GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 24, PAGES 3705-3708, DECEMBER 15, 1999

Implicit Noise Reduction and Trace Interpolation in Wavefield Depth Extrapolation

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Abstract. Various types of noise can obscure reflections and refractions on deep crustal seismic data. This study presents a simple but elegant approach to true wavefield processing where noise reduction and trace interpolations are applied implicitly during depth extrapolation. No velocity and source/receiver information is required and the proposed approach can be combined with conventional or available processing algorithms. Prestack processing is successfully applied to a complicated OBS data set, demonstrating an improvement in noise reduction and effective trace interpolation.

Introduction

In 1995, the Republic of China (Taiwan), the U.S. and France cooperated on a project to study the deep seismic structures in and around Taiwan acquired by the R/V Maurice Ewing and the R/V Ocean Researcher I [*Liu et al.,* 1995]. The TAICRUST large-scale seismic acquisition experiment included joint land and marine-based reflection and refraction surveys. Simultaneously, wide-angle ocean bottom seismographs (OBS) data obtained during shooting of marine multichannel seismic (MCS) surveys were collected at offshore eastern Taiwan (Figure 1).

Wide-angle OBS data recorded during shooting of MCS data often contain noise that interferes with deep crustal reflections and refractions. The OBS data were collected under adverse weather conditions, and thus noise reduction is crucial in prestack processing. Various noises may exist, including randomly occurring noise, strongly dipping noise, flow noise, waves, cable jerk, propellers and streamer depth controllers noise, and angle-dependent ghosting from air-gun source and receiver array effects in the marine data. The variation of the ship's speed when shooting at a constant distance interval may cause severe previous shot noise (PSN). This random time shift between shots produces shot noise with no trace-to-trace coherence. Shooting at a constant time interval also results in unevenly spaced traces. Some of the data acquired may be lost or dead during the data extraction or conversion stage due to instability of the recording medium when exposed to low sea-floor temperatures. As prestack analysis of wide-aperture data becomes common, better prestack processing techniques must be developed. This work develops and evaluates a wavefield processing method, both for prestack noise suppression and for trace interpolation, when data are missing and unevenly distributed.

Paper number 1999GL005421.
0094-8276/99/1999GL005421$05.00

The Algorithm

Two widely used wave-equation based imaging methods, reverse-time and Kirchhoff migration, have been thoroughly reviewed and compared by *Zhu and Lines* [1998]. Despite higher computational demands, reverse-time depth extrapolation tends to have a wider range of applications, such as the implicit ability of static corrections [*McMechan and Chen,* 1990; *Reshef,* 1991]; first arrival muting and ground-roll suppressing [*McMechan and Sun,* 1991]; and depth imaging in areas of rough terrain, both in 2D [*Rajasekaran and McMechan,* 1995] and 3D [*Chen and McMechan,* 1992]. A recent study indicated that interpolation of the missing trace in a complicated area is implicitly included during the reverse-time migration [*Zhu and Lines,* 1997], assuming the record is not spatially aliased. This work elaborates *Zhu and Lines* [1997] results using a different but conceptually similar approach and further illustrates that the algorithm can enhance signal-to-noise ratio via wavefield depth extrapolation. The main differences with the previous approach are that noise reduction and implicit interpolation can be achieved simultaneously through downward continuation followed by upward propagation of the wavefield back to the receiver surface (topography or arbitrarily specified datum).

Reverse-time extrapolation uses the finite-difference (FD) solution of the two-way wave equation to drive the wavefield. In the prestack wave-equation based processing system, the data are treated as wavefields and act as scattered sources to extrapolate the input wavefields. The extrapolation is performed backward in time in migration, but also can be performed forward in time during simulation. No limiting assumptions are made regarding the subsurface structures, velocity of the medium, source and receiver elevation or propagation angle. First breaks and surface waves are effectively separated from deeper reflections by downward continuation of the recorded wavefield to a depth beneath which these waves propagate. Subsequent up-

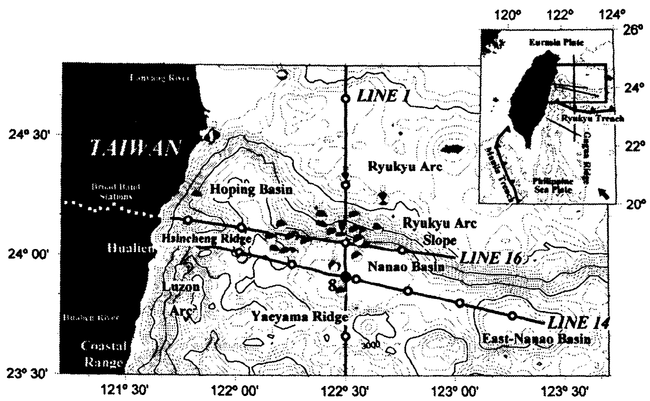

Figure 1. OBS and seismic lines of the western Ryukyu forearc region off Hualien. Black and white circles represent OBS stations. OBS 8 data is used for data processing. White squares denote land stations across central Taiwan. The contour interval is 200 m. Focal mechanisms from *Kao et al.*, [1998] indicate under-thrusting of the Philippine Sea plate (red), lateral compression (blue) in the Ryukyu Arc and normal faulting (purple) within the forearc region.The areas surveyed were Lines 14 and 16 running E-W along the Ryukyu forearc basin, and Line 1 running N-S across the arc-trench system.

ward continuation of the wavefield reconstructs the original surface-recorded wavefield with the subhorizontally traveling waves removed [*McMechan and Sun,* 1991]. Although the implicit noise reduction and trace interpolation can be achieved by using the same mechanism described above, the purpose and the outcome are different. The underlying premise is that if noise were not the solution of the wave equation then they will not propagate. However, the stationary noises may propagate predominantly in a vertical direction and may locally focus and defocus during extrapolation. The uncorrelated noise wavefield is suppressed by destructive interference and spherical divergence, and is then further attenuated by applying an absorbing boundary condition around the model. Missing or dead traces are interpolated simultaneously by the wave equation during extrapolation. The merit of reverse-time processing algorithm is that only a very simple velocity is needed and no distortion is produced as both downward and upward continuation are performed using the same velocity model.

Field Data Application

To illustrate many of the above points, the processing of an OBS common-receiver gather at station eight is presented. OBS 8 data, located at the center of the Nanao Basin, associated with two other cross-line profiles, is important for revealing a typical convergent margin structure in trench, accretionary wedge, forearc basin, arc and backarc basin (Figure 1). Therefore, structural interpretation and identification of particular phases from OBS 8 are crucial for the entire survey.

OBS 8 raw data (Figure 2a) show earlier arrivals on the north side, implying a shallower sea-floor and/or higher apparent velocities north of the station. The faster and weaker refractions on the north side branch result from the bathymetric and low transmission effects of the Ryukyu Arc Slope (Figure 1). Owing to the long offsets of wide angle data, high-amplitude, faster-propagating phases from the basement and deep crust overtake the slowly propagating water-borne noise from previous shots (PSN in Figure 2a). Such high-amplitude band of PSN can obscure significant portion of the wide angle signal. Highly oscillatory noises (N) are visible. These signals maybe generated from vibration of OBS instruments, biological activities on the sea-floor or ocean current flow. Notice that the data are unevenly distributed. The original shot records are not ideal from the conventional viewpoint of applying depth migration. The OBS data were processed through station relocation [*Christeson,* 1995], band-pass filtering (3-12 Hz), PSN reduction [*Holbrook and Reiter,* 1992] and 6 Hz notch filtering (for N) within the specified region. The preprocessed OBS 8 data (Figure 2b) shows a fairly significant improvement of seismic responses.

Noise Reduction and Trace Interpolation

For simplicity, only a portion of the data between -6.0 to 60.0 km was used to show the processing details (Fig-

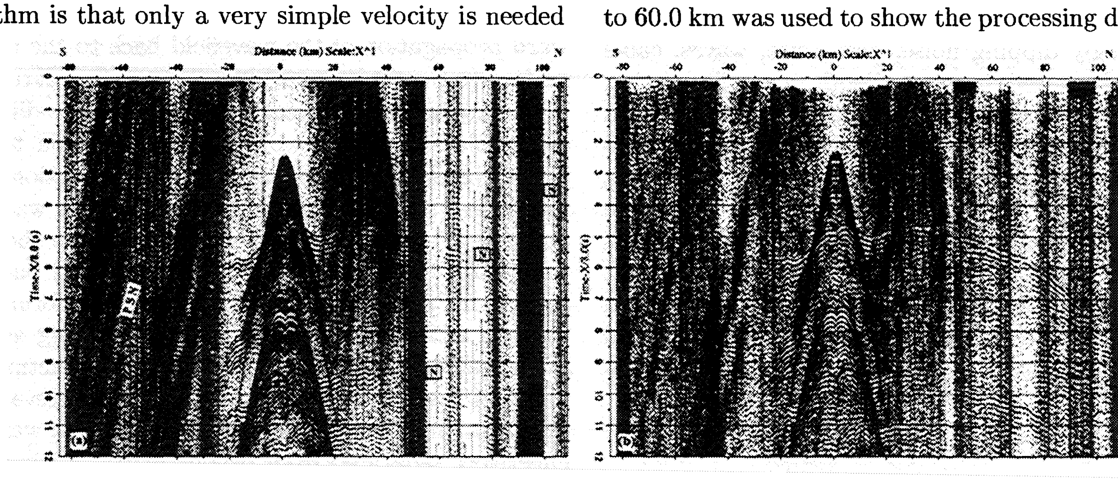

Figure 2. Vertical component of OBS data for station 8 (Fig. 1). The sampling interval is 4 ms and recording alias filter was set at 30 Hz. Distance dependent amplitude compensation is applied. Noise types are indicated with capital letters in Fig. 2a. The processed section is shown in Fig. 2b. See discussion in the text.

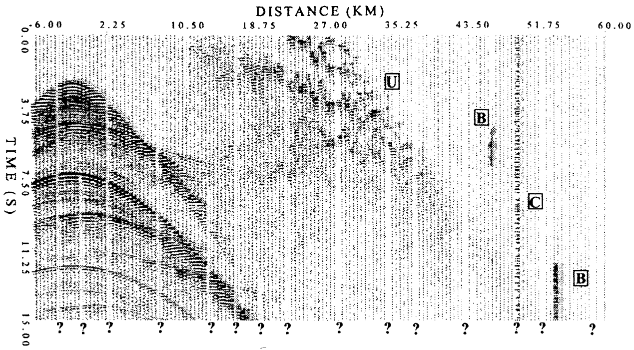

Figure 3. Representative portion of data between -6 to 60 km (Fig. 2) showing a fairly large amount of noisy and dead traces. Various types of noise persist after data pre-conditioning. Noisy arrivals are labeled with letters and symbols. See discussion in the text.

ure 3). Because our wavefield processing algorithm does not require accurate receiver location and velocity information, the data is purposely depth extrapolated and plotted in an evenly spaced format. Although the data have been processed, high-amplitude noise bursts lasting about 2.25 sec (B), different levels of ambient (random) noise on all traces, constant-signal noise (C), and non-coherent and scattered unknown noises (U) still exist. Because weather conditions during acquisition were relatively rough (2-3 m seas with 30-knot winds) noise was substantial. Approximately 10% of the dead traces (denoted ?) are visible.

For prestack processing, the structure is assumed to be 2D and invariant perpendicular to the survey line. This assumption is approximately true as Line 1 is located west of Gagua Ridge and is roughly perpendicular to the Ryukyu Trench. For this data set, the fourth-order in space and second-order in time, staggered-grid FD solution of the two-way scalar wave-equation was used. Absorbing boundary conditions were used on the edges of the model during downward and upward continuation. A very wide (66 km) aperture was used during extrapolation to facilitate the downward continuation of the data. Each data gather was tapered in time and space to minimize edge effects and was time-reversed prior to downward continuation. The data were also resampled in time to 1 ms to accommodate finite difference stability conditions and grid dispersion requirements. A homogeneous velocity distribution of 1.5 km/s was used for wavefield extrapolation.

The first pass is to perform downward continuation. The recorded wavefields are propagated backward in time (Figure 4a). The diffracted and reflected waves travel back in time through the medium, focus at the time and spatial location where energy was originally scattered, and then defocus. During reverse-time propagation, the seismograms are extracted at points along the specified datum (depth = 4 km) and stored in the disk for later upward continuation of the wavefield to recover the original recorded data. Three high amplitude

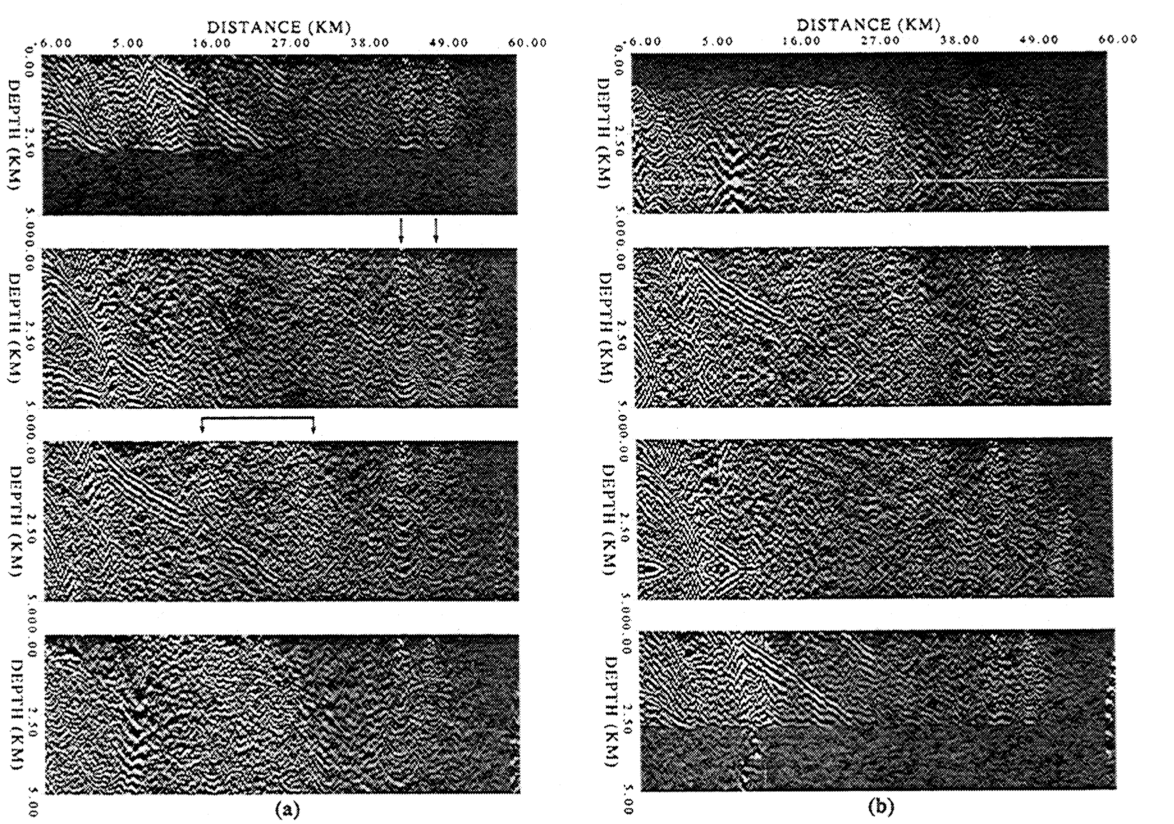

Figure 4. Selected snapshots taken during depth extrapolation. The datum is at a depth of 4 km (white line). (a) are the fixed-time snapshots, corresponding to 13 s, 9 s, 6 s and 2 s. The propagation behaviors of noises (arrows and bracket) are shown during downward continuation. (b) are the snapshots at 2 s, 6 s, 9 s, and 13 s during upward continuation. Symmetric propagating wavefield patterns are visible.

noisy seismic arrivals around 50 km are propagated vertically and locally with a peculiar smile pattern. The sanpshots taken at 6 and 2 seconds clearly indicate that the unknown noises (U), between 15 to 35 km and before the first arrivals, behave differently compared to the reflected energy.

The second pass is to perform upward continuation. The recorded data at the selected datum are extrapolated forward in time by driving the FD mesh in the subsequent upward continuation (Figure 4b). Notably, the wavefield patterns in the fixed-time snapshots are symmetric at the location of the datum. The extrapolation of the wavefield reconstructs the original recorded data with significant reduction of noise level (Figure 5). Comparison of Figure 5 with Figure 3 clearly demonstrates that trace interpolation of the input gather is automatically and implicitly included during extrapolation. Some artefacts before the first breaks are introduced mainly from the effect of finite recording aperture. The artefacts before the first arrival zone differ from the results of Figure 13 by *Zhu and Lines* [1997]. The difference may be attributed mainly to using a different propagation procedure.

Discussion and Conclusion

We have presented a novel approach for processing OBS data through wavefield extrapolation. The proposed algorithm is practical and is applied to a set of field data acquired in the TAICRUST project. The processing procedure does not require *a priori* information about accurate subsurface velocity structure and sources/receivers. Only a fictitious velocity model is required for propagating the recorded data. Both trace interpolation and signal-to-noise ratio appear able to be further enhanced through multiple passes of depth extrapolation procedure. The interpolated data contains no new information but stabilizes the computing. Although many solutions have been proposed to treat similar subjects, no work has reported on prestack applications of marine OBS data. The algorithm can combine with current standard processing methods as demonstrated in the example of processing OBS data. Application of the wavefield based processing method to field data can enhance events that are not visible in the input data, thereby improving the migrated image by reverse-time migration. The algorithm is limited in that the computation is expensive; however, this can be alleviated with more powerful computer and parallel processing [*Chen*, 1999]. In the future, 3D elastic depth extrapolation will be necessary for processing multi-component seismic data.

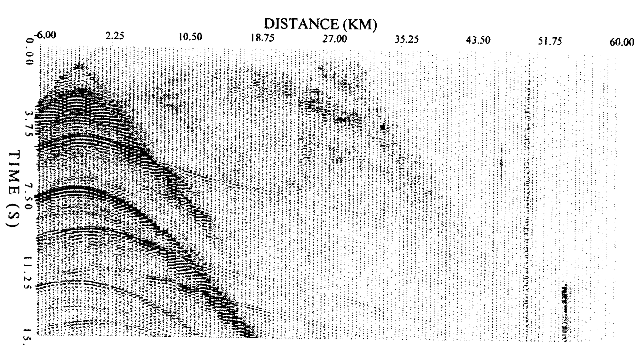

Figure 5. Processed results after two-pass depth extrapolation. All types of noises are suppressed and trace interpolations are implicitly and automatically accomplished.

Acknowledgments. The authors would like to thank the National Science Council for financially supporting this research under Contract No. NSC-88-2116-M-194 -006. The authors are grateful to Larry Lines and an anonymous reviewer for their constructive comments and suggestions.

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(Received July 12, 1999; revised October 06, 1999; accepted October 15, 1999.)