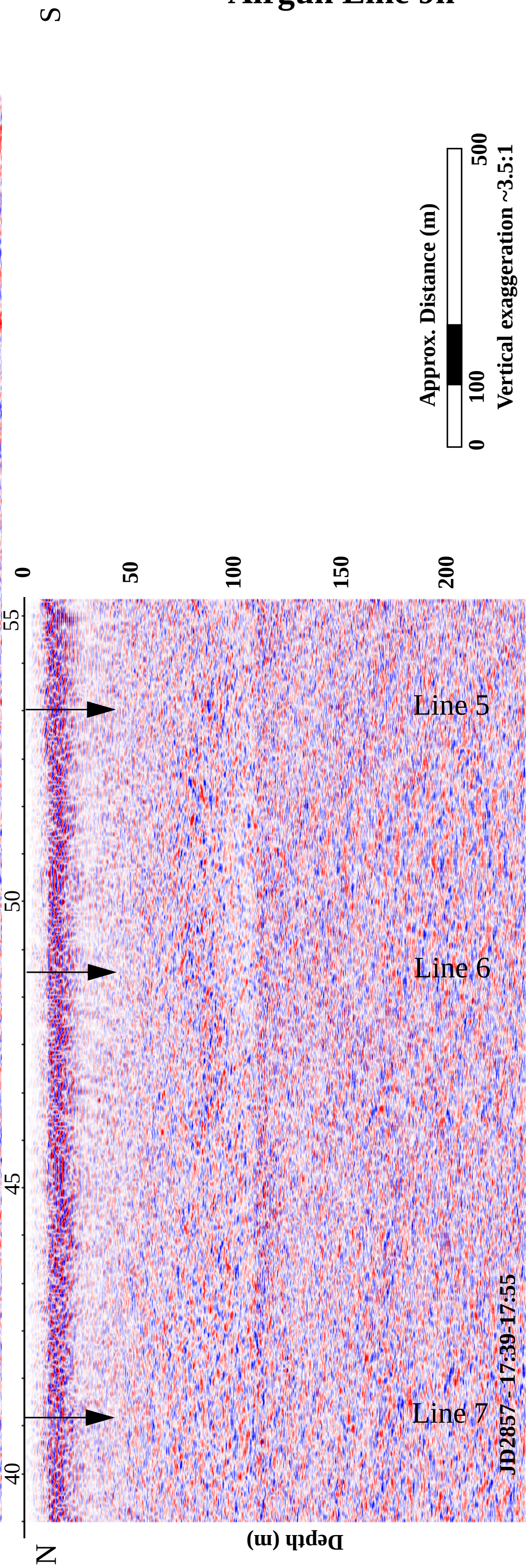
Airgun Line 0b



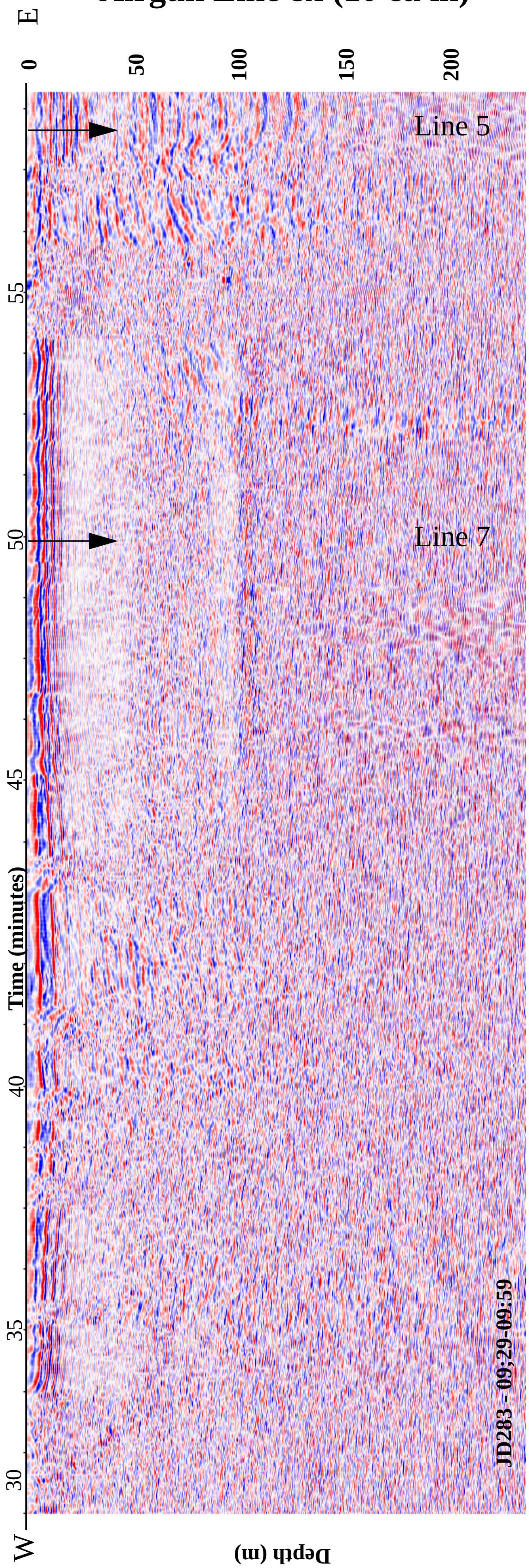
Airgun Line 9g



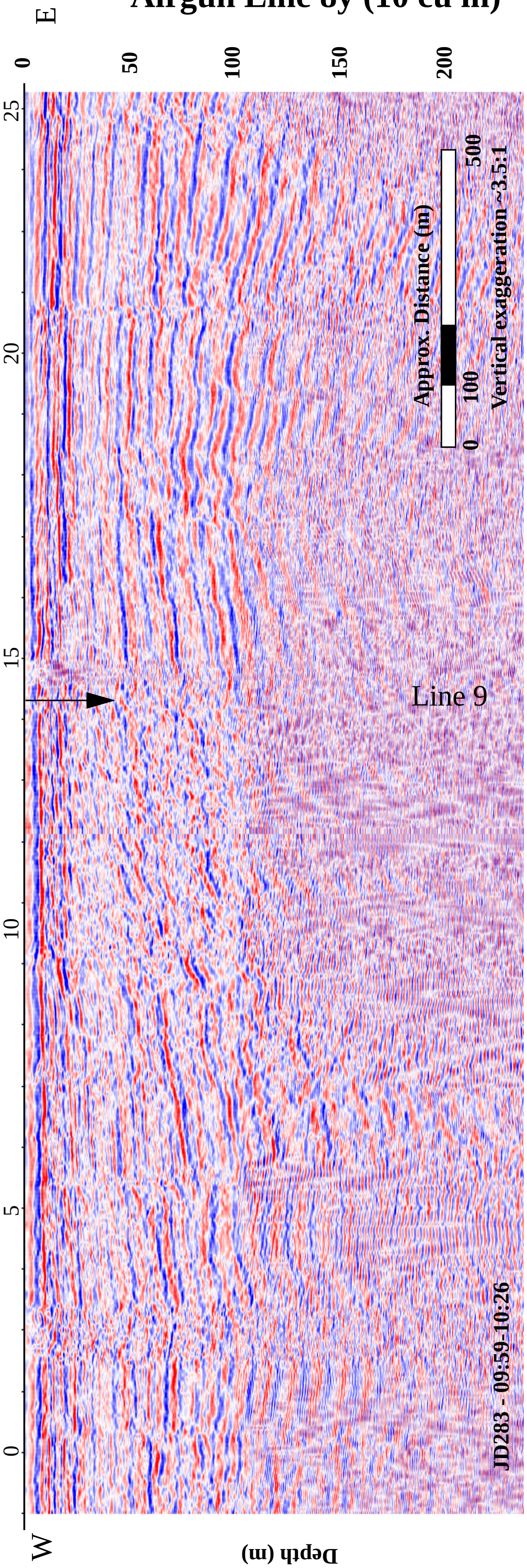
Airgun Line 9h



Airgun Line 8x (10 cu in)

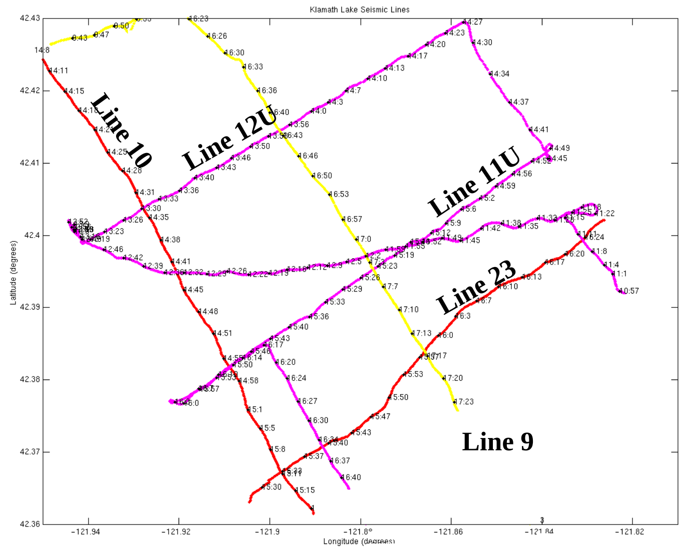


Airgun Line 8y (10 cu in)



Upper Klamath Lake - Squaw Point north to Bare Island

In this section, we present the seismic images and a brief summary of the data from Squaw Point to Bare Island.



We mixed airgun with Uniboom profiles for this portion of the lake. Data quality was mostly poor for this region.

Profiles

East-west profiles

Airgun Line 23 - **(A) JD288 - 15:28-15:58, (B) JD2858 - 15:58-16:28**

Uniboom Line 11 - **(A) JD283 - 22:49-23:02, (B) JD283 - 22:19-22:48, (C) JD283 - 21:49-21:18**

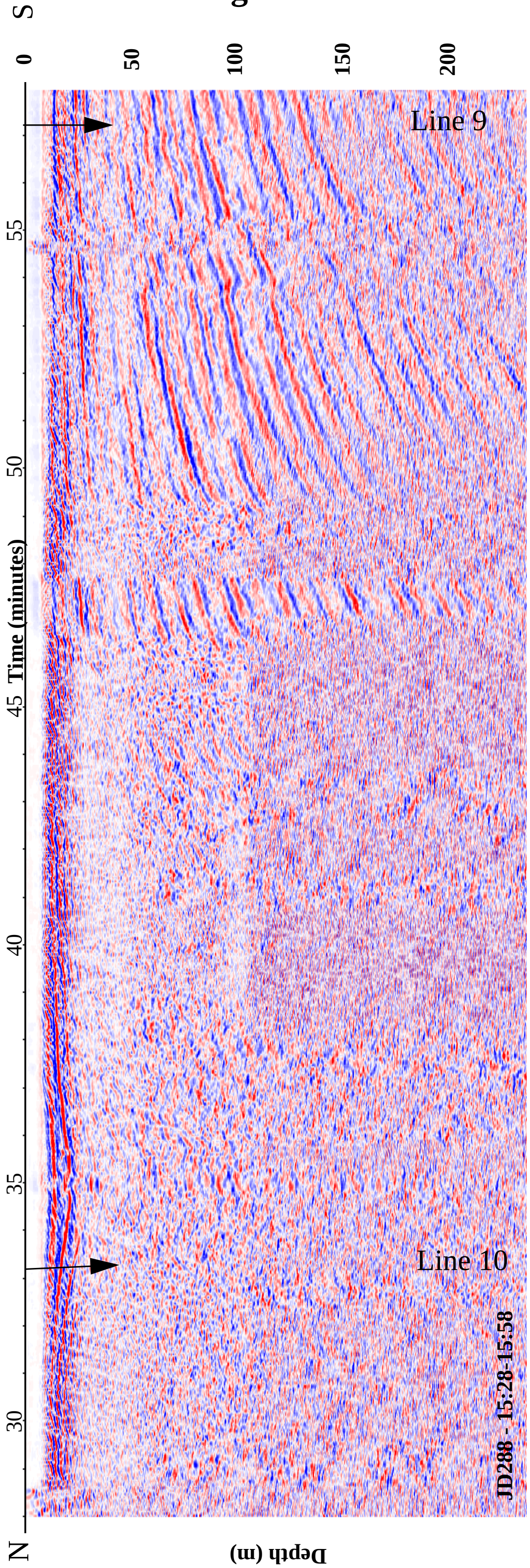
Uniboom Line 12 - **(A) JD283 - 20:17-20:47, (B) JD283 - 20:47-21:16, (C) JD283 - 21:17-21:31**

North-South Profiles

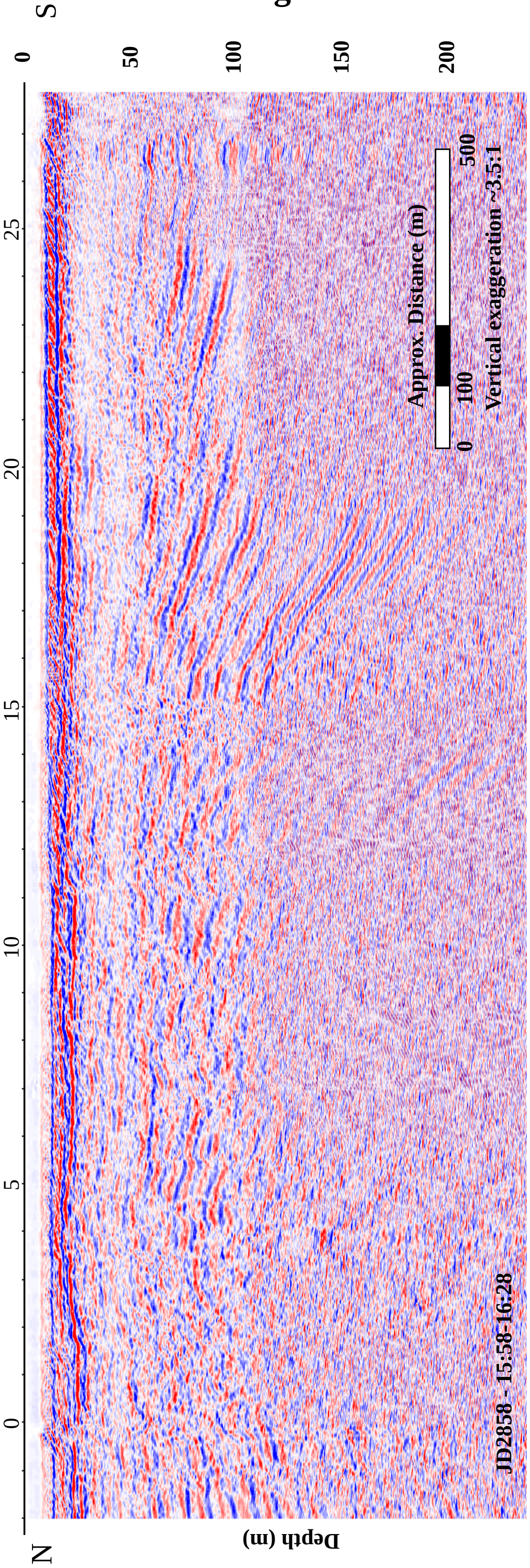
Airgun Line 10 - **(C) JD288 - 14:44-15:13, (D) JD2858 - 15:14-15:19**

Airgun Line 9 - **(E) JD286 - 16:27-16:50, (F) JD286 - 16:51-17:15**

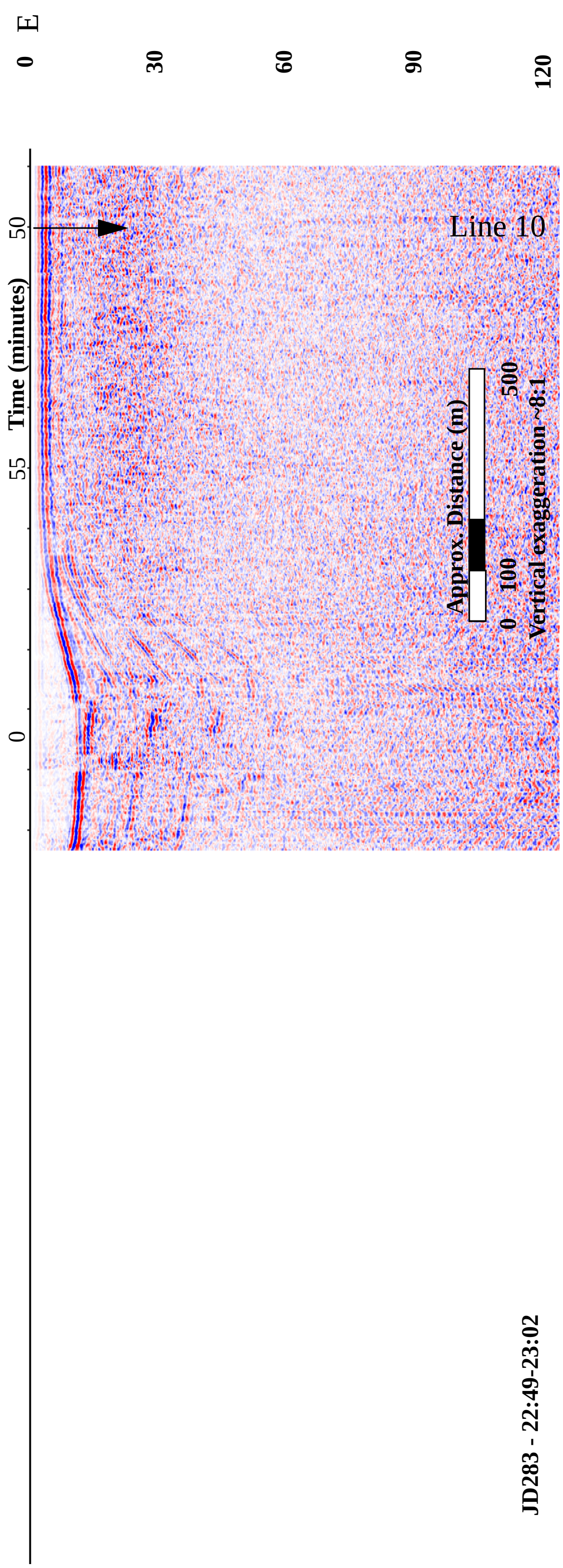
Airgun Line 23a



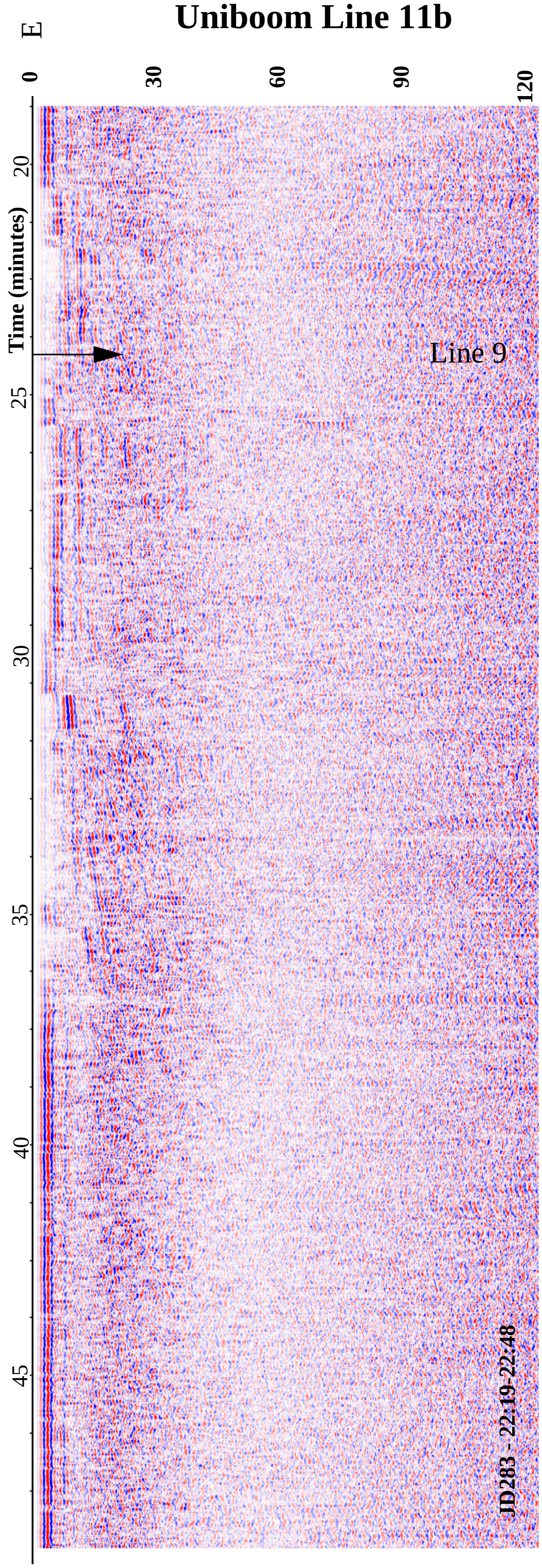
Airgun Line 23b

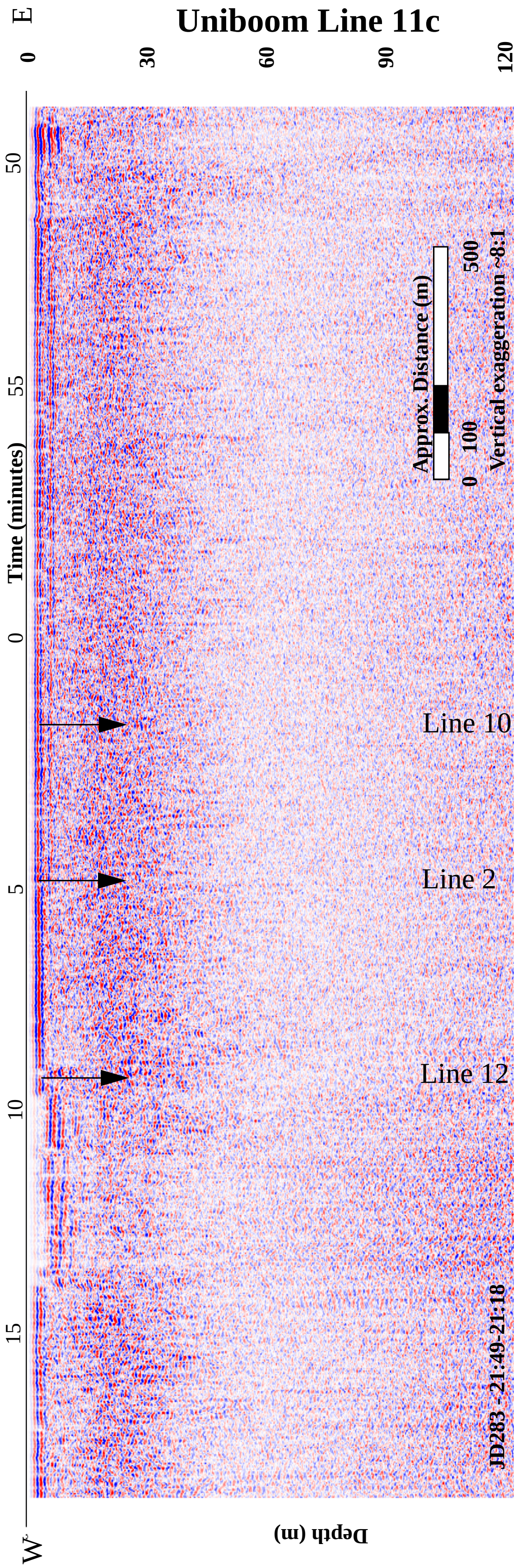


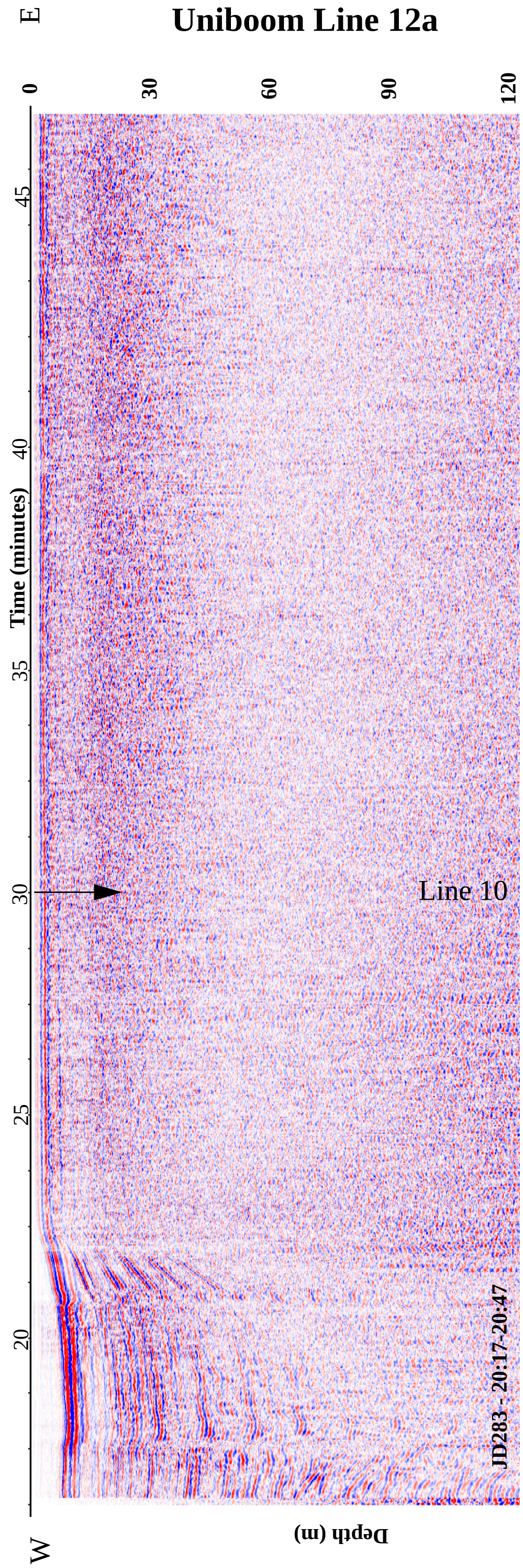
Uniboom Line 11a



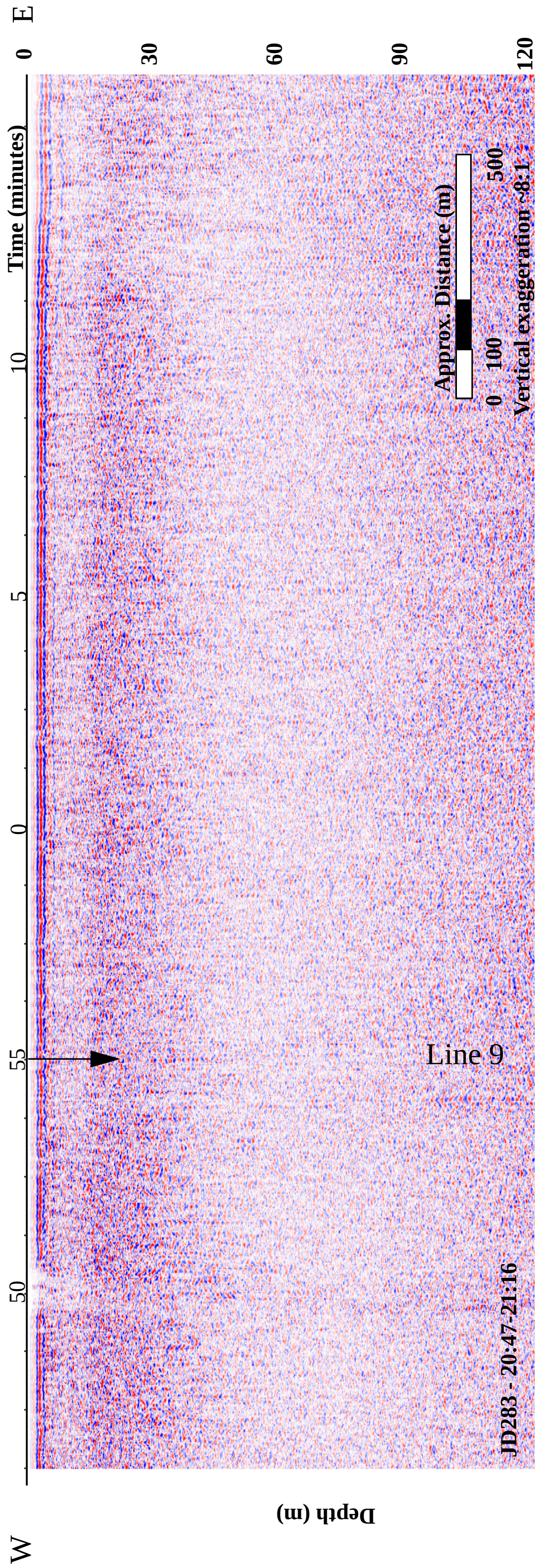
Uniboom Line 11b



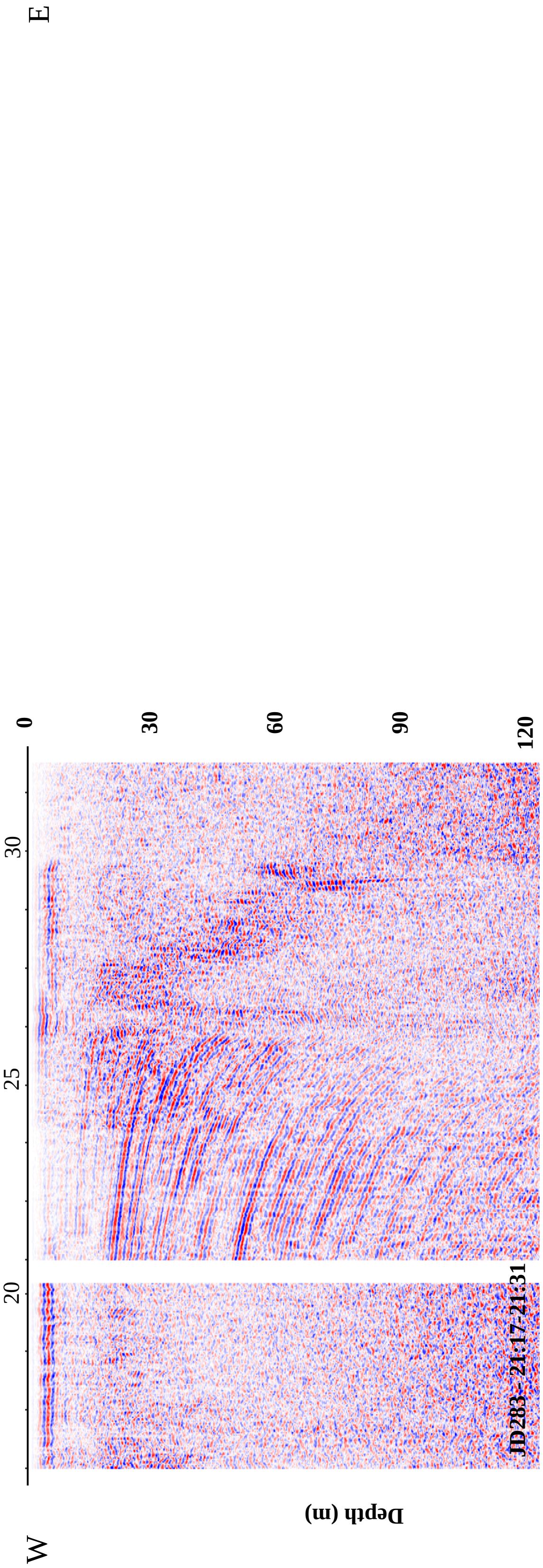

Uniboom Line 11c
E
W
0
30
60
90
120
Depth (m)
Time (minutes)
50
55
0
5
10
15
Approx. Distance (m)
0 100 500
Vertical exaggeration ~8:1
Line 10
Line 2
Line 12
JD283 - 21:49-21:18

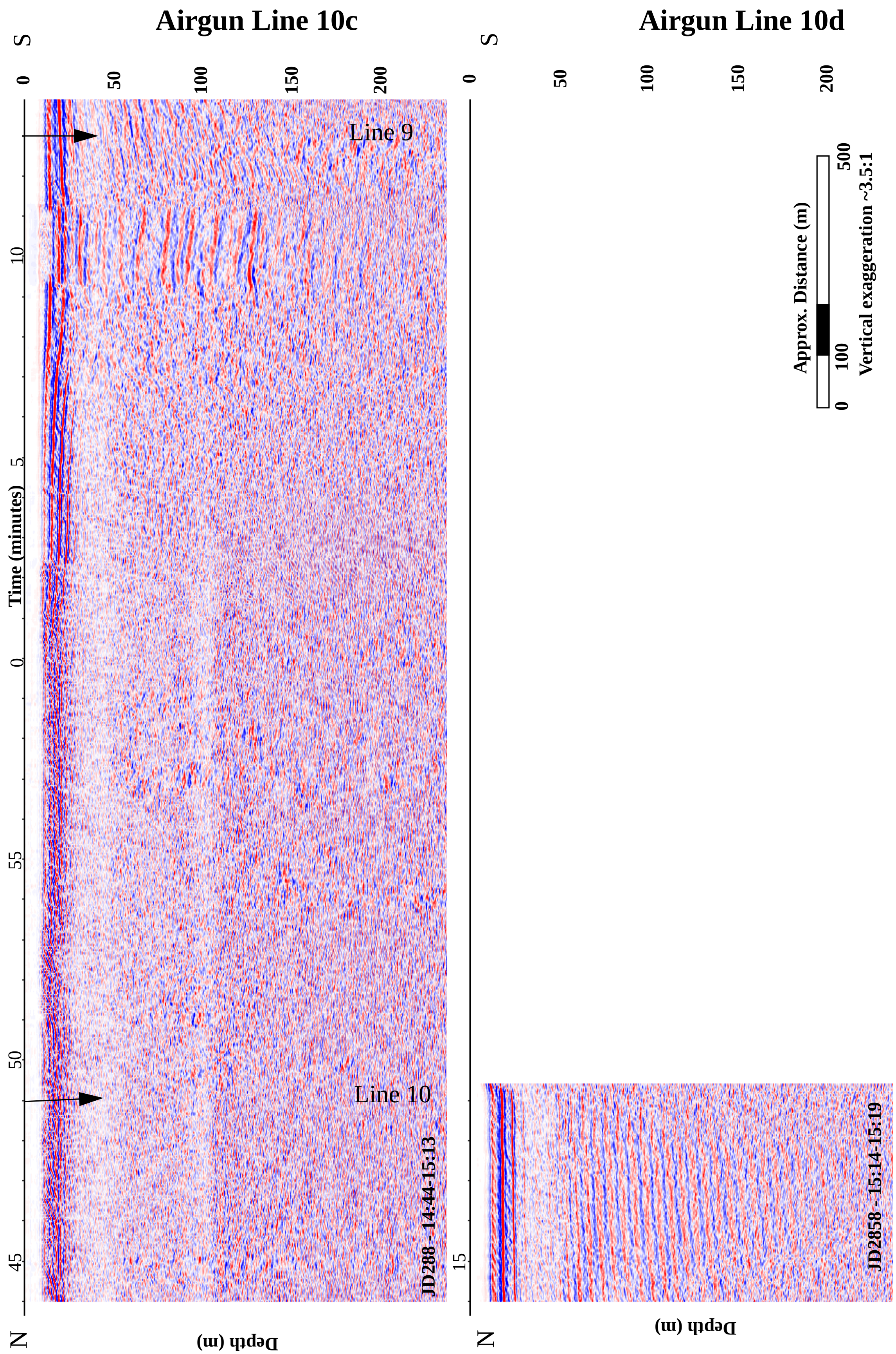

Uniboom Line 12a
E
W
0
30
60
90
120
Depth (m)
Time (minutes)
45
40
35
30
25
20
Line 10
JD283 - 20:17-20:47

Uniboom Line 12b



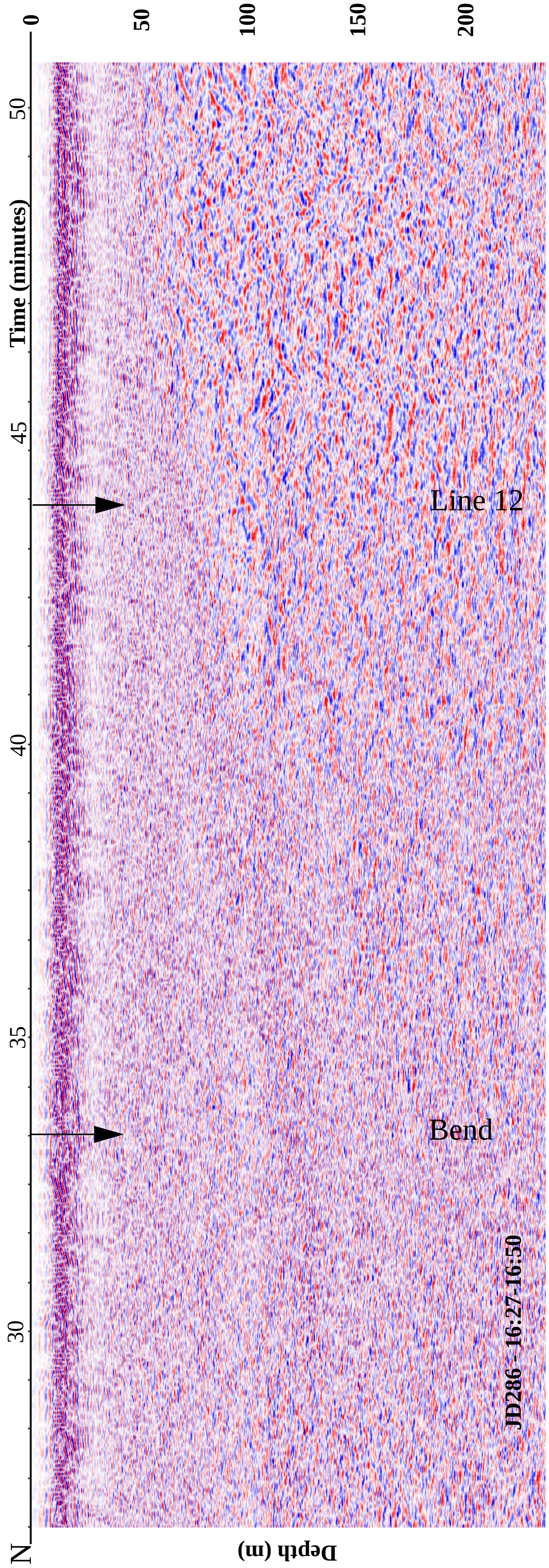
Uniboom Line 12



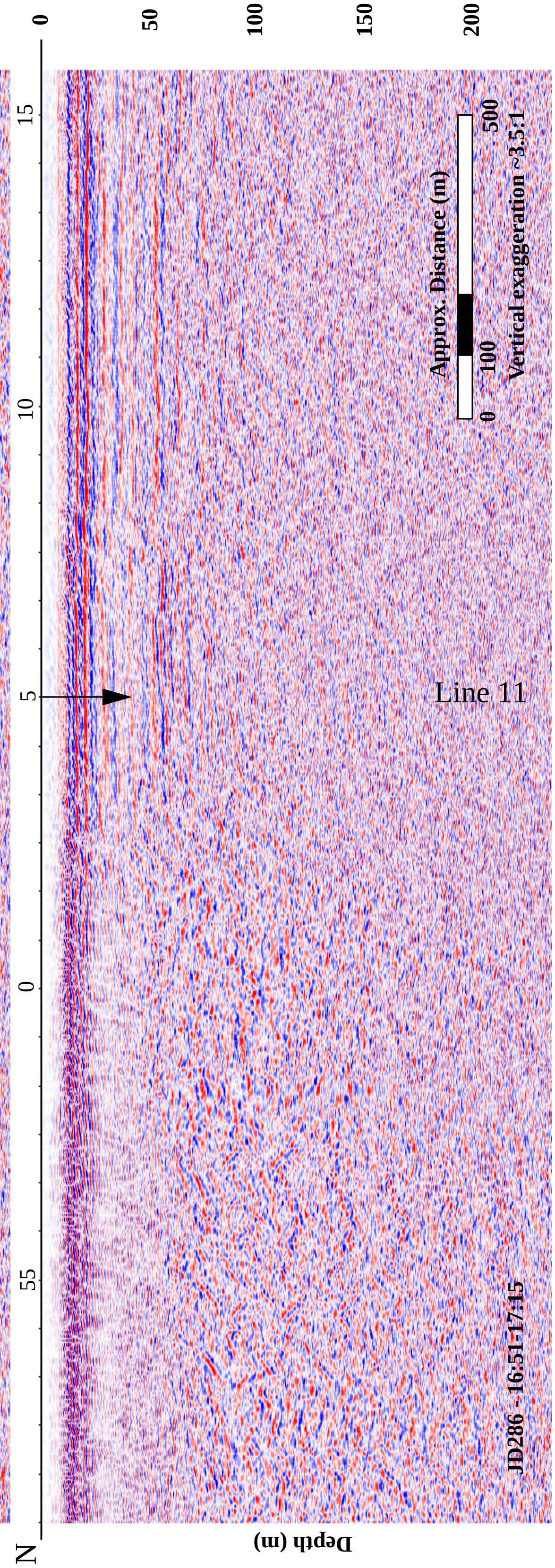


Airgun Line 10c
Airgun Line 10d
S
N
Depth (m)
Time (minutes)
Line 9
Line 10
JD288 - 14:44-15:13
JD2858 - 15:14-15:19
Approx. Distance (m)
Vertical exaggeration ~3.5:1

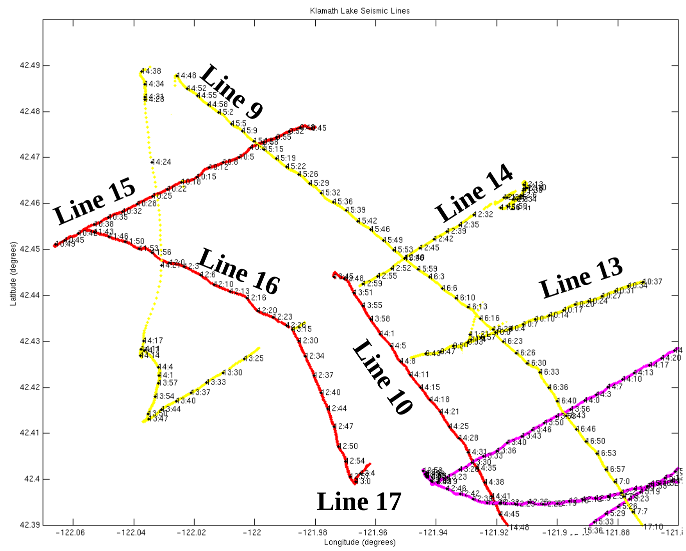
Airgun Line 9e



Airgun Line 9f



Upper Klamath Lake - North of Bare Island



Profiles

East-West Profiles (south-north)

Airgun Line 13 - **(A) JD286 - 09:34-10:04, (B) JD286 - 10:04-10:34, (A) JD286 - 10:34-10:50**

Airgun Line 14 - **(A) JD286 - 13:13-13:48, (B) JD286 - 12:37-13:13, (C) JD286 - 11:38-12:35**

Airgun Line 15 - **(A) JD286 - 10:12-10:42, (B) JD286 - 09:42-10:12**

North-South Profiles (west to east)

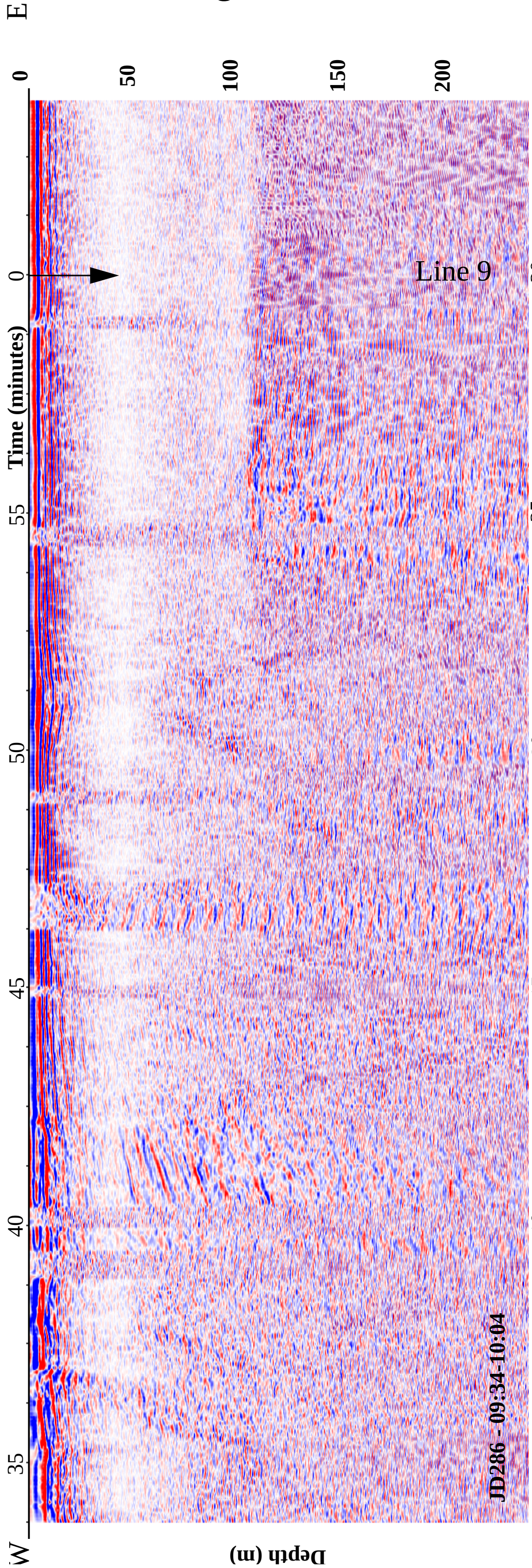
Airgun Line 16 - **(A) JD286 - 11:39-12:08, (B) JD286 - 12:08-12:28**

Airgun Line 17 - **JD286 - 12:28-12:57**

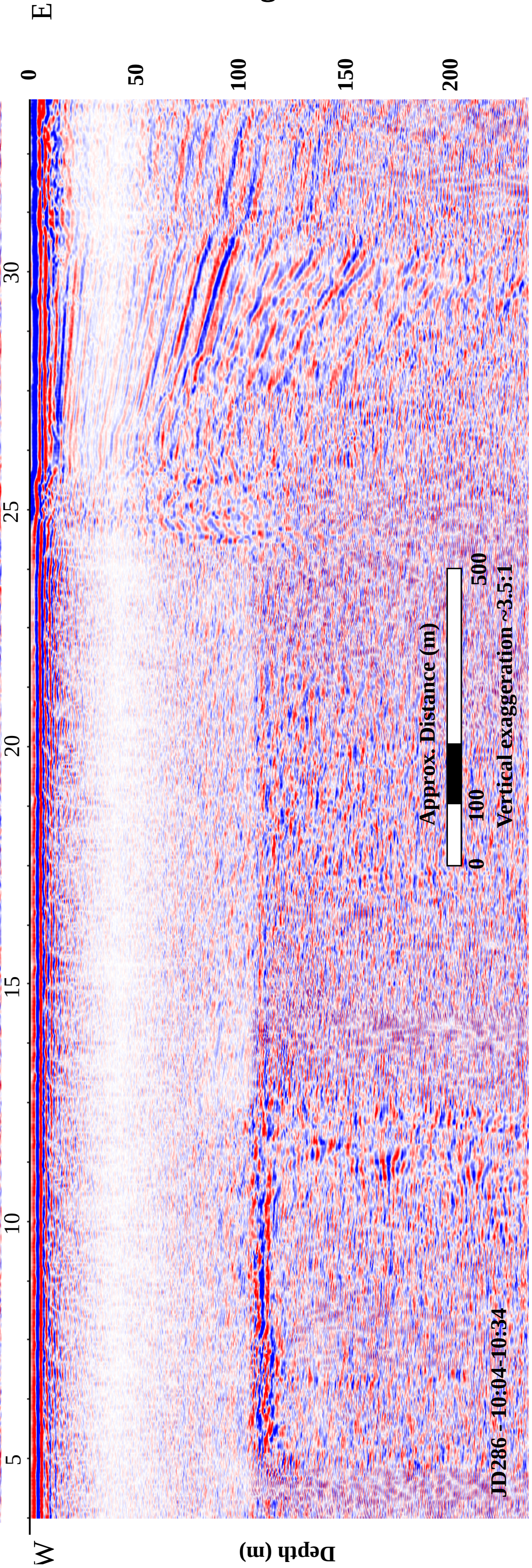
Airgun Line 10 - **(A) JD286 - 13:44-14:13, (B) JD286 - 14:14-14:44**

Airgun Line 9 - **(A) JD286 - 14:33-15:03, (B) JD286 - 15:04-15:34, (C) JD286 - 15:34-16:03, (D) JD286 - 16:03-16:26**

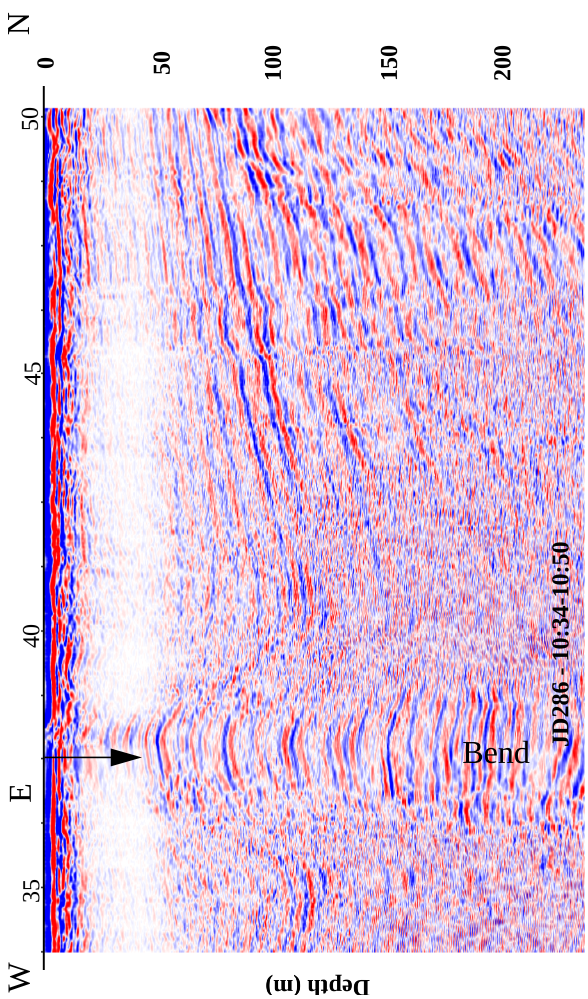
Airgun Line 13a



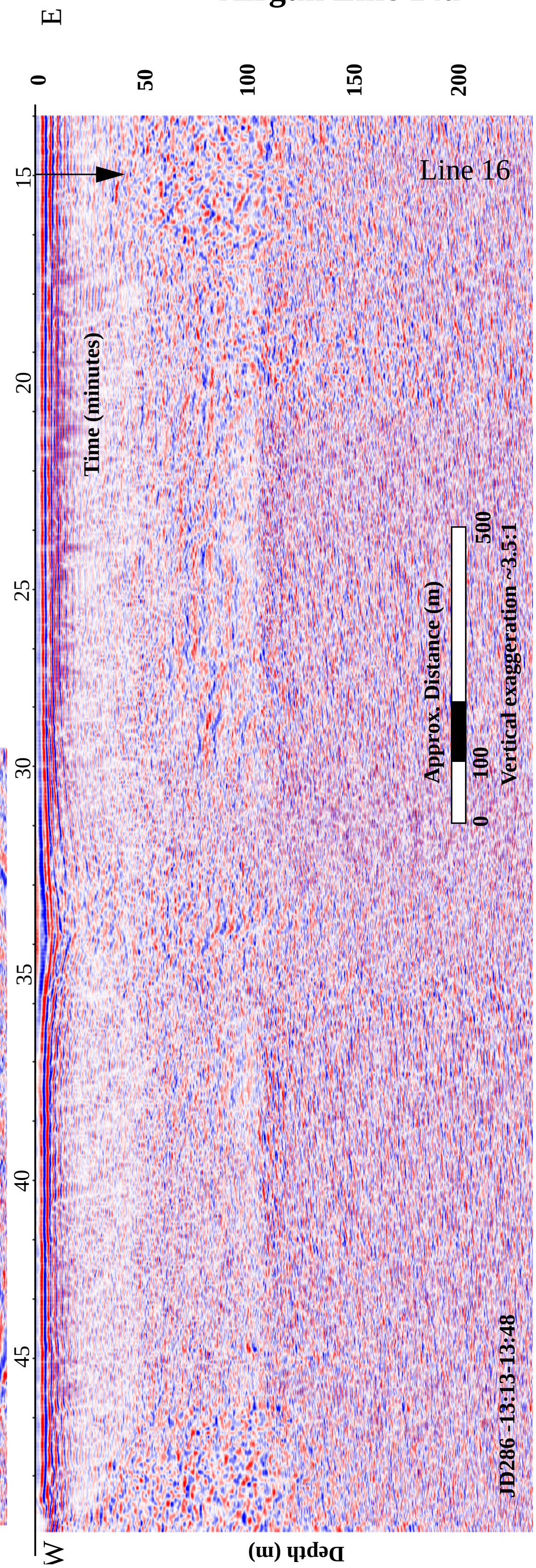
Airgun Line 13b



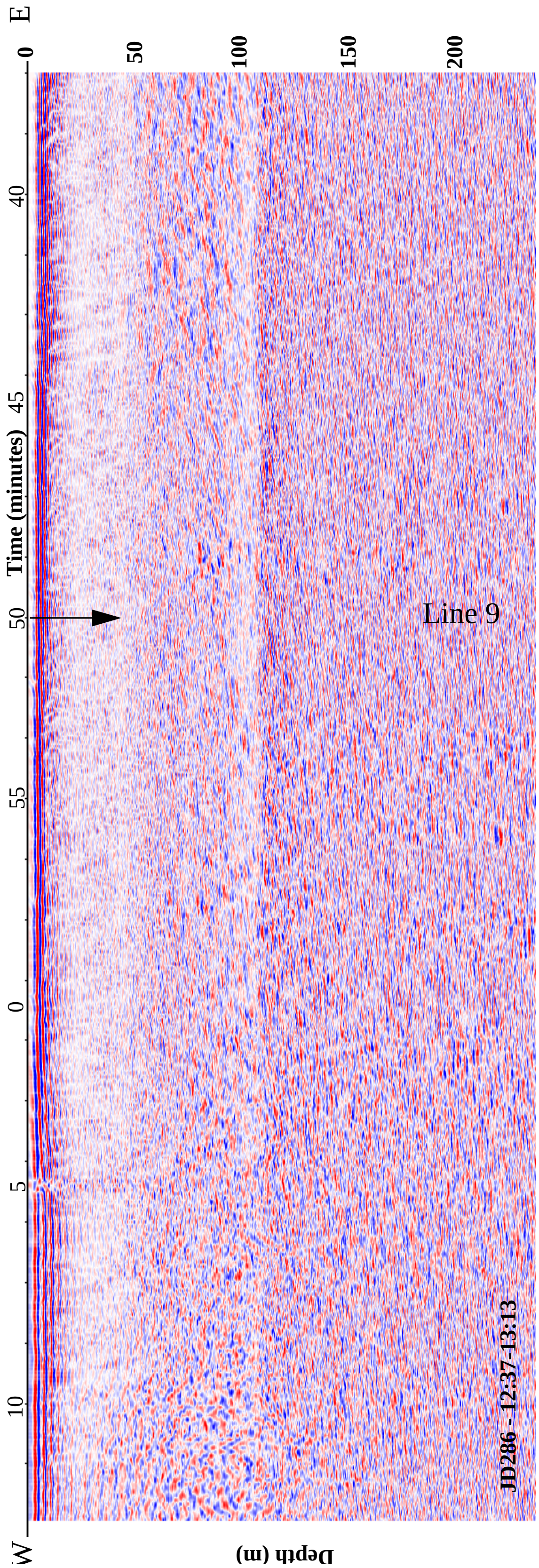
Airgun Line 13c



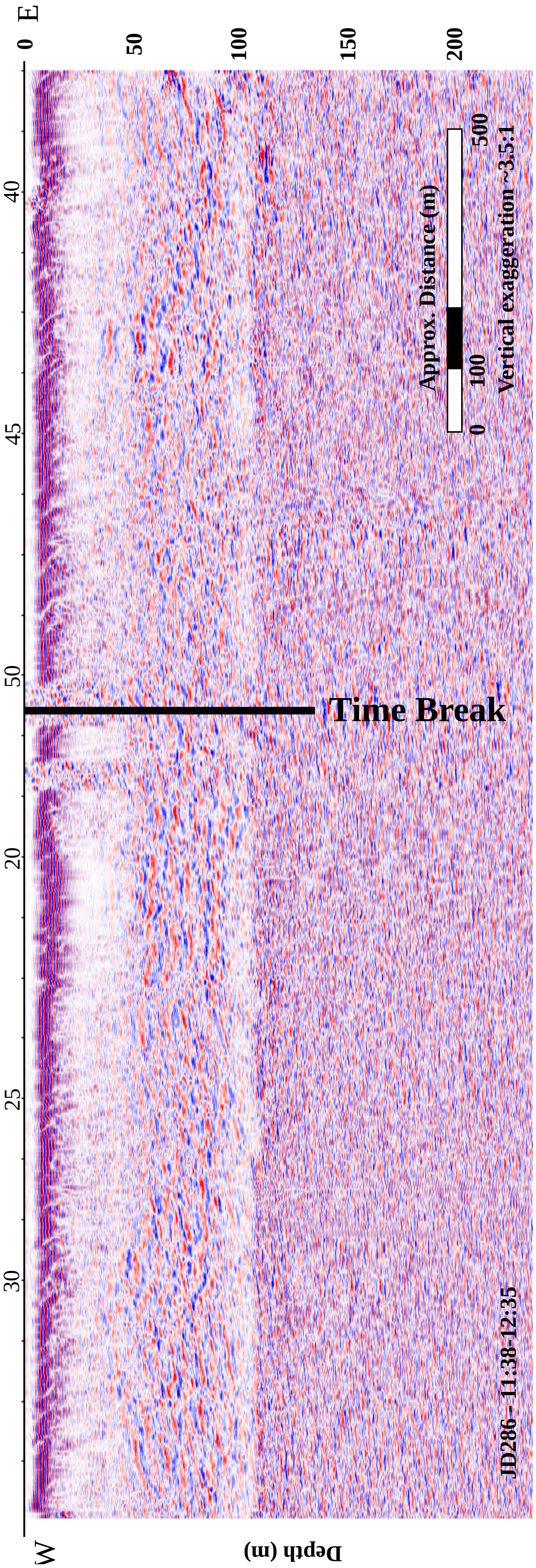
Airgun Line 14a

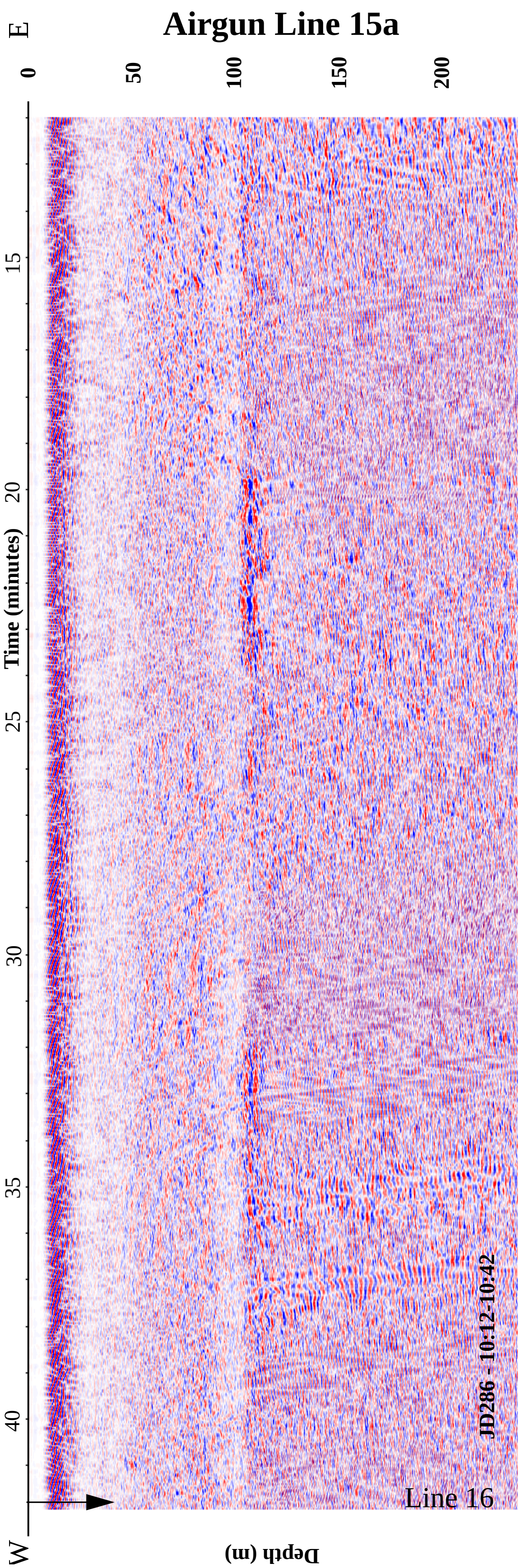


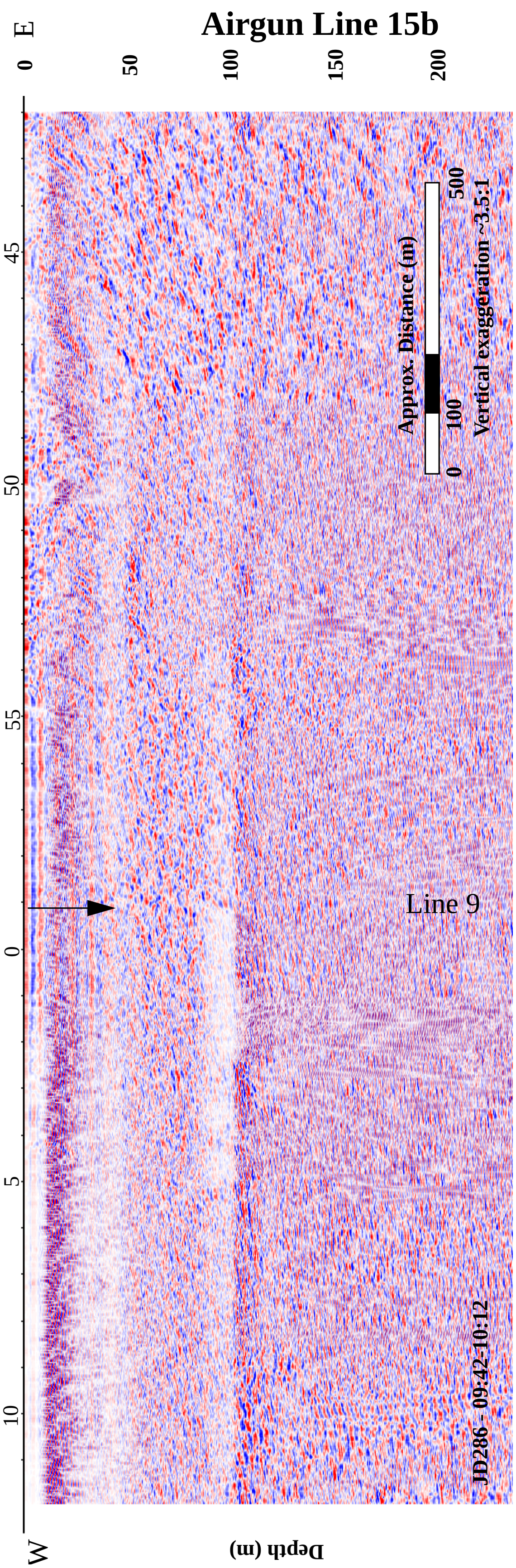
Airgun Line 14b



Airgun Line 14c

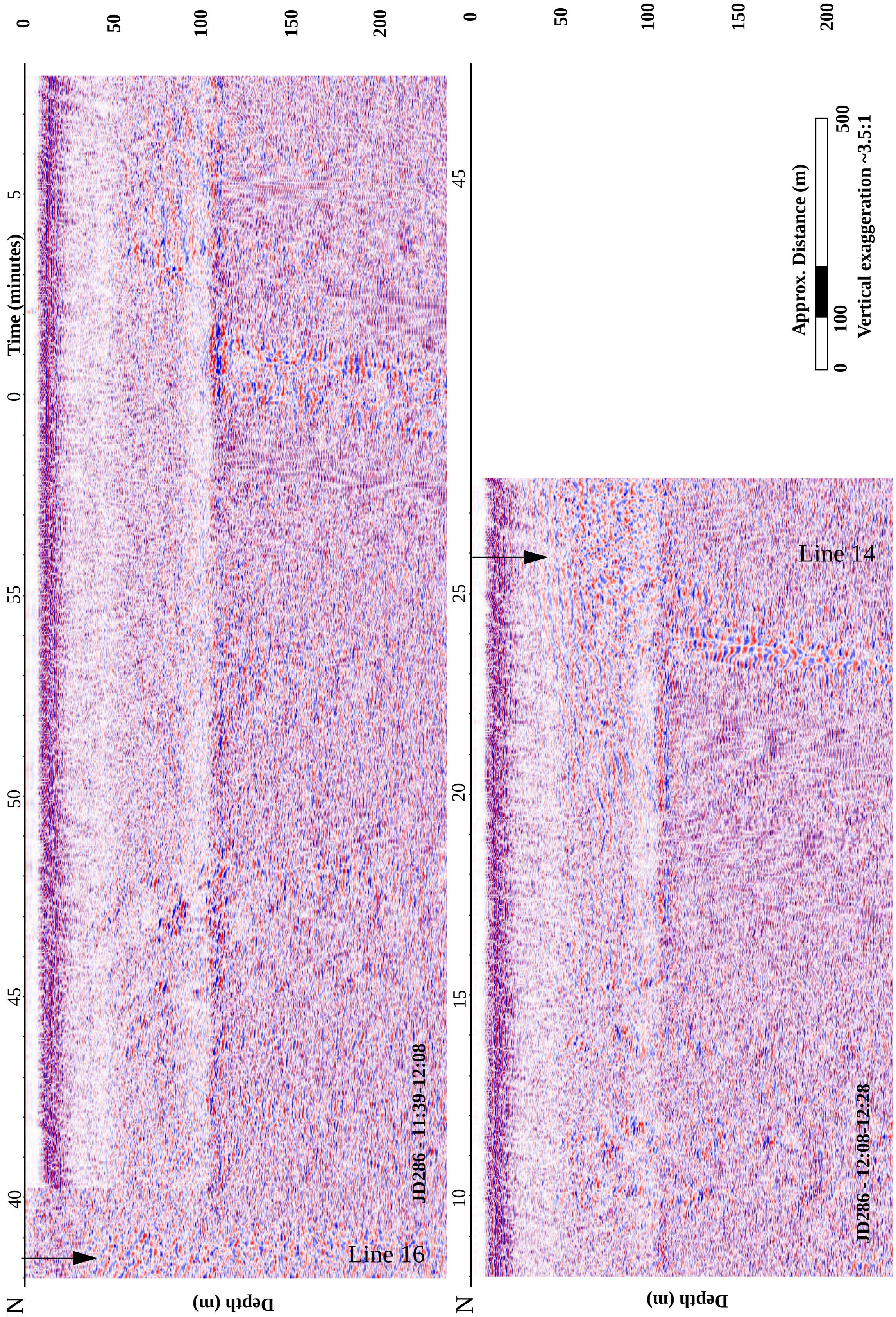


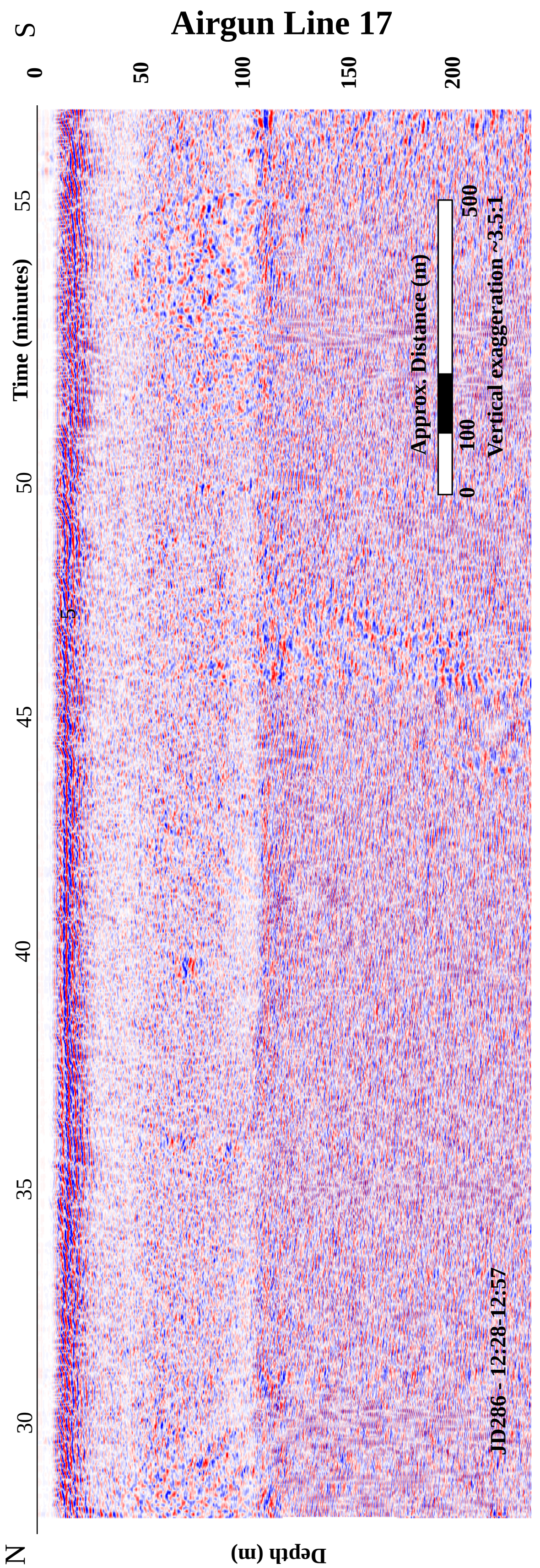

Airgun Line 15a
E
W
0
50
100
150
200
Depth (m)
Time (minutes)
15
20
25
30
35
40
JD286 - 10:12-10:42
Line 16


Airgun Line 15b
E
W
0
50
100
150
200
Depth (m)
45
50
55
0
5
10
Approx. Distance (m)
0
100
500
Vertical exaggeration ~3.5:1
Line 9
JD286 - 09:42-10:12

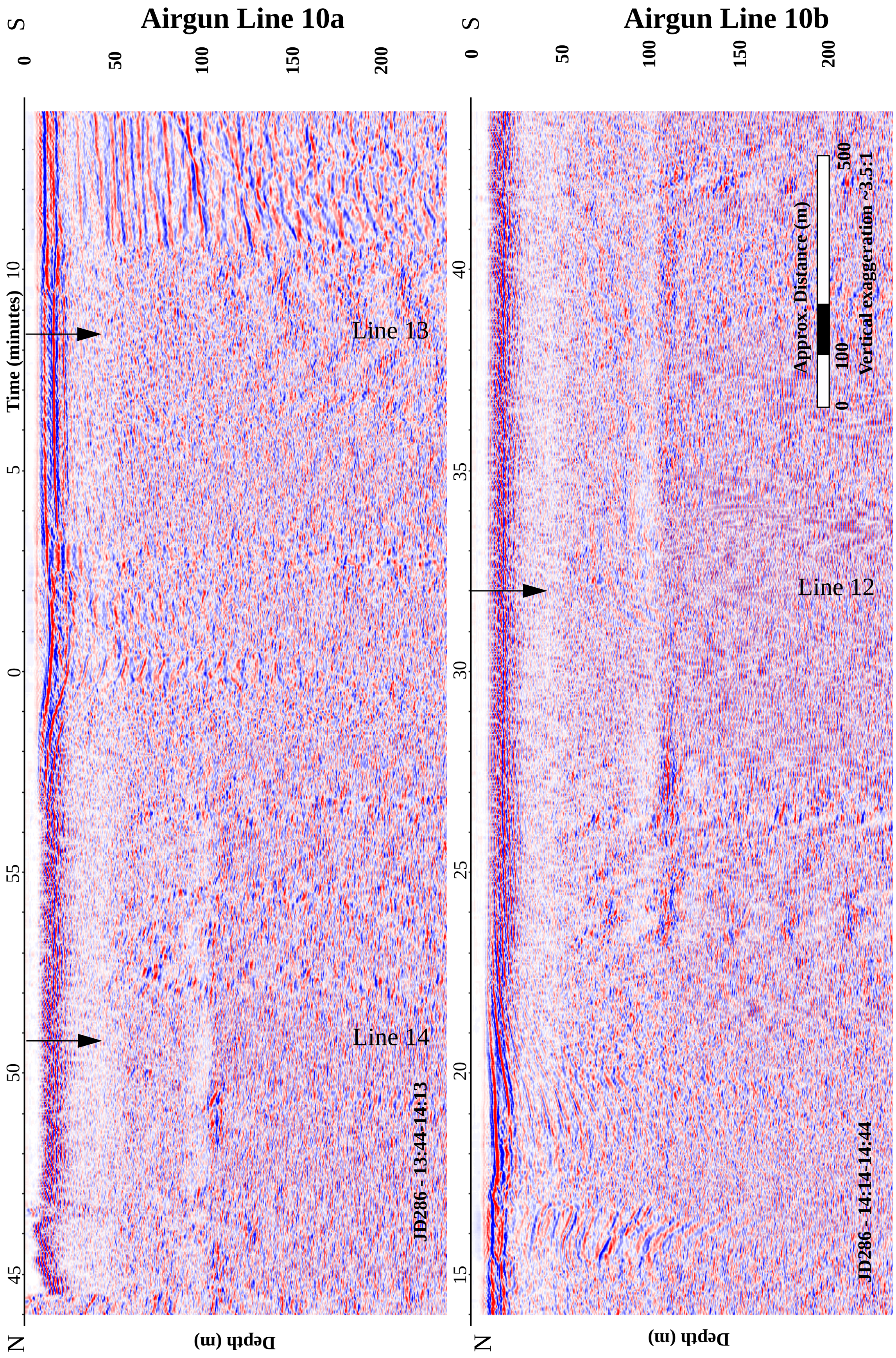
Airgun Line 16a

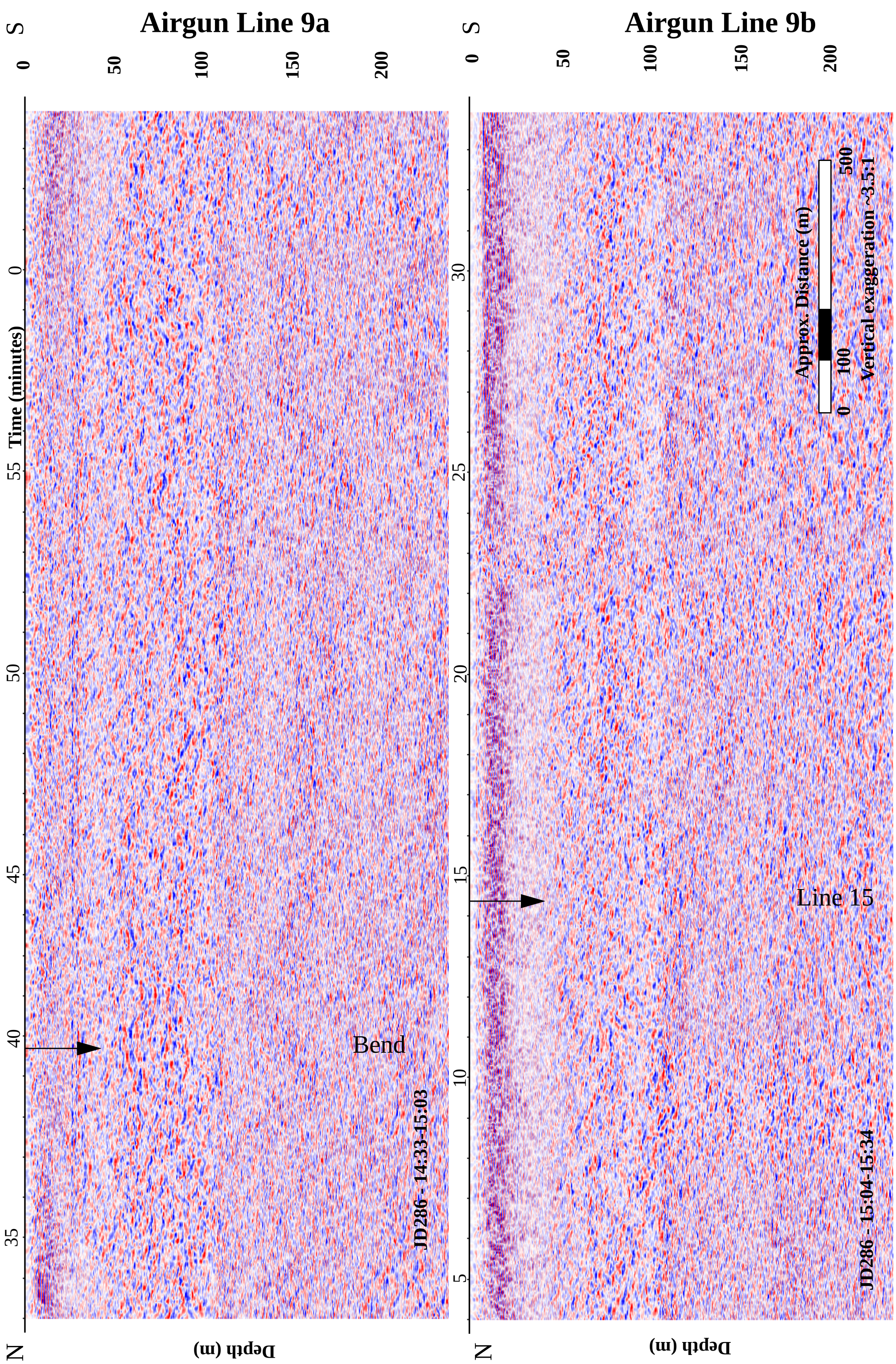
Airgun Line 16b

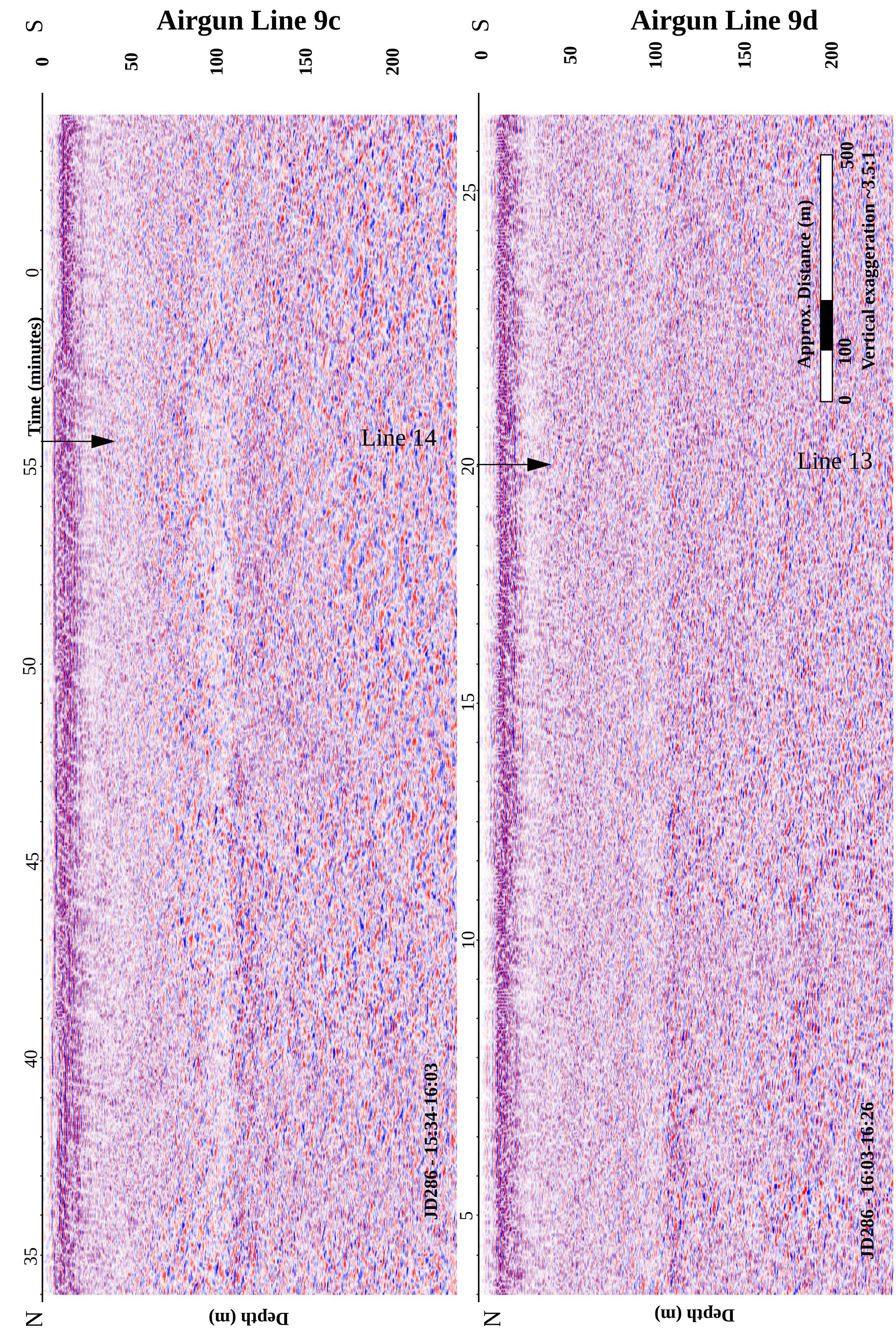




Airgun Line 17
S
N
0
50
100
150
200
Depth (m)
Time (minutes)
55
50
45
40
35
30
Approx. Distance (m)
0
100
500
Vertical exaggeration ~3.5:1
JD286 - 12:28-12:57


Airgun Line 10a
Airgun Line 10b
Time (minutes)
Depth (m)
Line 13
Line 14
Line 12
JD286 - 13:44-14:13
JD286 - 14:14-14:44
Approx. Distance (m)
Vertical exaggeration ~3.5:1
N
S


Airgun Line 9a
Airgun Line 9b
S
N
0
50
100
150
200
Depth (m)
Time (minutes)
35
40
45
50
55
0
5
10
15
20
25
30
Bend
Line 15
JD286 - 14:33-15:03
JD286 - 15:04-15:34
Approx. Distance (m)
0
100
500
Vertical exaggeration ~3.5:1


Airgun Line 9c
Airgun Line 9d
S
N
Time (minutes)
Depth (m)
Line 14
Line 13
JD286 - 15:34-16:03
JD286 - 16:03-16:26
Approx. Distance (m)
0 100 500
Vertical exaggeration ~3.5:1

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References

Braunmiller, J., Nabelek, J., Leitner, B., and Qamar, A., 1995, The 1993 Klamath Falls, Oregon, earthquake sequence; source mechanisms from regional data, *Geophysical Research Letters*, **22**; 2, 105-108.

Colman, S.M., Rosenbaum, J.G., Reynolds, R.L., and Sarna-Wojcicki, A.M., 2000, Post-Mazama (7Ka) faulting beneath Upper Klamath Lake, Oregon, *Bulletin of the Seismological Society of America*, **90**, 1, 243-247.

Dreger, D.; Ritsema, J., and Pasyanos, M., 1995, Broadband analysis of the 21 September, 1993 Klamath Falls earthquake sequence, *Geophysical Research Letters*. **22**; 8, 997-1000.

McQuillin,R., Bacon, M., Barclay, W., 1979, An introduction to seismic interpretation, Gulf. Publ. Co.. Houston, TX, 191 pp.

Pratt, T.L., Odum, J., Stephenson, W., Williams, R., Dadisman, S., Holmes, M., and Haug, B., in-review, Late Pleistocene and Holocene tectonics of the Portland Basin, Oregon and Washington, from high-resolution seismic profiling, *Bulletin of the Seismological Society of America.*

Sanville,W.D., Powers, C.F., and Gahler, A.R., 1974, Sediments and sediment-water nutrient interchange in Upper Klamath Lake, Oregon, U.S. Environmental Protection Agency Report EPA-660/3-74-015, 45 pp.

Wiley, T.J., Sherrod, D.R., Keefer, D.K., Qamar, A., Schuster, R.L., Dewey, J.W., 1993, Mabey, M.A., Black, G.L., Wells, R.E.,Klamath Falls earthquakes, September 20, 1993; including the strongest quake ever measured in Oregon, *Oregon Geology*, **55**, 6, 127-134.