

# 3-D SEISMIC IMAGING OF AN ACTIVE MARGIN HYDRATE SYSTEM OREGON CONTINENTAL MARGIN



## REPORT OF CRUISE TTN112 R/V THOMAS THOMPSON June 19 - July 3, 2000

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### **3-D seismic imaging of an active margin hydrate system Oregon continental margin**

In the past several years, international interest in gas hydrates in marine sediments has increased considerably because of increasing recognition that the large volume of gas stored in hydrates or trapped beneath them is a significant fraction of the global methane budget, and may therefore be a source of energy for the future. Because methane is a powerful greenhouse gas, hydrates are also being studied as a possible causative factor in global change. These studies, however, are hampered by our limited knowledge of how much gas is actually stored in this reservoir, its behavior during changing environmental conditions, and its mechanical effects on slope stability.

In June-July, 2000, we conducted a high-resolution 3-D seismic survey of a 4 x 9 km<sup>2</sup> region on Hydrate Ridge on the Oregon continental margin. The northern crest of this ridge was drilled during ODP Leg 146, and evidence for hydrate and underlying free gas was found. Multichannel seismic data collected in 1989 as a site survey prior to Leg 146 show that a BSR is ubiquitous beneath this ridge. A closer look at the 1989 seismic data and at seafloor morphology shows systematic coincident variations in stratigraphic and BSR reflectivity that suggest that tectonic activity, venting, and slumping are important controls on the distribution of hydrate and free gas. The subsurface reflectivity patterns are especially well defined in the region imaged in this survey. The volume that we imaged includes: the summit of southern Hydrate Ridge, where massive hydrates were recovered from near the seafloor in 1996 and 1999; an actively venting carbonate tower southeast of the summit that was observed and sampled using DSV Alvin in 1999; several "double BSRs," and crosscutting anomalously bright stratigraphic reflectors; and an adjacent slope basin within which the seismic signature of hydrate presence is markedly different than beneath the ridge.

The 3-D survey comprised 81 profiles spaced 50 meters apart. Shots from 2 GI guns fired simultaneously were recorded on a 600-m-long, 48-channel streamer and an array of 21 4-component ocean bottom seismometers. Several longer regional seismic reflection/refraction lines were also shot. For data quality control, each line was processed as a 2D profile immediately after acquisition, assuming a water velocity for normal moveout correction and f-k migration. The locations of the ship and of the streamer were determined via differential GPS and compasses, respectively, and 3D fold was monitored during the cruise to identify locations where additional data were needed. This resulted in reshooting 18 lines. Excellent data quality was obtained in spite of strong winds and high seas. Fortunately noise due to sea-state was at a considerably lower frequency than that used to image subsurface structure. Two preliminary OBS record sections were also produced, both of which showed arrivals to offsets >20 km, including Pn arrivals from the base of the oceanic crust. The GI-guns were demonstrated to be a very effective broadband source, producing useable energy from 10-150 Hz.

The data provide considerable new information on the pathways through which methane-rich fluids and free gas migrate from beneath the BSR to the seafloor and on the geological evolution of Hydrate Ridge. Some highlights of the 3D reflection survey include: possible imaging of the conduit feeding the carbonate chimney; observation of a strong acoustic "bubble" plume over the southern summit of Hydrate Ridge; identification of several new coherent secondary "BSRs;" documentation of the development of an apparently gas-rich anticline on the eastern flank of Hydrate Ridge; identification of several apparent slump deposits in the adjacent slope basin that can provide constraints on the growth history of Hydrate Ridge. Additional analysis, including modeling of the OBS data and 3D processing of the reflection data, will certainly lead to sharper images of the subsurface and new surprises.

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## Scientific Personnel:

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Peter Buhl	scientist	Lamont-Doherty Earth Observatory
John Diebold	senior scientist	Lamont-Doherty Earth Observatory
Robert Hagg	marine technician	University of Washington
Joel Johnson	graduate student	Oregon State University
Anubрати Mukherjee	graduate student	University of Texas at Austin
Yosio Nakamura	senior scientist	University of Texas at Austin
Andrew Maddingly	marine tech student intern	Monterey Peninsula College
Bill Martin	marine technician	University of Washington
Sue Pottter	graduate student	Oregon State University
Steffen Sastrup	seismic processor	University of Texas at Austin
Erich Schultz	GI gun technician	Borehole Professionals Inc.
Anne Trehu	co-chief scientist	Oregon State University
Mark Wiederspahn	navigation/computer expert	University of Texas at Austin
Ben Yates	OBS engineer	University of Texas at Austin
Ling Zhang	graduate student	Oregon State University

## Ship's Crew:

Andy Bartell	oiler	all from University of Washington
Christie Bettle	mess attendant	
Larry Branovitch	AB	
Gray Drewry	chief mate	
Ben Glass	AB	
Glenn Gomes	master	
Daniel Granstrom	oiler	
Joachim Heise	chief engineer	
Chris Hembree	AB	
Tim Hill	AB	
Logan Johnsen	third mate	
Richard Leonard	third AE	
Primo Matencio	second cook/baker	
Dan McBriar	chief steward	
Timothy McDaniel	wiper	
Richard O'Connell	second AE	
Russell Rowley	oiler	
Lew Skelton	first AE	
Frank Spetla	AB	
Robert Symonds	second mate	
Tim Younker	AB	

## Scientific Instrumentation:

48 channel, 600 m ITI streamer (Lamont)  
OYO 48 channel seismic recorder with 24 bit A/D (Lamont)  
4 GI guns (3 Lamont; 1 USGS) and associated hoses, harnesses and fittings  
2 compressors (R/V Thompson)  
21 ocean bottom seismometers (UTIG)  
RACAL differential GPS receivers and processor (UTIG)  
data logging computer (Lamont)  
navigation computer (UTIG)  
processing computers (UTIG/OSU)  
Bathy2000 3.5/12 kHz echosounder (R/V Thompson)  
Doppler current meter/sea surface temperature (R/V Thompson)

## Background:

Gas hydrate is an ice-like substance that contains methane or other low molecular weight gases in a lattice of water molecules. Methane hydrates are stable under the temperature and pressure conditions generally found in the Arctic and near the seafloor at water depths greater than 500 m. They are quite common beneath the continental slope of both active and passive continental margins, where methane originates from the decomposition of organic matter. However, hydrate distribution is observed to be highly variable, and no reliable geophysical techniques for mapping hydrate content have yet been developed. The strong pressure and temperature dependence of hydrate stability implies that tectonics and fluid flow should be significant factors influencing hydrate formation and dissolution. These factors are quite different in active and passive margin settings, and may explain some differences in hydrate occurrence between these two settings.

ODP has therefore scheduled a leg to drill Hydrate Ridge on the accretionary continental margin offshore Oregon to compare hydrate processes on an active margin to those on a passive margin (figure 1). This structure, located approximately 12 km landward of the present deformation front, has been the focus of numerous studies of fluid processes in accretionary prisms since the discovery of cold seeps and the associated biological communities two decades ago. A fault near the northern summit of Hydrate Ridge was drilled by ODP in 1992 during leg 146.

The southern summit of Hydrate Ridge has been chosen for drilling in 2001/2002 during a leg dedicated to hydrates in accretionary complexes both because of the observation of massive hydrate formation at the seafloor here (Bohrmann et al., 1998) and the ability of seismic data to image structures beneath the base of the hydrate stability zone as marked by the seismic reflection known as the BSR (Trehu et al., 1999). The observed complexity of subBSR reflectivity beneath southern Hydrate Ridge contrasts with the northern summit of Hydrate Ridge, which was drilled during ODP leg 146. Trehu et al. (1999) speculated that northern Hydrate Ridge represents a later stage of evolution in which subsurface structure is obscured by the development of a massive carbonate bioherm cap. On southern Hydrate Ridge, massive carbonate is restricted to a single 50 meter high tower located ~500 m SW of the summit (Torres et al., 1999). Comparison between northern and southern Hydrate Ridge should thus provide a spatial proxy for the temporal evolution of hydrate-bearing accretionary ridges in general. That hydrate-related processes operating at Hydrate Ridge are representative of general processes in accretionary complexes is supported by observations of venting from the summit of other features on the Oregon accretionary margin that were chosen for investigation solely on the basis of their morphological resemblance to Hydrate Ridge (eg. SE Knoll on Fig. 1; Bohrmann et al., 2000).

In addition to providing data to refine the location of the planned drill sites, which are were originally based on analysis of a regional 2D survey collected in 1989 as a site survey for ODP leg 146, objectives of this cruise are to:

- 1) Define the 3-D plumbing system beneath and within the hydrate stability zone as inferred from seismic reflectivity. The 1989 survey suggests a complicated interaction between stratigraphic conduits, faults, the BSR and seafloor vents, but the spatial scale is clearly smaller than the line spacing in that survey, and the high-resolution bathymetry, sidescan and seafloor video indicate several different types of vents within the study region.
- 2) Map 3-D variations in reflectivity and velocity as a potential indicator of variations in hydrate concentration. Detailed waveform inversion shows promise for resolving regions of hydrate and carbonate concentration near the seafloor, around vents, and at the BSR. Constraining these parameters will provide strong constraints on theoretical models of hydrate formation as a function of diffuse and advective fluid flow.
- 3) Map 3-D variations in reflectivity and velocity as a potential indicator of the volume of gas beneath the BSR. Variability in the concentration of gas immediately below the BSR is

evident from the large variations in amplitude of the BSR in the ODP site survey data; however, those data say nothing about the thickness of the free gas region. Refracted wave tomography shows promise for estimating the depth to which free gas extends in the incoherent subBSR region.

- 3) Relate sub-surface plumbing and hydrate concentration to tectonic history and to seafloor morphology and side-scan reflectivity. Seafloor morphology and reflectivity hold promise as an inexpensive and efficient means for mapping the seafloor over large areas and identifying regions where hydrate is being formed in response to focussed fluid flow. However, hydrate formation is primarily a sub-surface process, and the proposed data are essential for calibrating the bathymetry and side-scan data that are presently available and evaluating the use of this technique as a hydrate mapping tool.
- 5) Estimate the mechanical properties and gas content of hydrate-bearing and underlying sediments and their implications for slope instability and consequent release of gas to the ocean. The velocities derived to meet the above objectives will be used to place limits on the mechanical properties of the hydrate/gas system and the amount of gas stored in this reservoir. These parameters can then be used for physical models of slope stability and gas release.

This project is but one component of an multidisciplinary and multinational collaboration to use Hydrate Ridge as a laboratory to study the impact of gas hydrates on slope stability and environmental chemical balances and follows a series of cruises in 1996, 1998, and 1999 during which seafloor and water column biogeochemical processes were investigated on northern and southern Hydrate Ridge. It represents the first geophysical work focussed on hydrates on the Oregon continental margin. It will be followed in September/October 2000 by a second geophysical cruise led by Dirk Klaeschen (GEOMAR).

## **Preliminary Results:**

### *Ocean bottom seismometers:*

During the cruise, we first deployed an array of 21 four-component ocean bottom seismometers (OBS) on the seafloor (figure 2). Instruments were released at the planned locations and allowed to fall freely to the seafloor. Most instruments were dropped within 50 meters of the target (see acquisition, deployment and recovery parameters in appendix A). Final instrument locations and horizontal component orientations will be determined later by inversion of waterwave arrivals. Nineteen of the OBSs were equipped with 1.212 Gbyte disk drives and 2 (sites 19 and 21) were equipped with 500 Mbytes drives. All but one OBS was recovered, and all recovered instruments recorded data. Preliminary record sections were produced in the field for two instruments (using preliminary OBS and shot locations). These record sections (figure 3) show first arrivals to offsets as great as 45 km, including Pn arrivals from the base of the oceanic crust. Such long-range propagation of low frequency energy was a surprise from the relatively weak, high-frequency GI gun source used for this experiment.

### *Regional 2D OBS/MCS profiles*

After deploying the OBSs we shot six regional profiles using 2 GI guns with 105 in<sup>3</sup> chambers fired at 37.5 m intervals (figure 2). All shots for this project were triggered on distance using the RACAL differential GPS system contracted for this cruise. Maps in this report, however, were constructed from the ship's GPS locations. Navigation is discussed in more detail in Appendix B. While the primary purpose of the regional lines was to provide offsets of at least +/- 10 km to each OBS, they were also recorded on the multichannel streamer, providing new data on structural variations along the axis of Hydrate Ridge and across the eastern boundary of the adjacent slope basin.

After completing the 3D survey, we acquired 5 additional 2D regional lines. These lines were not recorded by the OBSs. Three of the lines are located south of the 1989 seismic

survey where no seismic data were available prior to this cruise. They were designed to provide insights into reasons for the considerable along-strike topographic variability of the accretionary complex. A strong BSR overlying an incoherent region beneath SE Knoll confirms the conclusion based on seafloor morphology that SE Knoll is another "Hydrate Ridge" (figure 4) even though it is located considerably further landward of the deformation front. In contrast, due south of Hydrate Ridge, this profile shows folded and faulted slope sediments and no BSR.

### *High-resolution 3D OBS/MCS survey:*

The 3D survey comprises 81 lines, numbered 100-180, and 18 reshoots, numbered 112A, etc. Lines for reshoots were determined based on evaluation of actual 3D coverage as determined from differential GPS locations and determinations of streamer position calculated based on 5 compass birds (see Appendix B).

The survey was shot in a "racetrack" pattern, starting on the western end of line 112, followed by 140 shot from east to west, followed by 114, 142, 116, 144, etc. Our strategy was to first acquire the central 75% of the survey at twice the desired spacing, followed by filling in the central part of the survey, followed by adding to the survey from the north and the south, and finishing with the reshoots needed to fill in 3D gaps resulting from variable degrees of streamer feathering or navigational problems resulting from strong currents. This strategy was adopted to ensure that the most critical parts of the survey would be acquired in the case of significant loss of working time due to equipment failures or poor weather conditions. We were fortunate, however, to lose very little time to weather or equipment failures.

During the cruise, all lines were processed for quality control within a few hours of being acquired. A 2D, straight-line geometry was assumed. Data were sorted into 12.5 m bins, resulting in 40 fold data for lines in the 3D grid and 16-24 fold for the regional lines. The data were corrected for normal moveout and stacked assuming a constant velocity of 1500 m/s. This assumption is justified by the short streamer length and by previous refraction work in this region, which shows velocities <1.8 km/s extending ~600 m beneath the BSR on northern Hydrate Ridge (Trehu and Flueh, in press). A velocity of 1500 m/s was also used for f-k migration of the data. A more detailed description of the processing sequence is given in Appendix C.

Figure 6 shows a comparison of line 112 to line OR2 and of line 180 to line OR1 from the 1989 site survey (MacKay et al., 1992) that was used to plan this survey. This figure illustrates the much greater resolution obtained with the high-frequency GI-gun source compared to the 64-air-gun array used for the 1989 survey. Many of the major features of the data were apparent in the older data, and the primary arguments for the proposed drill sites remain valid. However, the new data suggest that some sites should be moved a few kilometers to optimize their locations. The data also provide arguments for several additional shallow holes designed to investigate variations newly identified structural and stratigraphic features.

Every 10<sup>th</sup> line of the 3D survey is shown in figures 7a-i. Details of the data near the summit are shown in figure 8. Subtle, but significant, changes in reflector geometry and amplitude can be seen from line to line, indicating that 3D processing will be both successful and exciting. In this report, we point out several interesting features of the data. Undoubtedly many new conclusions will become apparent with further processing and interpretation of the data and integration of the seismic data with seafloor and drilling results.

- 1) The data show considerable stratigraphic complexity both above and below the BSR that was not previously apparent. Certain stratigraphic reflections are anomalously bright, and these amplitude anomalies are consistent for hundreds of meters along strike.

Stratigraphic amplitude anomalies are observed both above and below the BSR. Additional amplitude anomalies cut across stratigraphic horizons.

- 2) Two distinct, internally incoherent horizons are recognized within the slope basin east of Hydrate Ridge. The shallower of these horizons thickens to the north, reaching a thickness of ~35 m, whereas the deeper one thickens to the south. These may be the record of massive slope instabilities. Constraints on the age and character of these horizons combined with the seismic data will provide information on the temporal evolution of Hydrate Ridge and its role in the evolution of the accretionary complex.
- 3) Several double BSRs are observed. The "double BSR" originally identified in line OR2 deepens to the north and shallows to the south of OR2 (figure 7a - 7d). A marked change in frequency content is observed across this boundary. Its nature remains enigmatic. A second double BSR is observed beneath the western flank (figures 7 and 8) and is parallel to the primary BSR. Although it may be an artifact of the source signature, this seems unlikely because it is consistently observed beneath the western flank and not observed elsewhere. It may reflect the presence of a second type of hydrate-forming gas. Further analysis of the seismic data and ultimately drilling are needed to determine the nature of both BSRs.
- 4) The region beneath the carbonate pinnacle is non-reflective (line 154, figure 8). Determining whether this is due primarily to energy not penetrating through the seafloor carbonates or to the subsurface effect of a conduit bringing fluids from beneath the BSR to the seafloor will require further analysis of the data.
- 5) Chaotic bright reflectivity is observed just beneath the seafloor beneath the summit (line 150, figure 8). This pattern is coincident with observations of a persistent acoustic "bubble" plume over the summit in 12kHz data (figure 9). This plume was seen on lines 146-151 and during 2 additional crossings over this region. No acoustic "bubble" plumes were seen elsewhere during the survey except for at the summit of SE Knoll (note: we did not steam over the northern summit of Hydrate Ridge, where acoustic "bubble" plumes have been seen on other cruises). It also corresponds to the region of massive hydrate on the seafloor. Determination of whether it indicates the depth extent of massive hydrate or ponding of gas (or something else) will require additional modeling of the data. Shallow drilling into the summit using an autonomous drill rig such as PROD may also be used to address this question.

In summary, even this first look at the new data indicates that the strategy of nesting a high-resolution 3D survey within the existing low-resolution 2D survey has been very successful. The 2D survey, combined with seafloor observations, served to identify a region of particular interest for further study, and the high-resolution 3D survey, combined with drilling, promises to provide a significant increase in our understanding of the processes whereby fluids migrate in the accretionary complex to form massive hydrate deposits and the feedback mechanisms whereby the presence of gas and gas hydrate affects geologic evolution.

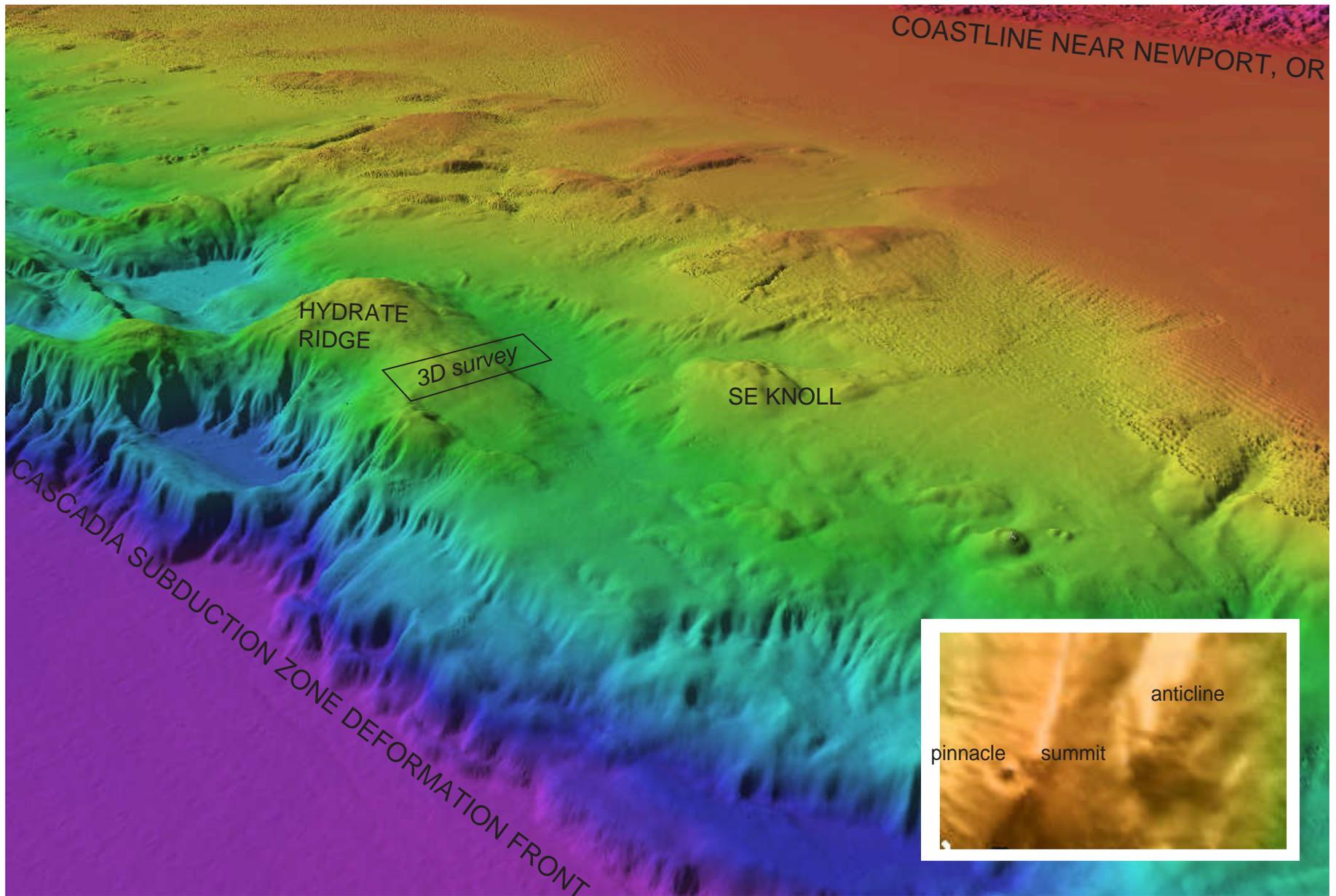


Figure 1. Perspective view of the continental margin offshore Oregon looking NE from ~100 km offshore. Methane hydrate is wide spread on the continental margin at depths >550 m. The location of the 3D seismic survey is shown. Insert shows a detailed view of the southern summit of Hydrate Ridge within the region covered by the 3D survey.

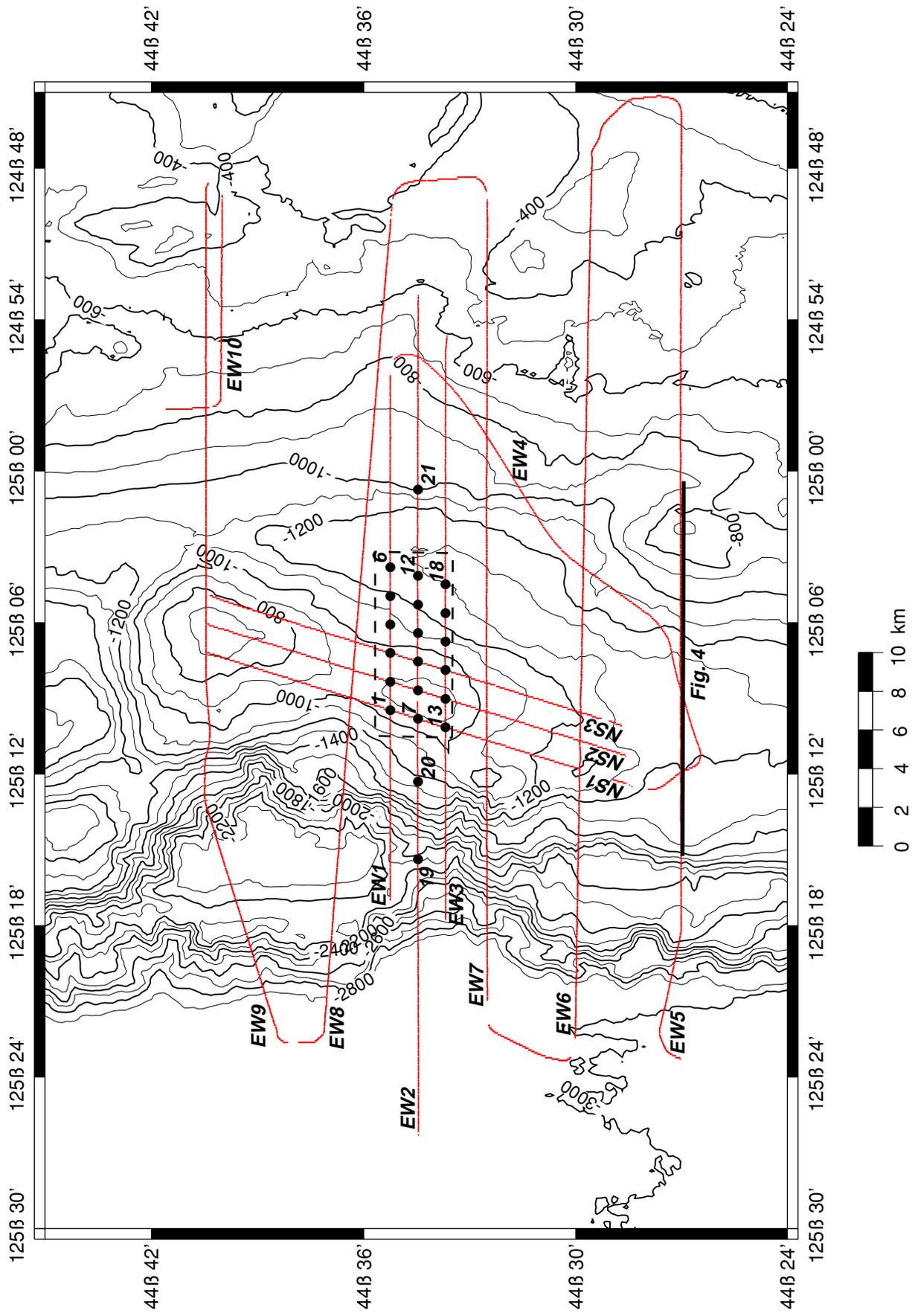
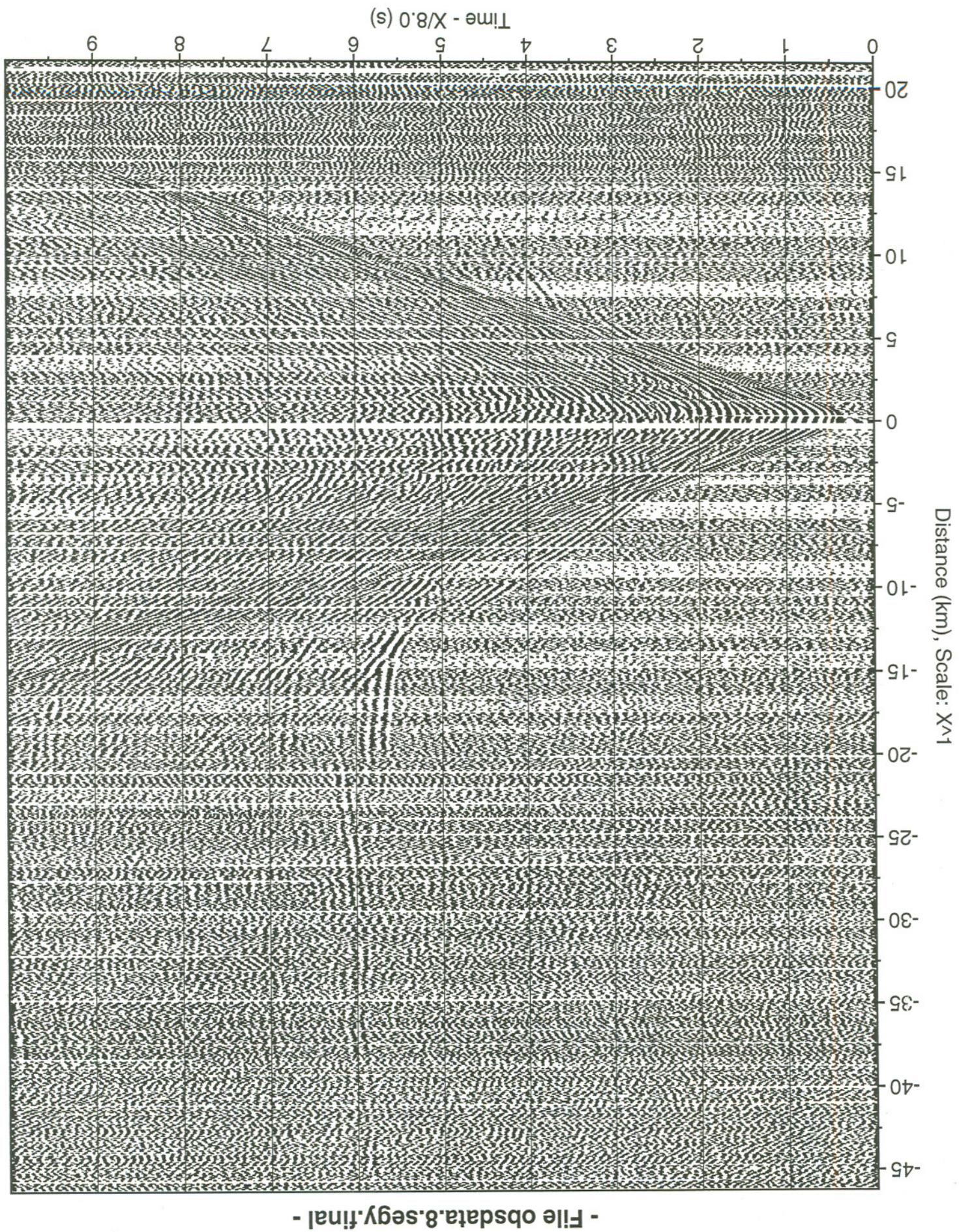


Figure 2. Bathymetric map showing regional lines, OBS locations (numbered dots), and the location of the 3D seismic survey (dashed box).



- File obsdata.8.segy.final -

figure 3a

- File obsdata.20.segy.final -

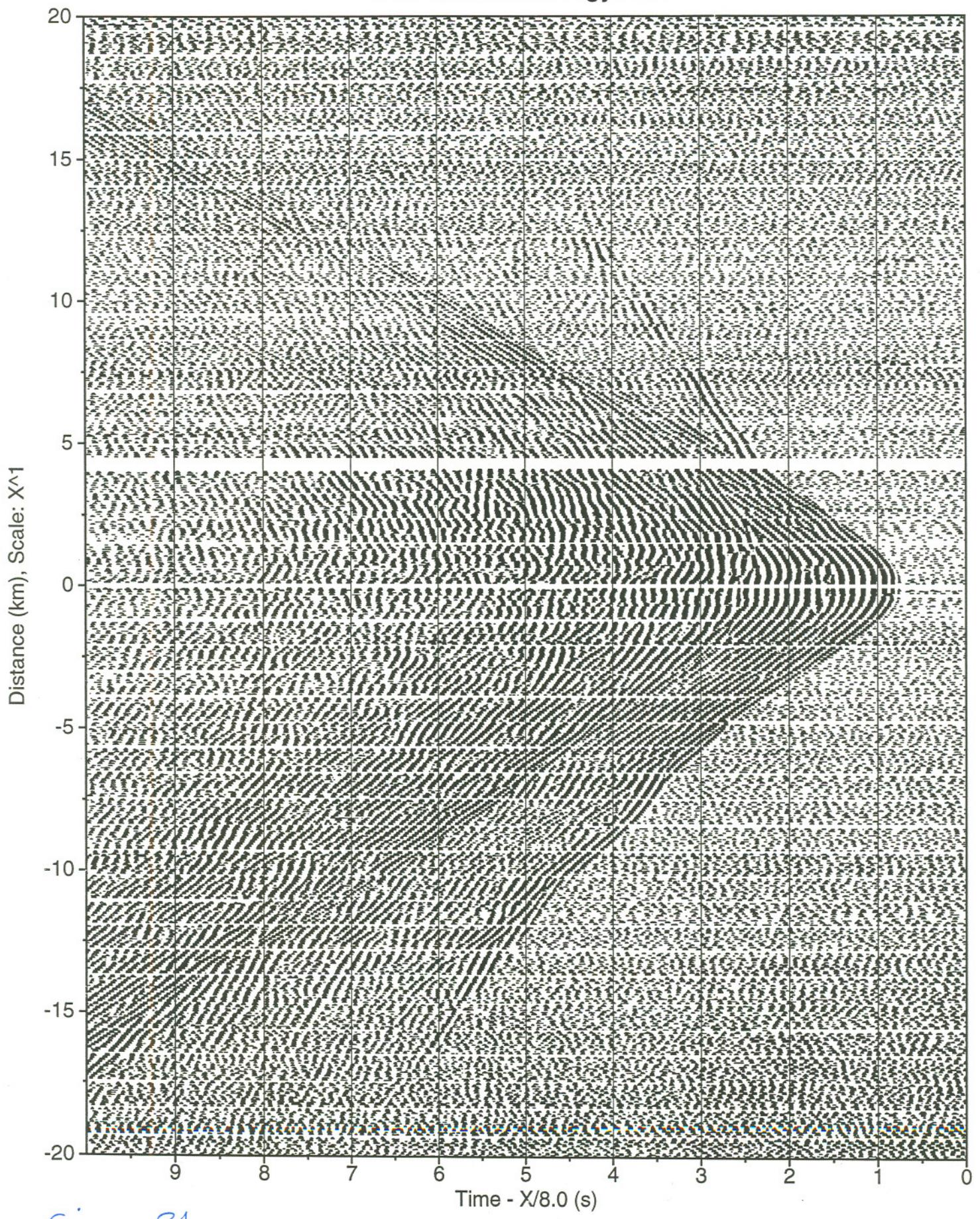


figure 3b

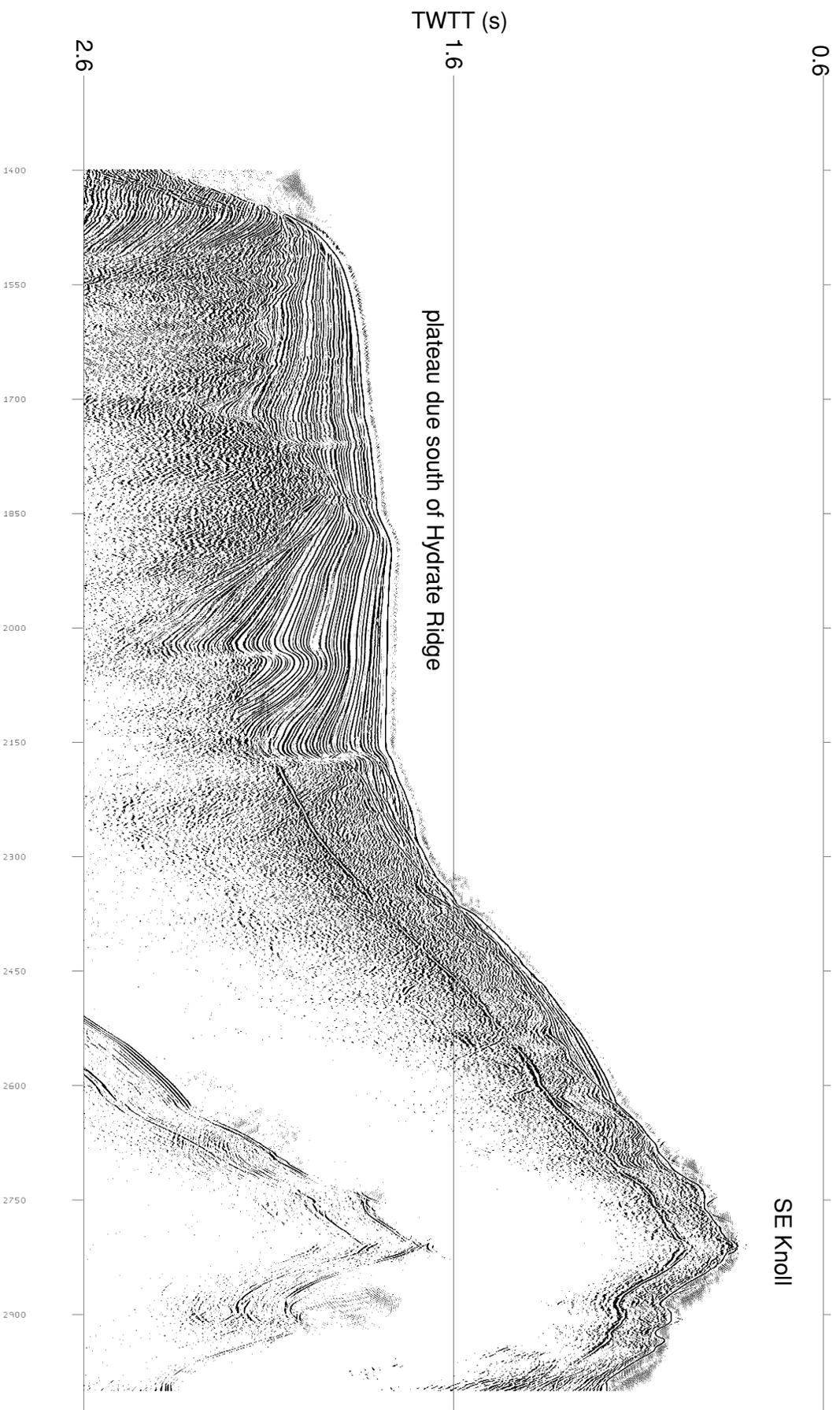


Figure 4. Example of data from regional line EW5. See figure 2 for location of seismic section.

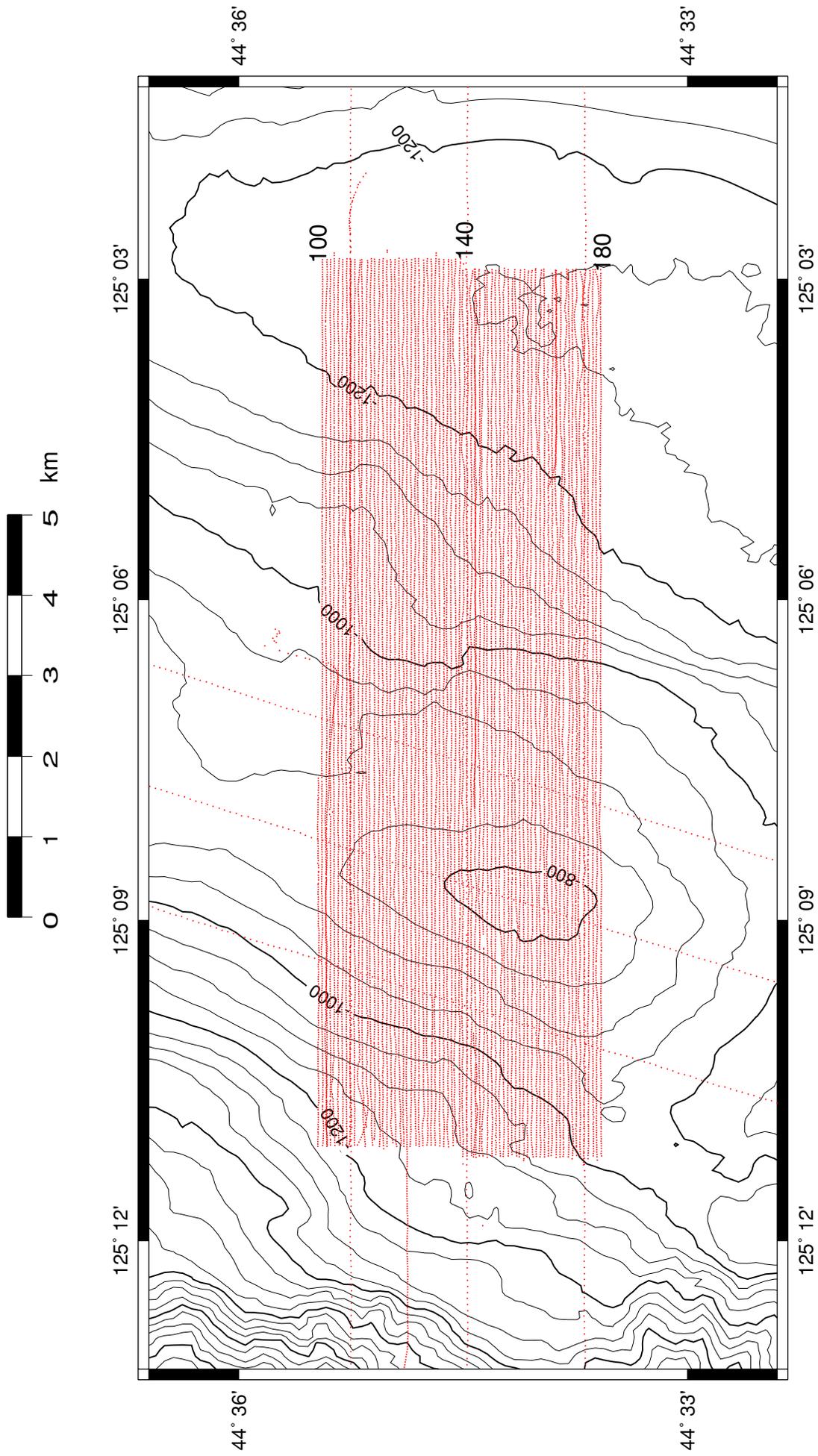


Figure 5. Map of every second shotpoint for the 3d survey. Line numbers increase from north to south. Line numbers 100, 140 and 180 are labeled.

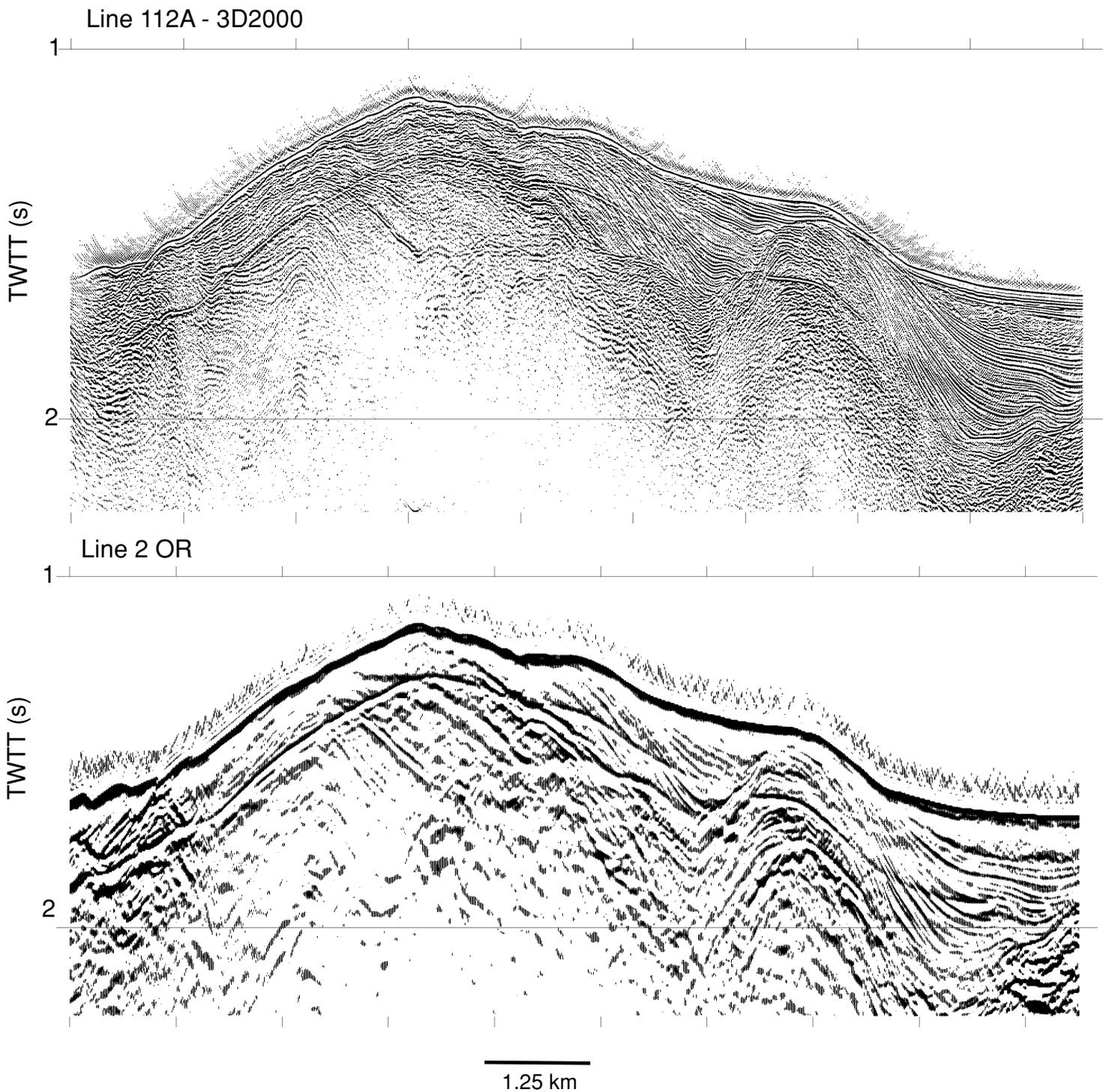


Figure 6a. Comparison of coincident data from the 1989 site survey and the new data. The 1989 survey, which was designed to image deeper structure and a larger region and thus was focussed on lower frequencies, shows the primary structural features, but higher frequencies are needed to image stratigraphic and structural details.

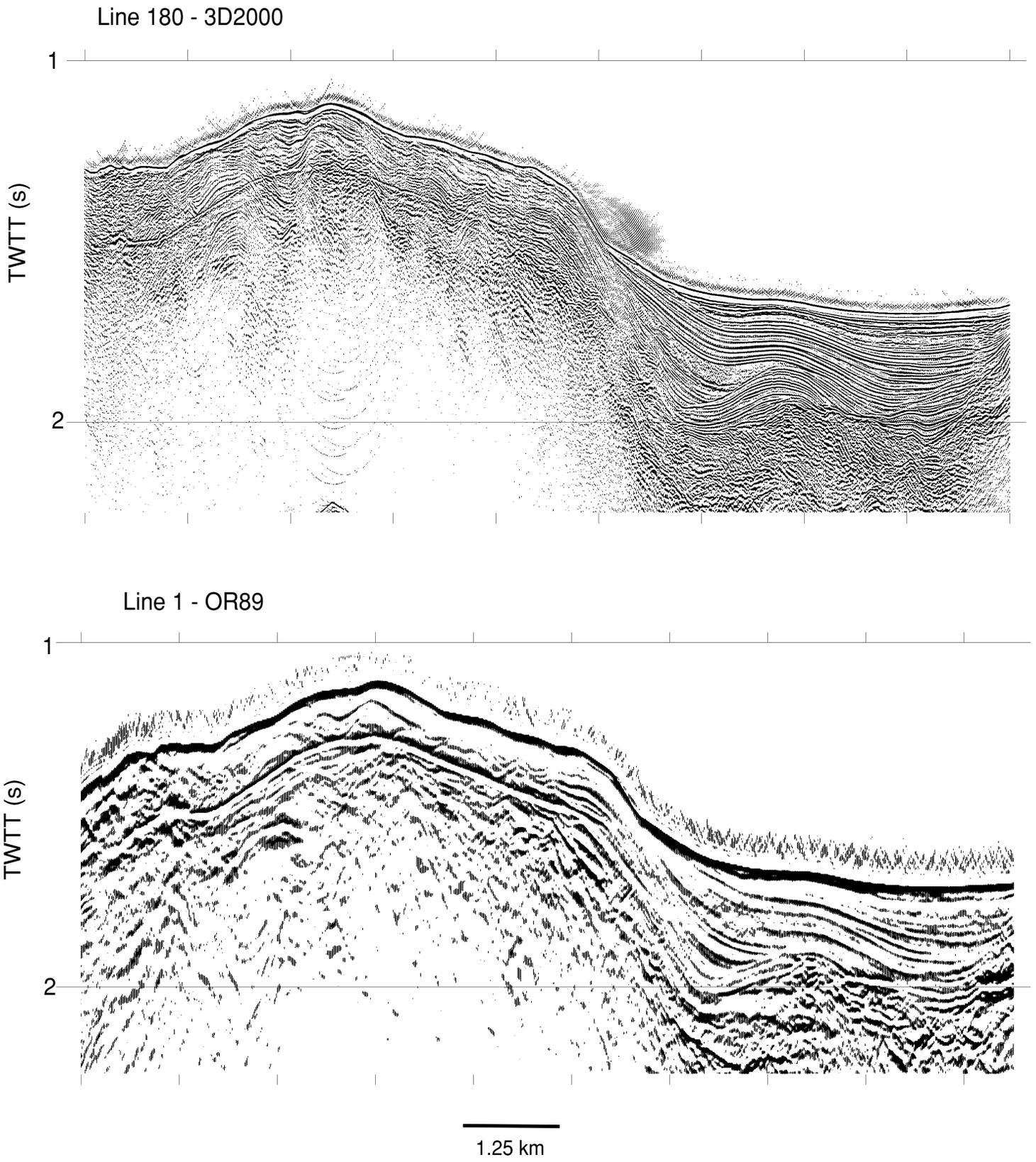


Figure 6b. Comparison of line 1, the southernmost line from the 1989 site survey, to line 180 from this survey. Note that the spacing of lines 1 and 2 in the 89 survey is such that many features cannot be correlated between the lines. Those data provided little insight into the plumbing feeding the vents at the southern summit of Hydrate Ridge. The new survey spans the region between these two lines.

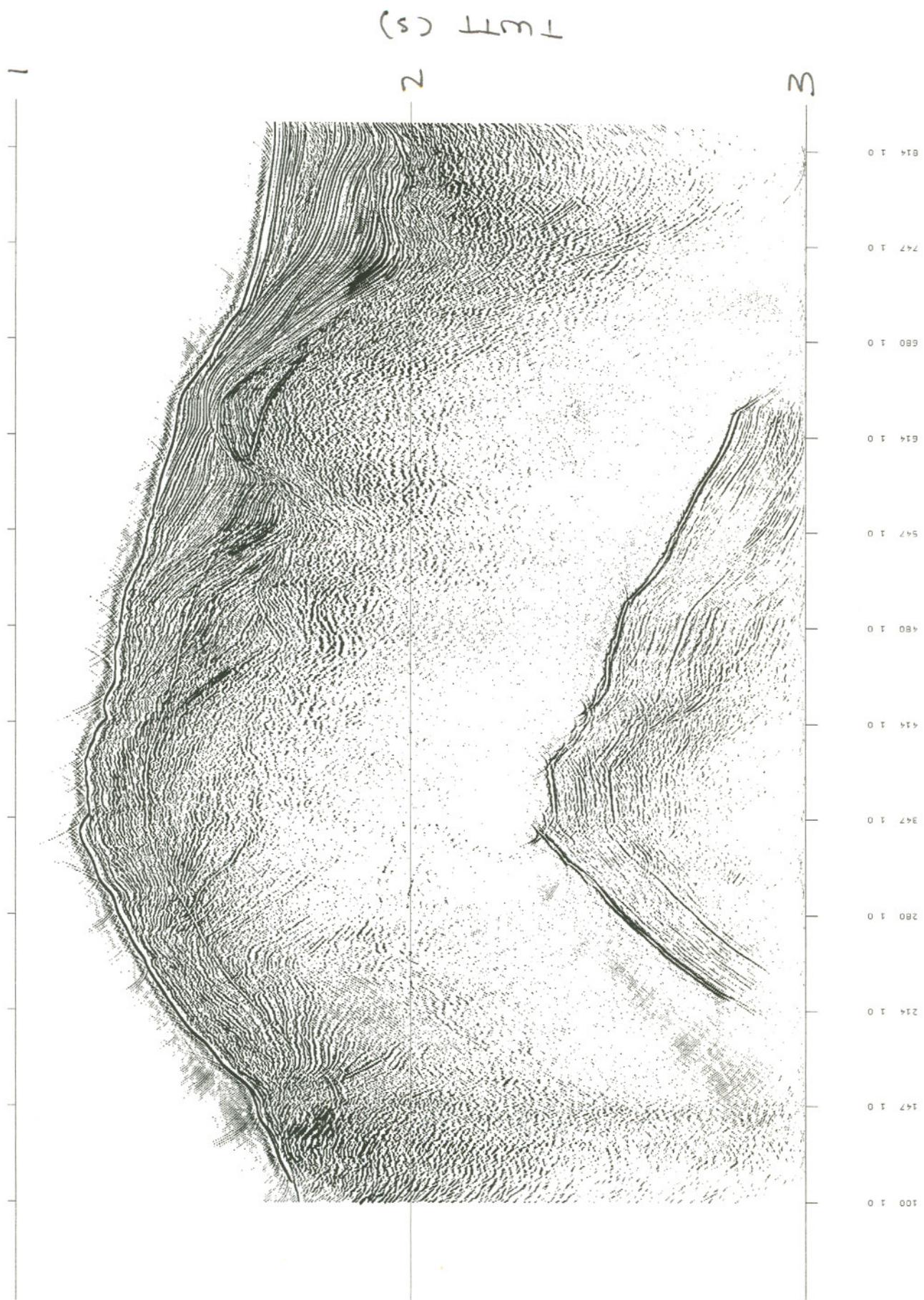


Figure 7a. Line 100

TWTT (s)



Figure 7b. Line 110

(S) LLMI

2

3



figure 7c. Line 120

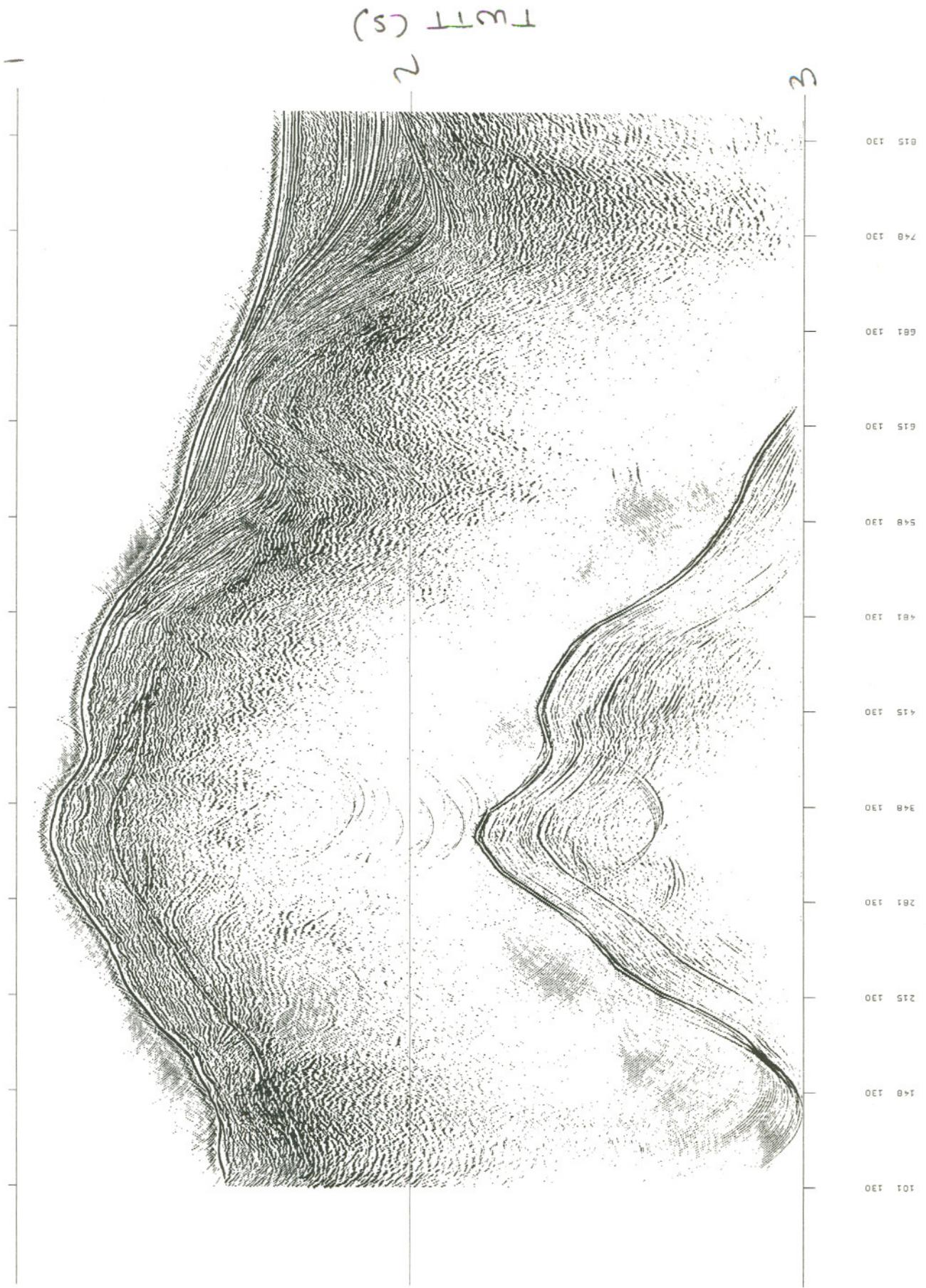


Figure 7d. Line 130

TWT (s)

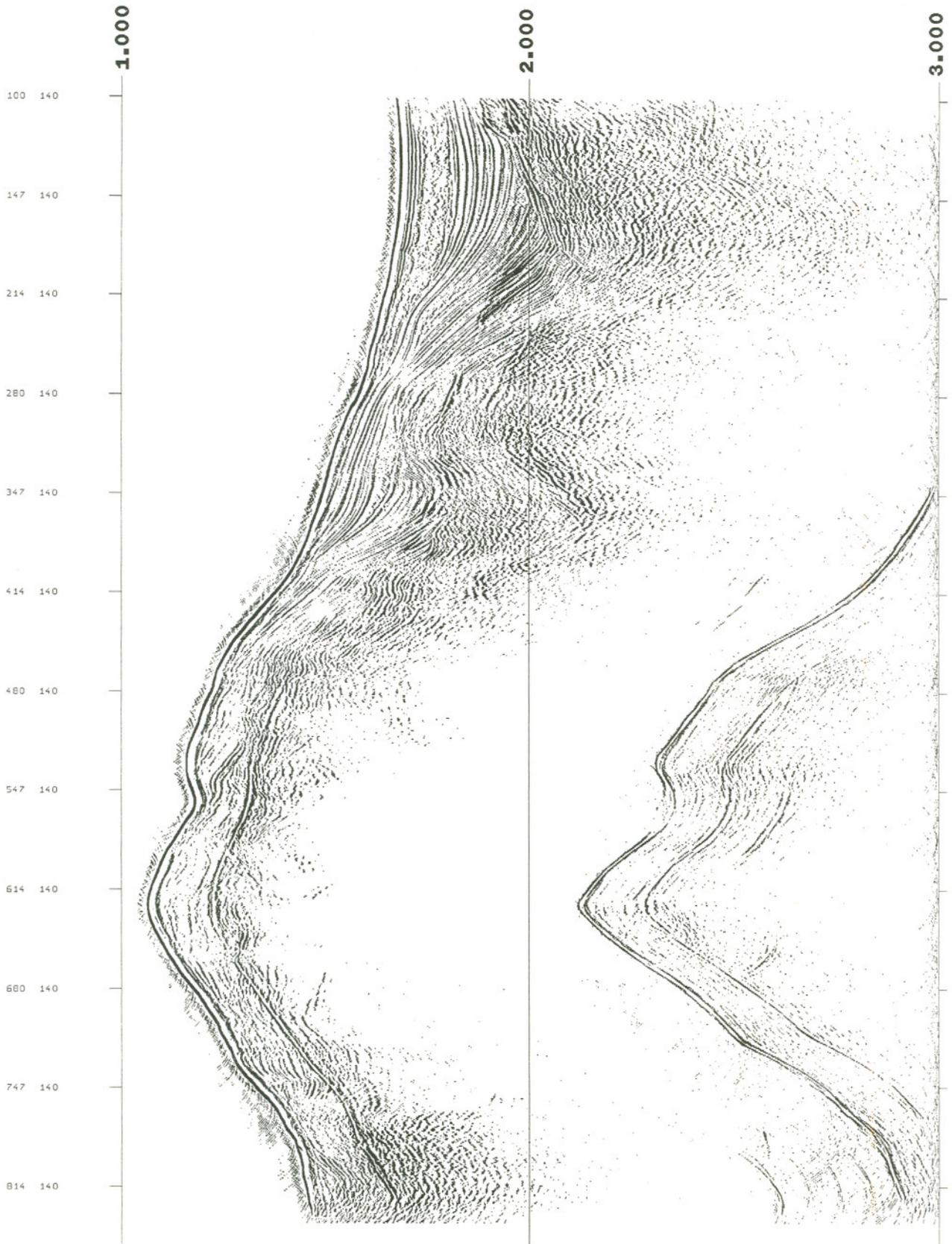


figure 7e. Line 140

TWT (s)

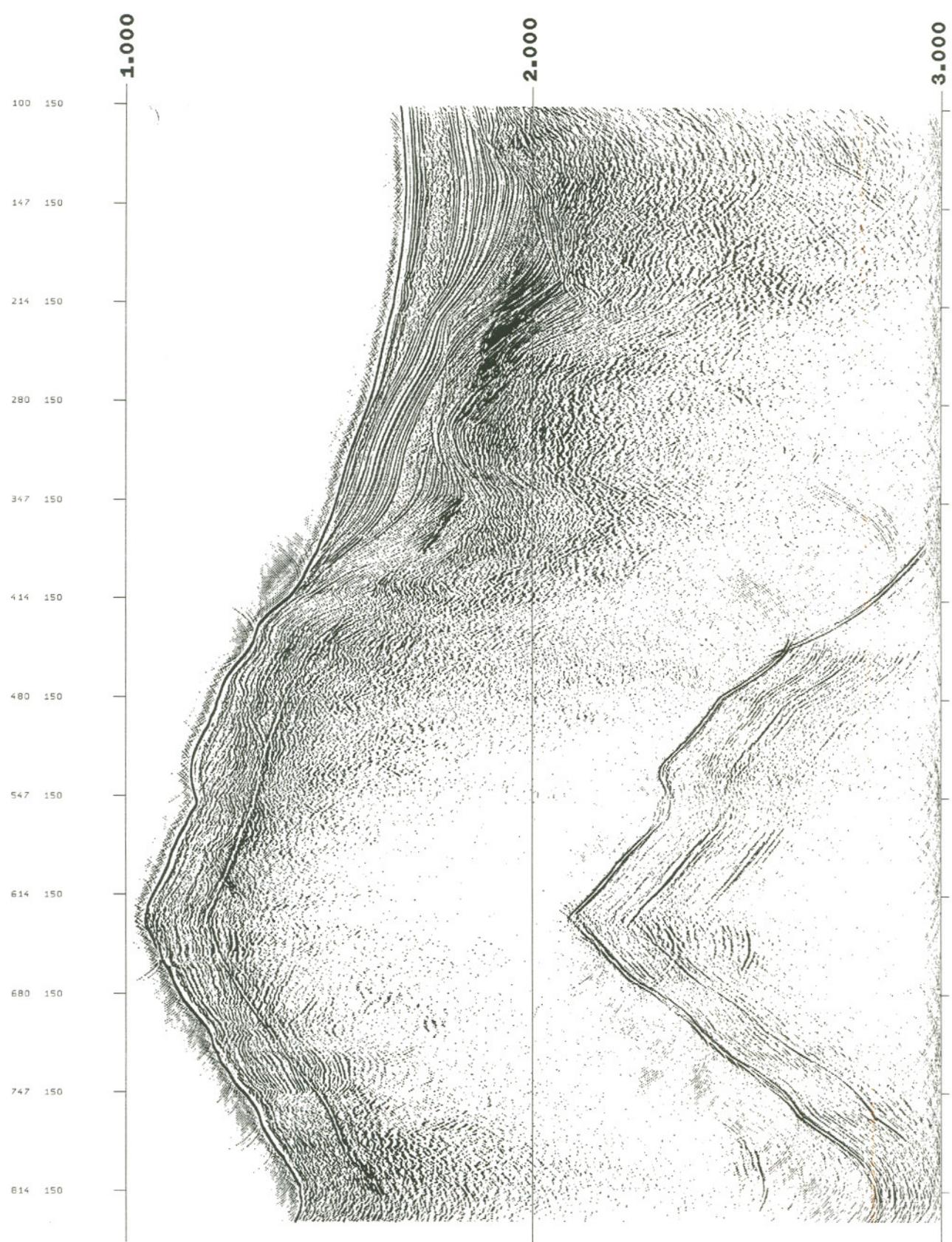


Figure 7f. Line 150

TWT (s)

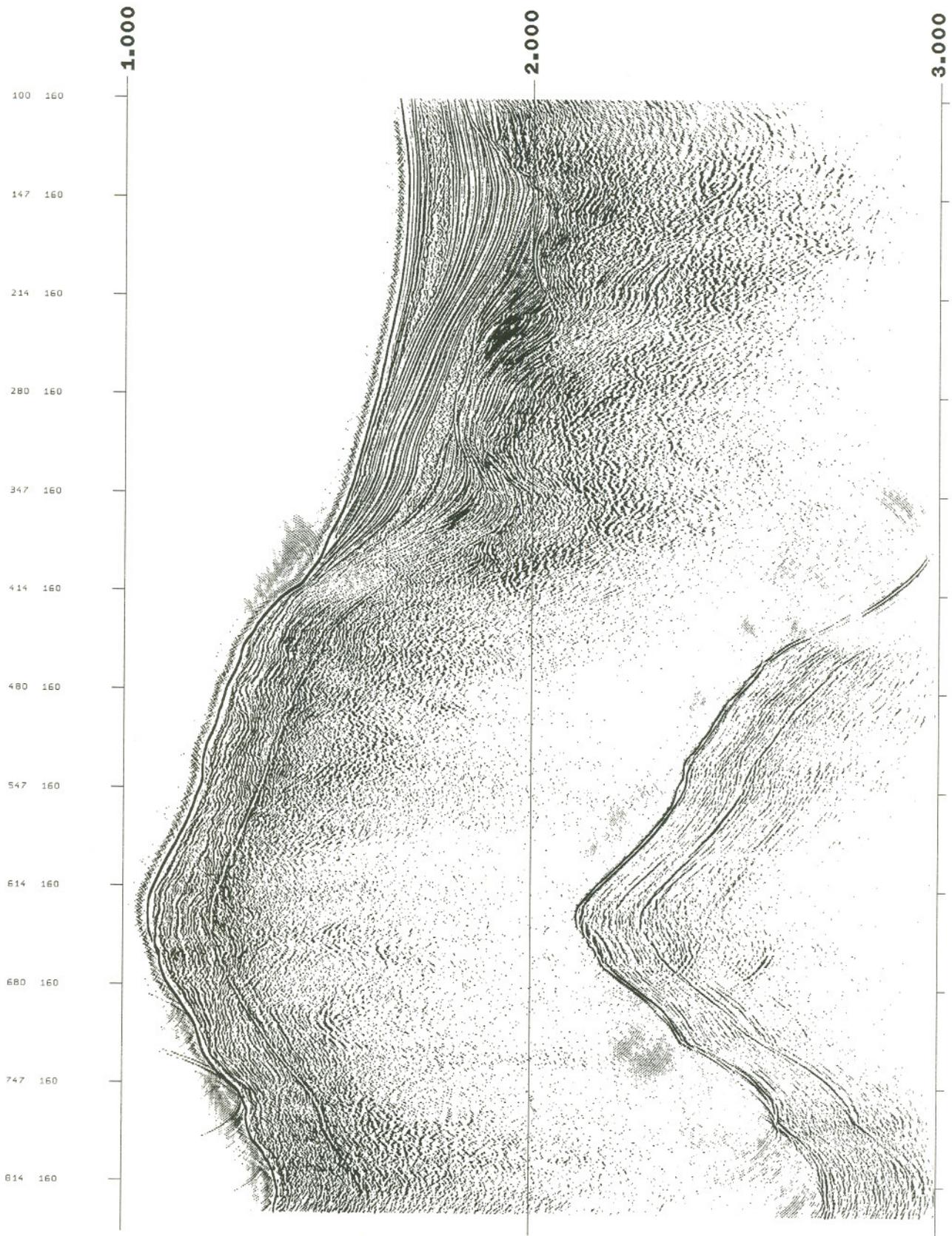


Figure 7g. Line 160

(S) L1M1

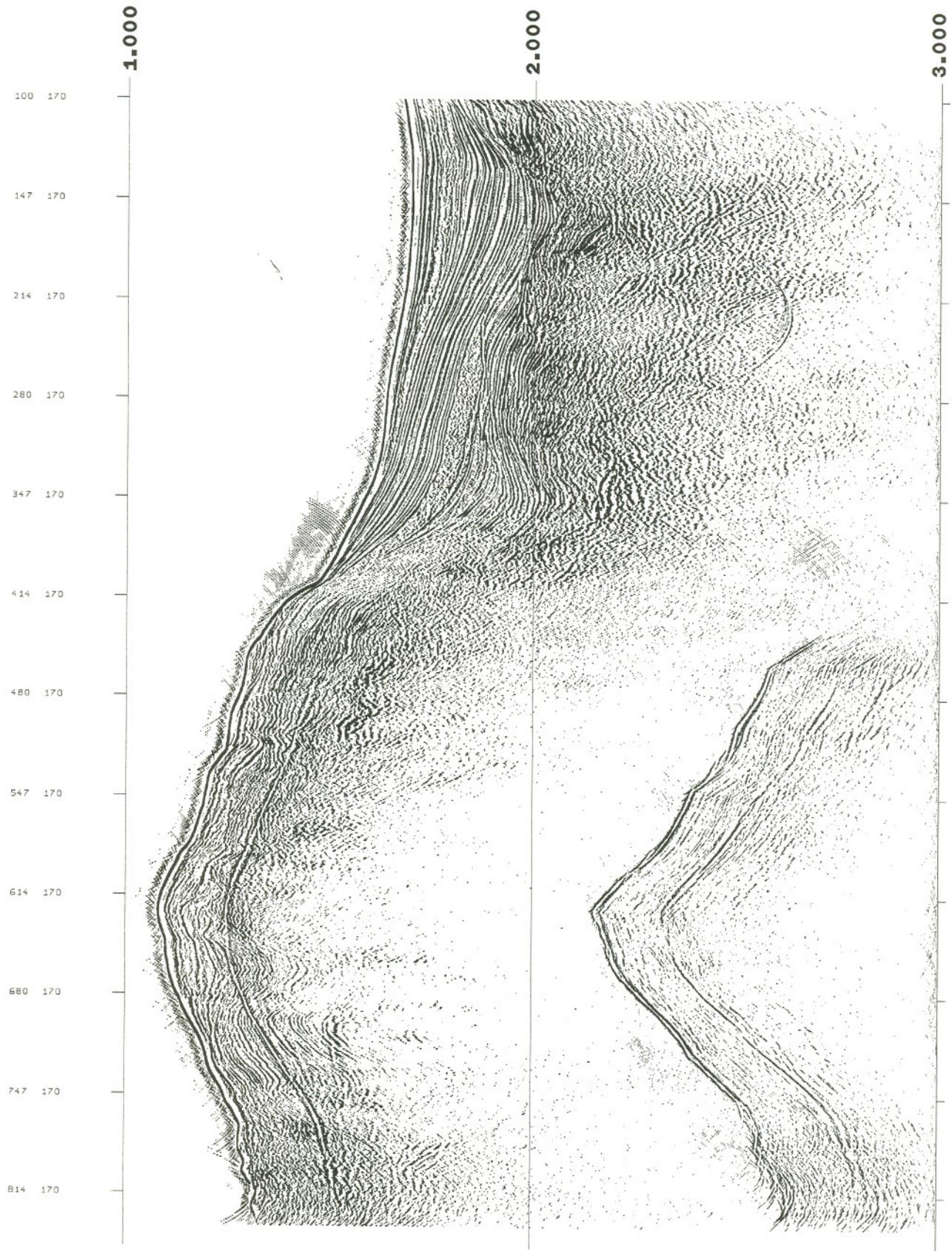


Figure 7h. Line 170

(S) LLM

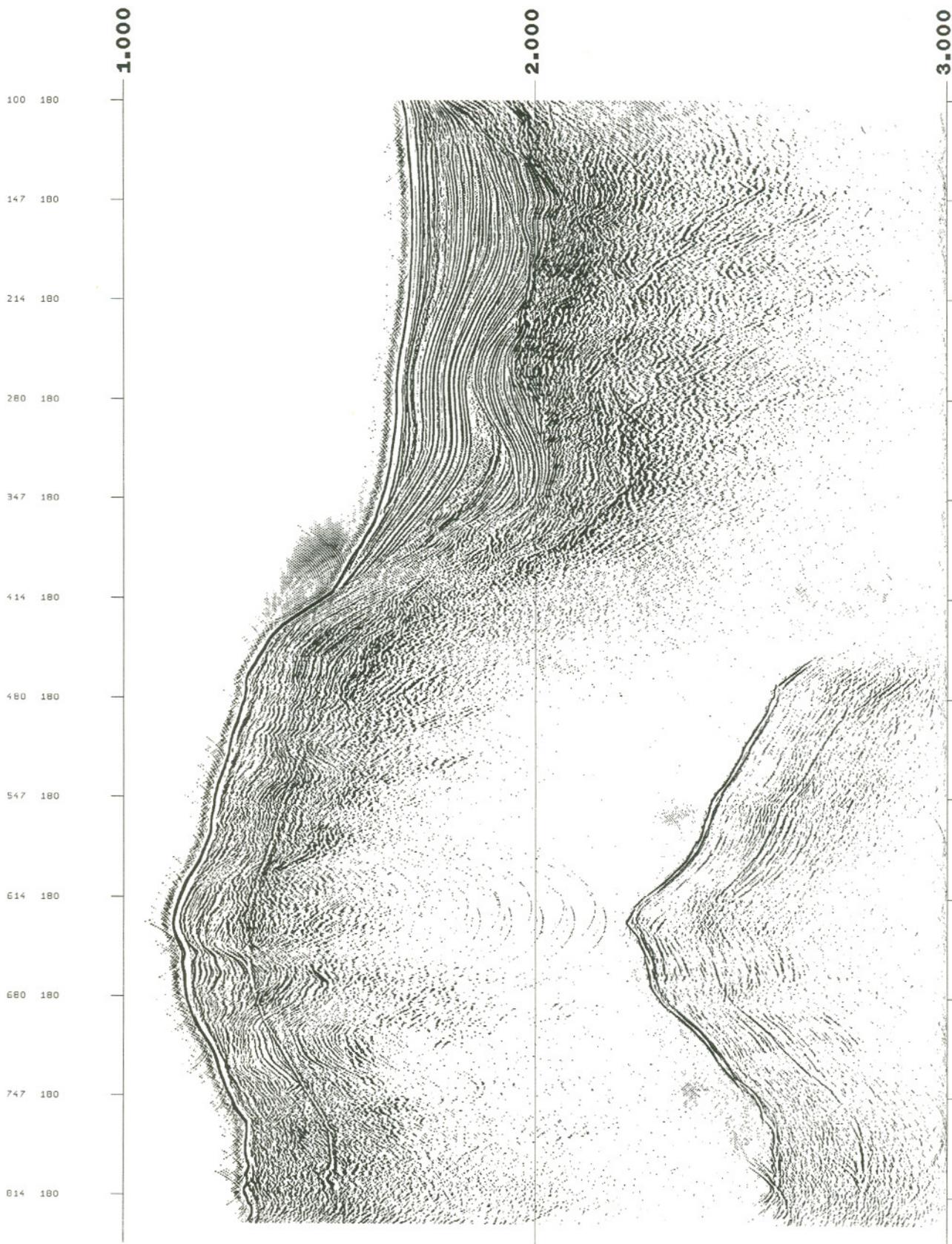


Figure 7 i. Line 180

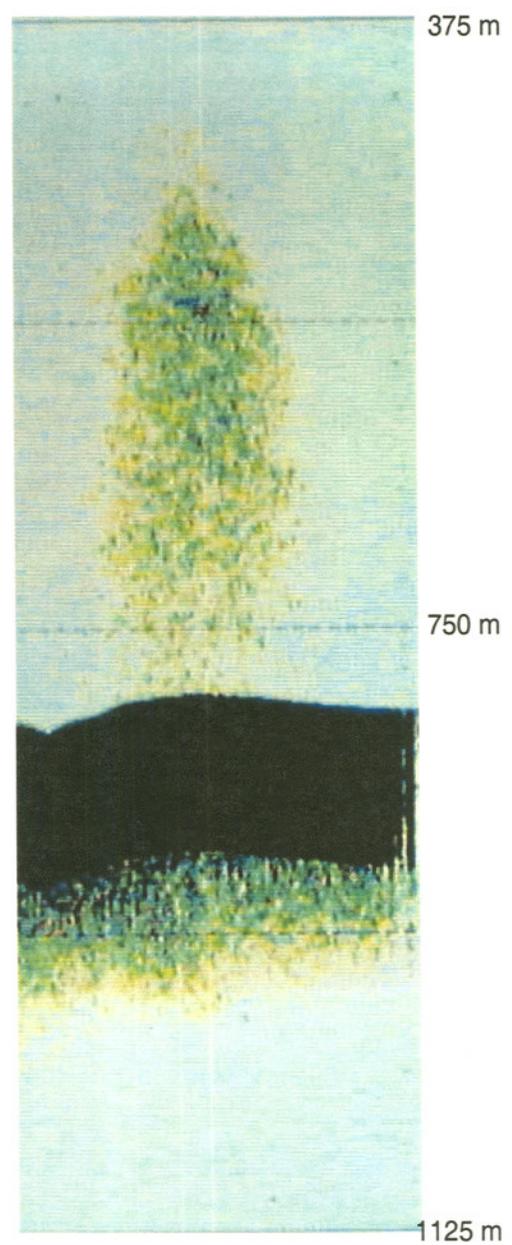
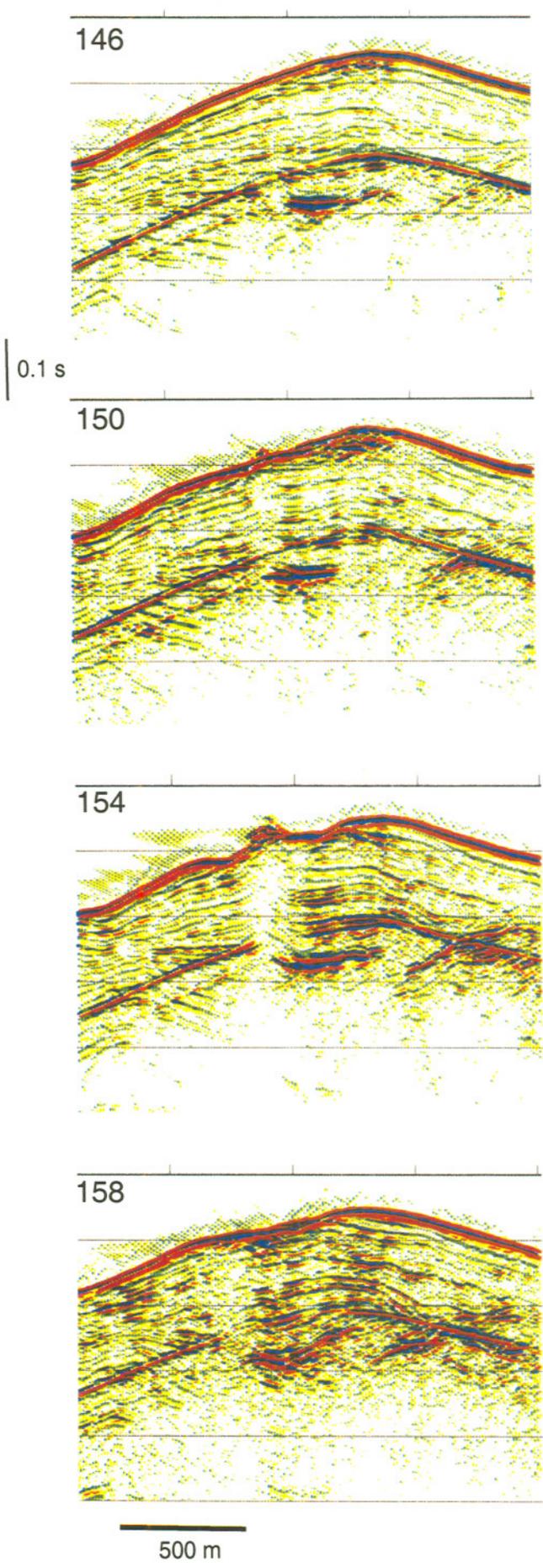


Figure 9. (above) Acoustic "bubble" plume over the southern summit of Hydrate Ridge. This plume was a persistent feature observed every time the summit region was crossed (lines 146-151) and nowhere else during the cruise except for at the summit of SE Knoll.

Figure 8. (left) Details of seismic sections across the southern summit of Hydrate Ridge. Some features to note are the large range in amplitudes in the data, with large amplitudes probably indicative of the presence of fluids. Such zones of high reflectivity are found both above and below the BSR. Beneath the summit, where bubbles are seen in the water column, a zone of chaotic bright reflectivity is observed just below the seafloor. Beneath the western flank of HR, a "double BSR" is apparent. Reflections are absent beneath the carbonate pinnacle. Additional work is needed to determine geological implications of these observations.

## Cruise Narrative:

Yosio Nakamura and Ben Yates arrived in Seattle on June 10. They were the first participants to arrive and spent 8 days at the Un. of Washington preparing ocean bottom seismometers (OBS) for deployment. They were joined for the day on June 11 by Anne Trehu for a general tour of the ship and for planning of where to install various operations. John Diebold arrived June 14 to receive shipment of and install the Lamont high-resolution MCS system and Nathan Bangs and Mark Weiderspahn arrived June 15 to install the UTIG navigation system. Because this was the first time the Lamont high-resolution MCS system and the UTIG navigation system had been interfaced, extra time had been allowed for installation. The rest of the science party arrived June 16-18.

At 7:30 am, June 19, Sally Mizroch and Lisa Hiruki, from NOAA's National Marine Mammal Laboratory, met with members of the science party to train us to identify marine mammals. As a service to NOAA, we kept log sheets of marine mammal sightings during the cruise, and agreed to follow a shooting protocol that would minimize the impact of our experiment on marine mammals. This entailed starting shooting during daylight hours and delaying the start if whales were sighted within 100 m of the ship.

The ship left the dock on schedule at 16:00 (9:00 am local time) on JD171 (June 19), with all equipment installed and all initial tests complete. We enjoyed a slow but scenic trip through the docks and locks of Seattle, leaving the locks at 19:49. Another 11 hours of transit brought us to Cape Flattery, the northwesternmost point of the continental US, and into the open ocean. An additional 19 hours of transit brought us to the first OBS deployment site (figure 2). During this transit, Anne Trehu led an informal discussion in the lounge on the objectives of the cruise and showed footage of hydrates and vent structure on the seafloor beneath the survey site that were taken by ROV ROPOS and DSV Alvin in 1998 and 1999.

The first OBS was deployed at 01:43 on JD173. Deployments went smoothly, taking an average of 20 min/instrument, including transit. Transit distances from site to site were small (~1.5 - 4.5 km). OBS deployments were completed at 08:37 on JD173 (TABLE 1 - OBS deployments). OBSs were programmed to record 4 components of data continuously.

As soon as OBS deployment was complete, we deployed the streamer. While in port, the streamer had been installed on the starboard side of the fantail, with the two GI guns towed from the center and port side of the fantail. The rationale for this layout was that it would avoid tangling the guns with the streamer during turns. This layout restricted us to doing starboard turns since the streamer was expected to follow the ship more slowly than the guns. Although this layout seems to have prevented interaction between the guns and streamer, it did lead to collisions between the guns.

Deploying and balancing the streamer took began at 09:02 on JD173 and was completed in 4 hours, including bringing the streamer back on board once to adjust weights. We then deployed the two GI guns, each configured in 105 cubic inch GI mode. Test fires indicated a problem with one of the guns, and it was retrieved and replaced by a spare. It turned out that several seals had been incorrectly installed in the gun that was retrieved. This was fixed, and the gun was readied to serve as a spare. We also had on board a second spare, on loan from USGS.

Data acquisition began at 22:20 on JD173, ~54 hours after leaving Seattle. We first shot a series of 20-30 km long lines over the OBS array (figure 2 - map with OBSs, long lines and survey

box). These lines were designed to provide offsets of at least  $\pm 10$  km over each OBS, and if signal to noise ratios are good, data will be used for tomographic inversion for velocity and attenuation structure beneath the BSR. The data also provide transects across the mid-slope region and the southern flank of Hydrate Ridge, which are poorly covered by existing seismic data.

The first line shot was EW2x, a western extension to planned EW2. This was followed by EW2, EW1, EW3, EW4 (the diagonal transit from the EW to the NS lines), NS1, NS3, and NS2. These lines provided a general warm up to test data acquisition, processing, watchstanding and navigation procedures under less stringent conditions than required for the 3D survey. Acquisition went relatively smoothly, with only a few missed shots during lines. Scripts using a combination of SIOSEIS and FOCUS/DISCO seismic processing software were set up and tested to load raw data onto disk, process the data through NMO (water velocity), stack, FK migration (water velocity) and plot page-size quality control plots of seismic sections within several minutes after the end of the line (See appendix C). Data were also accessible for more detailed interactive viewing and analysis via FOCUS seismic processing software and production of larger scale and color hardcopy using SIOSEIS and the R/V Thompson's 36" Novajet plotter.

The long lines were shot with the streamer at a depth of 4m, the guns at 2m and a shot interval of 37.5 m. For the last line (NS2), the streamer depth was decreased to 3 m to see if the background noise level would increase in the poor weather conditions we were experiencing (wind speeds  $> 20$  knots, gusting to  $\sim 35$  knots). The shallower depth did not decrease the signal-to-noise level and improved the spectral content of the data, so we decided to tow the streamer at 3 m for the 3D survey and to increase gun depth to 2.5 m. We were fortunate that the weather-induced noise affected frequencies  $< 25$  Hz and that our primary signal range was 40-200 Hz. The weather conditions would have been a serious problem for a project with crustal-scale objectives.

The 3D survey began at 0259 on JD175 with line 112. The start was a bit rocky, with only one gun firing for the first 14 minutes, and only every other shot being recorded. However, the acquisition problem was quickly traced to a hidden but easily reset delay in the OYO. By the middle of the line, acquisition was proceeding smoothly.

On line 148, which crosses the southern summit of Hydrate Ridge, we were surprised to see a strong acoustic "bubble plume" rising from the seafloor to  $\sim 550$  m water depth. This plume was later seen on several adjacent lines and has a diameter of  $\sim 250$  m. Such plumes have been observed several times rising from the northern summit of Hydrate Ridge, but were thought to be intermittent on the southern summit. The excitement about seeing bubbles was soon followed by a spectacular image of the conduit feeding the "Pinnacle" that had been discovered during Alvin dives in 1999.

After  $\sim 13$  lines had been shot we discovered apparent 2.5 second jumps between the OYO clock and the nav clock. The source of this was tracked down to spurious triggers that would accumulate in the OYO logging buffer. The solution to this problem was to stop acquisition and stop shooting for a few minutes prior to starting a new line. Timing for lines that had already been shot can be corrected during postprocessing.

Shooting of lines continued uneventfully for 31 hours until 0635 on JD177, when SPLITTER, the computer merging navigation and shot instant data, froze. Seventy-six shots were missed on line 143 before the computer could be rebooted. Line 143 was later reshot.

After another 21 hours of recording, the blast phones on the GI gun 1 failed at . The gun appeared to still be firing, so we finished line 157 before pulling in the gun. After replacing the gun with a spare, we discovered that the tow line had parted and that the gun was being towed by the cable. Collisions between the guns were starting to take their toll. After 1.25 hours, the guns were back in the water and line 131 was started. The next problem occurred 7.75 hours later, when a hose feeding GI gun x ruptured and had to be replaced during line 163. We returned to the start of line 163 while this problem was being repaired and restarted line 163 2 hours later.

After 24 hours of uneventful surveying, one of the GI guns failed during line 106. Pulling in the gun revealed fishing gear tangled with the gun, streamer and Z-drive. After untangling this mess (3.5 hours) we began to reshoot line 106.

The next problem occurred only 7 hours later, when the compass on the "bird" nearest the ship failed. The streamer was partially brought in to replace this bird with a spare during the transit between lines and no time was lost.

All seismic gear worked flawlessly for the next 44 hours, until the end of the 3D survey at 23:25 on JD181. This included 18 reshoots, for a total of 99 lines in the survey. The streamer and guns were then brought on board.

Retrieval of OBSs began at 01:35 on JD182 with the sighting of OBS19 on the surface and continued for 22 hours. At the 4<sup>th</sup> site, a crab leg was caught between the flag and the radio beacon. At the 5<sup>th</sup> site, recover of OBS15 was suspended when it failed to surface after 1.5 hours. After all the other OBSs were on board, we returned for a second attempt to retrieve OBS15. After 2 hours, this attempt was also abandoned.

We then redeployed the seismic gear and spent 29 hours shooting 2D regional lines. At 0500 on JD184, the streamer and GI guns were retrieved and we transited to the site of OBS15 to be in position to retrieve it if the backup timed release worked. On the way, we passed once more over the southern summit of Hydrate Ridge with the 12 kHz echosounder turned on to detect a "bubble" plume. We made 2 crosses over the plume, which was unusually strong, extending from the seafloor at ~780 m to a water depth of 462 m below sea level.

Unfortunately OBS15 did not appear, and we headed back to Seattle at 0800 on JD184. The return to Seattle was uneventful. Watches continued until editing of traces from the 3D survey was complete. While passing through the locks from Puget Sound, we were entertained by a large number of lively salmon. We tied up at the dock the University of Washington before noon and spent the afternoon unloading.

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### Hydrate Ridge Experiment OBS Deployment, Recovery and Data Summary

Station	Chassis S/N	Sphere S/N	Disk Drive S/N	Deployment			Recovery			Acquired Data			
				Time	Location	Depth m	Time	Location	Depth m	Channels	Period	Hrs.	Mb
1	92-2	59105•	IBM 7L4G2383	6/20 20:57	44°35.251'N 125°09.488'W	955	6/30 08:26	44°35.253'N 125°09.488'W	953	1,2,3,4	6/21 05:00 - 6/29 13:11#	200.2	776
2	92-5	56962	IBM 7L4C0505	6/20 20:40	44°35.252'N 125°08.352'W	859	6/30 07:44	44°35.280'N 125°08.371'W	855	1,2,3,4	6/21 05:00 - 6/30 07:07	218.1	1125
3	94-5	60352•	IBM 7L4M3079	6/20 20:14	44°35.243'N 125°07.218'W	913	6/30 07:08	44°35.252'N 125°07.249'W	910	1,2,3,4	6/21 05:00 - 6/30 06:35	217.6	1124.5
4	94-7	57112	IBM 7L4M4672	6/20 19:56	44°35.244'N 125°06.075'W	1018	6/30 06:22	44°35.180'N 125°06.088'W	1020	1,2,3,4	6/21 05:00 - 6/30 05:45	216.8	1120.5
5	94-8	59126•	IBM 7L4Q0272	6/20 19:40	44°35.240'N 125°04.947'W	1083	6/30 05:33	44°35.173'N 125°05.025'W	1071	1,2,3,4	6/21 05:00 - 6/30 05:00	216.0	1116
6	94-10	55496	IBM 7L1Q4981	6/20 19:21	44°35.243'N 125°03.806'W	1225	6/30 04:47	44°35.139'N 125°03.918'W	1219	1,2,3,4	6/21 05:00 - 6/30 04:08	215.1	1112.5
7	94-4	40365	IBM 7L4Q0357	6/20 21:17	44°34.470'N 125°09.826'W	943	6/30 09:07	44°34.528'N 125°09.689'W	932	1,2,3,4	6/21 05:00 - 6/30 08:29	219.5	1141.5
8	94-12	52239	IBM 7L4W1755	6/20 21:38	44°34.466'N 125°08.693'W	798	6/30 09:45	44°34.511'N 125°08.582'W	804	1,2,3,4	6/21 05:00 - 6/30 09:09	220.2	1144
9	94-13	55454	IBM 7L4Q0584	6/20 21:52	44°34.476'N 125°07.558'W	872	6/30 10:22	44°34.480'N 125°07.492'W	874	1,2,3,4	6/21 05:00 - 6/30 09:43	220.7	1141
10	94-15	59368•	IBM 7L4P9978	6/20 22:09	44°34.477'N 125°06.456'W	1001	6/30 11:02	44°34.451'N 125°06.439'W	1004	1,2,3,4	6/21 05:00 - 6/30 10:21	221.4	1145
11	94-1	58732•	IBM 7L4M4374	6/20 22:28	44°34.484'N 125°05.309'W	1133	6/30 11:49	44°34.419'N 125°05.299'W	1142	1,2,3,4	6/21 05:00 - 6/30 11:00	222.0	1147
12	94-18	55458	IBM 7L4M4328	6/20 22:41	44°34.479'N 125°04.156'W	1252	6/30 12:32	44°34.441'N 125°04.195'W	1226	1,2,3,4	6/21 05:00 - 6/30 11:50	222.8	1152

Appendix A. OBS deployment and acquisition parameters.

Station	Chassis S/N	Sphere S/N	Disk S/N	Deployment			Recovery			Acquired Data			
				Time	Location	Depth m	Time	Location	Depth m	Channels	Period	Hrs.	Mb
13	92-3	40373	IBM 7L4Q0377	6/21 00:46	44°33.675'N 125°10.162'W	921	6/29 21:17	44°33.689'N 125°10.326'W	941	1,2,3,4	6/21 05:00 - 6/29 20:41	207.7	1073
14	93-10	55427	IBM 7L4Q0297	6/21 00:29	44°33.696'N 125°09.016'W	818	6/29 22:15	44°33.656'N 125°09.154'W	824	1,2,3,4	6/21 05:00 - 6/29 21:33	208.6	1077.5
15	93-12	55477	IBM 7L4P9984	6/21 00:08	44°33.675'N 125°07.888'W	896	Not recovered						
16	93-14	31615	IBM 7L4Q0481	6/20 23:46	44°33.678'N 125°06.765'W	976	6/30 00:55	44°33.559'N 125°06.846'W	9764	1,2,3,4	6/21 05:00 - 6/30 00:14	211.2	1089.5
17	93-15	40372*	IBM 7L4Q0267	6/20 23:24	44°33.678'N 125°05.626'W	1191	6/30 01:50	44°33.604'N 125°05.738'W	1180	1,2,3,4	6/21 05:00 - 6/30 01:09	212.2	1095
18	93-16	44398	IBM 7L4Q0227	6/20 23:01	44°33.681'N 125°04.508'W	1239	6/30 02:39	44°33.572'N 125°04.623'W	1238	1,2,3,4	6/21 05:00 - 6/30 02:01	213.0	1103.5
19	94-16	55472	Toshiba 94U11794W	6/21 01:37	44°34.474'N 125°15.380'W	2068	6/29 19:11	44°34.321'N 125°15.979'W	2216	1,2,3,4	6/21 05:00 - 6/25 05:45	96.8	500
20	94-3	60543•	IBM 7L4Q0301	6/21 01:09	44°34.471'N 125°12.299'W	1272	6/29 20:20	44°34.506'N 125°12.459'W	1279	1,2,3,4	6/21 05:00 - 6/29 19:39	206.6	1066.5
21	94-11	55478	Toshiba 94J30827W	6/20 18:41	44°34.473'N 125°00.738'W	1031	6/30 03:43	44°34.383'N 125°00.861'W	1039	1,2,3,4	6/21 05:00 - 6/25 05:43	96.7	500

\*Geophone axes of sphere 40372, deployed at stations 17, are of left-hand system, i.e., horizontal axes are reversed.

•Spheres 59105, 60352, 59126, 59368, 58732 and 60543, deployed at stations 1, 3, 5, 10, 11, and 12, respectively, have Oyo GS-11D geophones, while all others have Mark Products L-15B geophones.

#Continuous till 6/25 21:32 and intermittent afterwards because of disk problem.

Water depths are from Bathy 2000 and are not corrected for sound speed (1500 m/s assumed) nor transducer depth (5.6 m).

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## Hydrate Ridge Experiment OBS Data Acquisition Parameters

Sensors: Channels 1-3: Gimbaled 4.5 Hz geophones, Mark Products L-15B or Oyo GS-11D,  
70% damping  
Channel 4: Hydrophone, OAS E-2PD

Signal polarity: Channels 1, 2 and 3 form a right-hand system with channel 1 positive  
downward, except as noted; channel 4 positive for increasing pressure

Preamplifier low-frequency cut-off: Channels 1-3: 1 Hz  
Channel 4: 3 Hz

Antialias filters: 50 Hz low-pass, 4-pole (24 dB/oct) Butterworth

Nominal overall sensitivity: 2.5 (nm/s)/DU with Mark Products geophone  
1.5 (nm/s)/DU with Oyo geophone  
1.0 mPa/DU with OAS hydrophone

A/D 14 bits with dynamic gain ranging up to x125

Sample interval: 5 ms

Data acquisition mode: Continuous recording with a ~22 s data gap every 6.8 minutes  
while transferring data to disk

Recording capacity: 235 hours on IBM 1.212 Gbyte disk drive  
97 hours on Toshiba 500 Mbyte disk drive

## Appendix B. Navigation

### Grid Design and Shooting the Grid

The 3-D survey grid consisted of 81 11 km long lines oriented nominally E-W, spaced 50 m apart. The grid was laid out on a UTM projection with the central meridian at 123 W scaled to 0.9996 there. Shots were fired on distance at 15 m intervals based on a smoothed velocity estimate from the differential GPS fixes. The program "shooter" (by M. Wiederspahn) sent a fire request to the LDEO multi-gun controller, which fired the guns, and sent an external trigger to the OYO-DAS and GPS clocks at the gun aim point. The two guns were synchronized with an oscilloscope, as the automatic controller could not be made to work. Nominal shot times were 6 s, but varied with the currents and ship's speed in the water. For the regional lines, shot distances were 37.5 m (lines EW1-4, NS1-3) or 25 m (EW5-10).

A display of the ship's position relative to the 3D grid was shown on computer terminals in the labs and on the bridge. The graphical location of the ship relative to the line as well as digital readouts of offline and downline distances and speeds were all used by the bridge to steer the source location down the selected line. This program (Nav99, MW) also provided a minimum radius turn path between lines, which were always shot heading east in the northern half of the grid (with line number 100..139) and west in the southern half (140..180). Shotpoint numbers increased from west to east, from 100 to 833.

### Ship's Navigation

The ship was navigated by a differential GPS system supplied by RACAL. This system provided a DGPS correction from a weighted average of 4 RACAL base stations: Vancouver, Washington State, Northern California, and San Diego. The 1 Hz raw fixes were filtered to smooth the rolling and pitching of the ship, to derive a location and velocity at each update. We recorded the raw DGPS stream, as well as the Thompson's processed dual pcode and USCG DGPS combined location. This fix was plotted at one second intervals together with the primary filtered navigation to provide an immediate comparison between the independent systems. The unfiltered RACAL location could also be displayed to assess the degree of smoothing of the filter. The displayed location for the ship was actually that of the guns, set back from the antenna locations along the reciprocal of the ship's gyro.

### Streamer Navigation

The streamer shape was determined by 5 bird compasses positioned at 150 m intervals along the streamer. The compasses were interrogated at each shot and these data were logged with a time stamp. The raw compass data were used to locate the end points of a sequence of semi-circles forming a piece-wise continuous curve moving aft from the stern of the ship; each receiver channel position is then located along this curve. There was no tail-buoy, nor independent determination of the location of the end of the streamer. The depths and the wing angles of the birds were not logged, but were monitored by the watch-standers using a graphical display.

# Appendix C. Seismic processing

## HYDRATE RIDGE 3D TN112

### Summary of Problem Channels

- 1-4 Intermittent wave noise.
- 5 Occasional spikes and noise.
- 16 Occasionally noisy.
- 17 Occasional high-amplitude spikes.
- 20 No signal. Occasional spikes.
- 23 No signal.
- 29 No signal.
- 32 Low-amplitude or dead. 60-cycle noise. Occasional spikes.
- 38 Low-amplitude or dead. 60-cycle noise. Spikes later in survey.
- 39 No signal.
- 46 Low-amplitude 60-cycle noise.

### SHIPBOARD PROCESSING OF HYDRATE RIDGE SEISMIC DATA

48-channel MCS data were 2-D processed aboard R/V Thomas Thompson using Sioseis and Paradigm Geophysical's FOCUS software according to the following processing flow:

- 1) Raw SEG-D field data copied from 3480 tape to SEG-Y disk files using Sioseis.
- 2) SEG-Y disk files converted to FOCUS internal format.
- 3) Geometry definition (15.0 m shot spacing, 12.5 m bins, 40 fold nominal).
- 4) Trace edit (7 problem traces killed for all shots).
- 5) High Pass filter (ramp from 25 to 35 Hz).
- 6) Spherical divergence correction ( $V^2 \cdot T$  using FOCUS generic velocity function)
- 7) CDP sort
- 8) Normal Moveout Correction (constant 1500 m/s).
- 9) Stretch Mute (35% maximum stretch).
- 10) Stack.
- 11) Trace output (both SEG-Y and FOCUS formats).
- 12) F/K migration (constant 1500 m/s).
- 13) Trace output (both SEG-Y and FOCUS formats).
- 14) Hardcopy display.

In addition, source navigation and streamer location data for the 3D grid were converted to UTM coordinates and written in UKOOA90 format. These navigation data were converted into FOCUS format 3D navigation traces and binned using the FOCUS 3D QC/binning package. Fold maps were generated and optimized for 50m x 25m and 25m x 12.5m bin sizes. In both cases, the optimum grid azimuth was 348.5 degrees.