SEISMIC IMAGING OFFSHORE POHANG USING SMALL-BOAT ULTRA-HIGH-RESOLUTION 3D SEISMIC SURVEY

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ABSTRACT

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A joint study by the Korea Institute of Geoscience and Mineral Resources (KIGAM) and Geoview Co. Ltd. has developed a new 3D ultra-high-resolution (UHR) seismic survey system called the Engineering Ocean Seismic 3D-Streamer (EOS3D-Streamer). The EOS3D-Streamer is a receiver system comprising two, 8-channel 93 meter streamers that are used in conjunction with a small air gun system as a seismic source. To verify the new system, a test survey was performed over two years in 2016 and 2017 in Pohang City's Yeongil Bay located offshore the southeastern part of Korea. In the test survey, 139 lines of seismic data were acquired in a survey region of 1,400 m x 500 m. A basic seismic data processing algorithm was applied to the data that was divided by channel. Subsequently, a 3D seismic cube was produced for each channel using a radial basis function (RBF) interpolation method in a stage of 3D flexi-binning. A final 3D cube with an improved signal to noise ratio was produced after normal move-out correction using a 1D velocity model and multi-channel stacking. Finally, a shallow fault and gas analysis was performed through a data interpretation process. Through this study, we confirmed that it is possible to perform economical UHR 3D surveys using general-purpose small vessels in coastal areas where it is difficult for large seismic vessels to enter and perform surveys.

KEY WORDS: ultra-high-resolution, seismic survey, 3D, small-boat, EOS3D project.

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INTRODUCTION

Seismic surveys create seismic waves through active sources such as air guns, sparkers, and sub-bottom profilers, and a receiver records the characteristics of the waves that are refracted, diffracted, and reflected off the bottom in order to describe complex geological structures. Seismic surveys are widely used by large petroleum companies and government-funded research institutes around the world to perform petroleum and gas exploration. By using air-gun arrays with volumes of 3,000–8,000 cubic inches capacities that create high-energy low-frequency (a central frequency range below 100 Hz) seismic waves and large streamers that are several kilometers long, it is possible to perform imaging of complex geological structures at deep depths where oil and gas reservoirs are located. Doing this can increase the success rate of drilling, which requires large amounts of capital. Unlike these traditional seismic survey methods, ultra-high-resolution (UHR) seismic surveys using high-frequency (a central frequency range of hundreds to thousands of Hz) seismic sources are performed in coastal areas for a wider variety of purposes. UHR seismic surveys are performed to find more detailed structures at shallow depths, and they are variously used for scientific and public interest purposes that are outside of normal commercial purposes, such as resource exploration. These non-petroleum purposes include quaternary mapping, geotechnical evaluations, and engineering applications for aggregates and placers (Mosher and Simpkin, 1999).

In UHR seismic surveys that are performed in coastal areas, analogue acquisition methods with single channel receiver systems are traditionally used for long periods of time (Reynolds, 1990). However, digital acquisition techniques are now typically used and it has become possible to apply a variety of digital signal processing techniques to high resolution seismic data (Lee et al., 1996; Lericolais et al., 1990; McGee, 1995). Subsequently, it became possible to improve the seismic section's signal to noise ratio by stacking seismic data acquired from several receivers due to the development of multi-channel receiver systems. It also became possible to perform imaging on geological structures at deeper depths through the use of long offset receivers (Lee et al., 2004; Marsset et al., 1994; Nissen et al., 1999; Pugin et al., 1999). In traditional 2D seismic surveys, seismic sources and receiver arrays, which are arranged in a line, move along a set line to perform the survey, and ultimately a section of the underground structure is obtained. However, in reality, seismic waves spread in all directions, and geological structures have characteristics which change not just in the vertical direction but also in the horizontal direction as well. Because of this, artifacts that cannot be properly interpreted occur in 2D seismic survey results. To resolve this, 3D surveys are starting to be used, even in coastal areas. These surveys use two or more streamers and ultimately produce a 3D seismic cube (Mjelde, 2006; Müller et al., 2002; Scheidhauer et al., 2005).

This study has developed a portable UHR 3D survey system which can be operated in a general-purpose small vessel, rather than a special vessel designed for seismic surveying. The fact that it is possible to use a typical small vessel which can easily be found anywhere is very significant for being able to reduce the preparation time and cost needed to perform an high resolution 3D seismic survey. Furthermore, using a small vessel has the advantage of allowing easy access to very shallow waters and fishing areas that cannot be accessed by normal special-purpose seismic survey vessels. An air-gun system that can provide high vertical resolution and deep imaging depths was used as the seismic source, and a portable air compressor was constructed for this. Two, 93-m long streamers comprising eight channels and additional equipment (deflector and tail buoy, etc.) were produced to receive seismic wave data with a long offset and a wide azimuth angle. By processing the data acquired from offshore Pohang, Korea in 2016 and 2017, it was possible to create a high-resolution 3D cube and discover areas of free shallow gas and fault zones, which show a north-northeast strike-slip component.

Existing research of portable 3D seismic survey system

This section provides a simple introduction to the features, advantages, and disadvantages of previously proposed small-scale 3D seismic survey systems that use small vessels. The small-scale 3D seismic survey systems that have been presented in the literature up until now can be divided into two types: rigid-body and streamer-types.

The rigid-body type is a method that makes maximum use of the advantages that can be obtained from a small survey system, and the seismic source and receiver are built and operated as a single rigid body (Henriet et al., 1992; Marsset et al., 1998; Missiaen, 2005; Müller et al., 2009). The survey system's various components are fixed together as a single piece of equipment so that it has the advantages of easy operation and simple adjustment of the distance between the seismic source and receiver. However, it has the disadvantages of a shallow imaging depth due to a limited offset and small fold of coverage at the image point. Therefore, it is considered appropriate for surveying small anomalies when examining undersea cables, pipelines, and archeological sites.

The streamer type is a method that operates a seismic source and two or more receiving streamers independently, and it is a miniature form of the conventional 3D seismic survey system used for resource exploration (Mjelde, 2006; Müller et al., 2002; Scheidhauer et al., 2005). It has a disadvantage in that operating a variety of additional equipment independently is complex, but it has the advantage of being able to acquire data from relatively deep depths by adjusting the length of the streamers. Therefore, it is suitable for examining undersea faults and geological structures in areas that are difficult to access via conventional large survey vessels. We examined previous studies on streamer-type system development individually and are summarize them here. Müller et al. (2002) designed and performed a 3D survey using a boomer source and 2 streamers. It had the feature of two different streamer lengths of 50 and 100 m, and the receiving channels' intervals and number were set differently. An analysis of the raw data acquired from the two streamers was performed to find the offset and hydrophone array variables appropriate for processing data in the boomer's frequency range. However, the system was unable to acquire the source and receiver's relative position information, so it had a limited ability to produce a satisfactory 3D stack cube. Scheidhauer et al. (2005) performed a 3D survey by putting support bars on both sides of a small vessel and attaching 2 streamers to each side. An air gun was used as the seismic source, and a navigation system which can be used in field surveys were used to acquire the survey data. Mjelde (2006) presented a method that performs 3D surveys by firing two sound sources in succession on both sides of a single streamer.

Brief description of EOS3D-Streamer

The streamer-type small 3D seismic survey system developed in this study is called the Engineering Ocean Seismic 3D-Streamer (EOS3D-Streamer) to emphasize that it is a system for engineering purposes and to distinguish it from existing resource exploration systems (Fig. 1). This section provides a simple introduction to the features of the EOS3D-Streamer, which is composed of a seismic source system, receiver system, and data recording system.

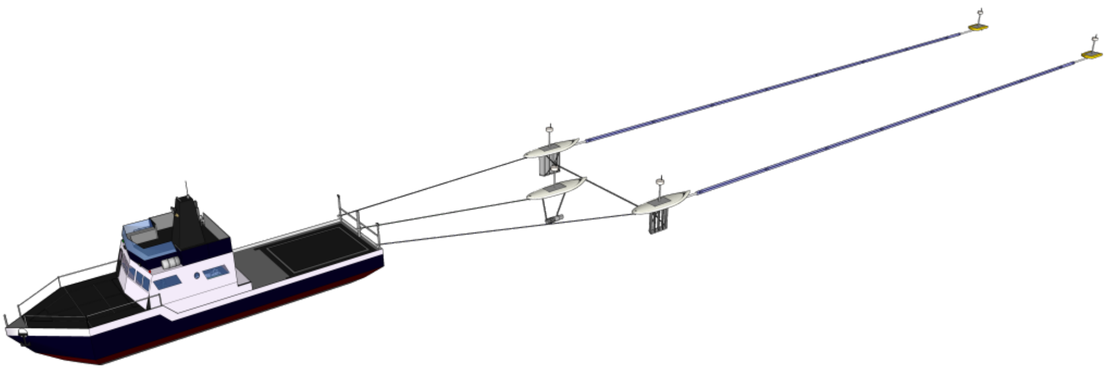


Fig. 1. Diagram of EOS3D-Streamer.

This study used a single-unit air gun that has high vertical resolution and deep penetration depth (1–50 cubic inches air gun volume) as the source of seismic signals. A portable electrical generator and air compressor were used so that the high pressure (13,000 kPa) air needed by the air gun could be produced independently in the small vessel, and a 300 liter capacity reserve storage tank was designed to allow for 6 hours of continuous surveying (at an air gun chamber volume of 3 cubic inches and a 1 second firing interval).

Two 8-channel streamers were constructed to receive seismic signals that were diffracted and reflected from beneath the sea bed. Each channel included 3 hydrophones with a sensitivity of -202.5 dB and a 1 Hz−10 kHz frequency range, as well as one preamplifier that can amplify received signals by a factor of approximately 100. The receiver interval for each channel was 5 m., distributed over 43 m of the cable, after a 50 m lead-in, giving a total length of 93 m. The outer sheath that surrounded the hydrophone, preamplifier, and other cables was made out of a polyurethane material, which has good elasticity and little deformation. The inside was filled with silicone oil, which has excellent insulating properties.

A fixed separation distance between two or more streamers must be maintained to perform the 3D seismic survey reliably. A deflector system was developed in this study to fulfill that role so that the streamer intervals could be reliably maintained in a fluid environment by controlling the number of vanes on the heads of the two streamers (A minimum of 1 and a maximum of 5 vanes can be attached). The number of vanes and the water speed of survey vessel were designed to maintain a semi-proportional relationship to cope with variable environment condition.

The data recording system was built in the form of a portable box located within the vessel. It performed analog signal processing on the analog signals received from the streamers and converted them into digital format. Five differential GPS modules having 1 meter error accuracy installed at the source and both ends of the streamers transmit coordinate information to the recording system every second via Bluetooth communication. Finally, by processing the received GPS coordinate information including UTM conversion and interpolation, the standard SEG-Y data is saved in real time.

FIELD DATA ACQUISITION, PROCESSING and INTERPRETATION

Acquisition

To verify the performance of the EOS3D-Streamer, a test survey was performed in waters offshore Pohang, which is a city located in the southeast part of Korea (Fig. 2a). The Pohang region has excellent topographical and geological characteristics, including the widest and thickest distribution of the Cenozoic Era third substratum, which has high potential for coal or petroleum reserves. Consequently, it is an area where national research projects are actively being carried out, including projects related to seabed geology and ocean surveying, such as undersea geological mapping, geothermal power generation, and development of carbon capture storage (CCS) sites (Lee et al., 2017, 2004; Park et al., 2017).

The field survey was performed over the course of two years, in 2016 and 2017, and it covered an area of 0.7 km^2: 1,400 m in the east-west direction and 500 m in the north-south direction. The northern area (red lines) in Fig. 2b is the area of the survey that was carried out in 2016, and the southern area (blue lines) is the area where the survey that was conducted in 2017. One thing to note is that in 2016, the vessel unavoidably strayed from the survey lines due to fishing activities, but in 2017 a supplementary survey for these areas was performed. The survey consisted of 126 basic lines (1,400 m long) in the east-west direction and the 13 additional lines (800 m long) over the course of two years. The distance between neighboring survey lines was 2 m and 6 m by turn (The distance between the source and receiver mid-point was 2 m). An air gun with a capacity of 3 cubic inches was moved at a speed of 3–5 knots considering the drift of a current and fired at 1 second intervals so that the average distance between the source positions was 1.77 m. The receiver system recorded 3,500 samples at 100 microsecond intervals. The distance between streamers was set at 8 m, and the minimum and maximum offsets of each streamer were an average of 10.5 m and 44.9 m, respectively.

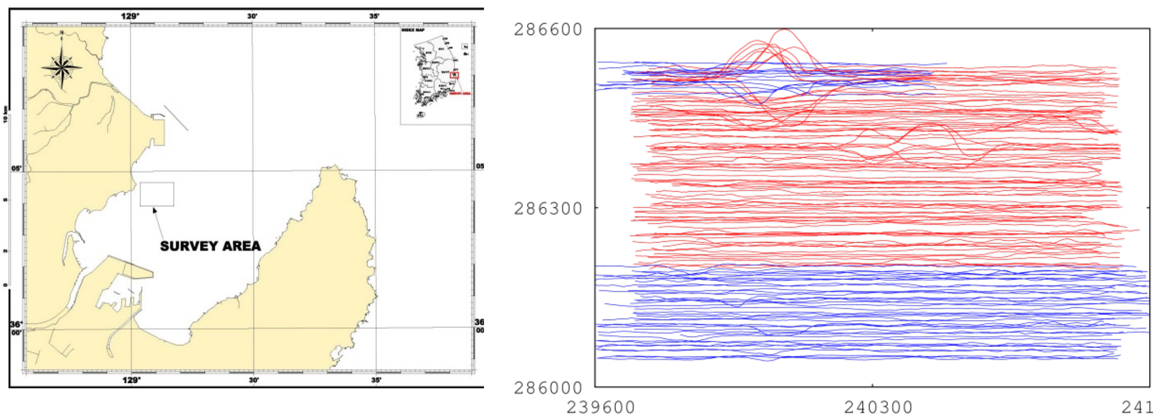
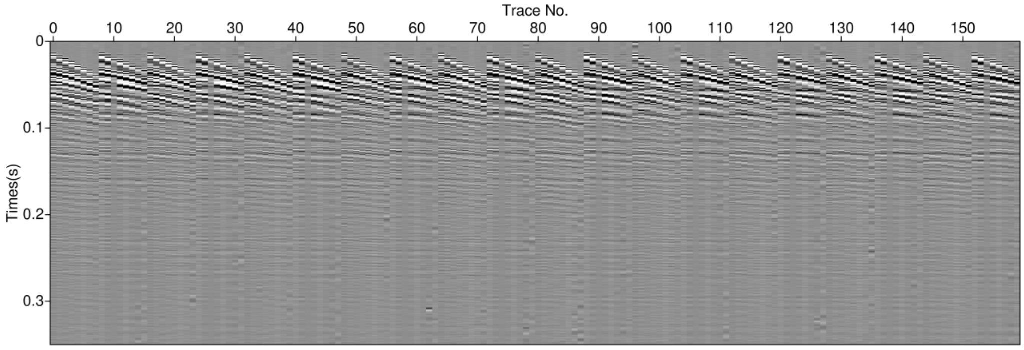
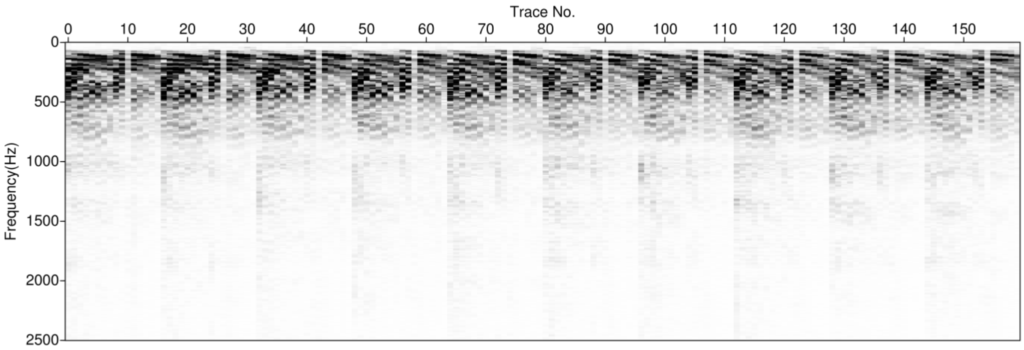


Fig. 2. (a) Survey position chart and (b) line chart. The 2016 survey lines are in red, and the 2017 survey lines are in blue.

Ultimately, the data acquired in the overall area consisted of seismic records for 92,199 source positions. Fig. 3 shows a group of 10 randomly extracted common source seismic gathers and their frequency domain spectrum.



(a)



(b)

Fig. 3. Group of 10 randomly extracted common source gathers and their frequency domain spectrum.

Digital processing

This section describes the seismic data processing sequence that was used to produce a 3D seismic cube from the acquired survey data.

To process seismic data acquired for resource exploration, common midpoint gathers are created for all the seismic data, typically. In this gathering process, virtual grid points are shared as the midpoints between sources and receivers. Stacking the common midpoint gather after compensating for the effect of different offsets to produce a single stacked trace is performed on each grid cell, repeatedly, to create a final section or cube. Compared to a normal seismic survey which has a grid size of tens of meters (e.g., 12.5 – 25.0 m), a UHR seismic survey requires a small grid size of several meters (e.g. 1 – 2 m). In such a survey, it is difficult to steer accurately by 1 – 2 m units, and the effects of the external marine environment are relatively large in a 3D grid, so it is difficult to perform the traditional data processing which creates common midpoint gathers for each grid cell. Therefore, seeing that single channel seismic survey are normally used for UHR seismic surveys, this study used a method that divides the overall seismic data by the receiving channel number so that they are independent but consistent data processing is performed (Fig. 4).

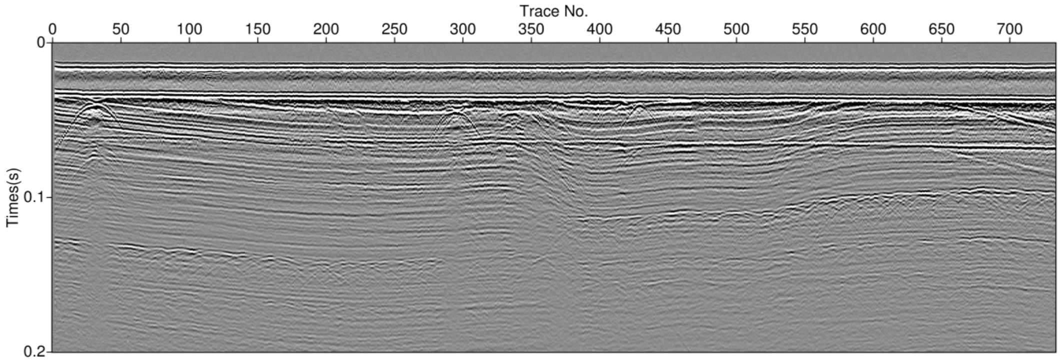


Fig. 4. Seismic data divided by receiving channel. This figure shows the common-receiver gather of channel 1.

Initial data processing was applied to the common receiver gather that had been divided by channel number. First, electrical noise generated by the survey equipment and flow and swell noises generated by the marine environment were observed to dominate the data acquired from the field, so a trapezoid shaped frequency filter (50, 100, 650, 700 Hz) was applied to remove such noise. Second, trace normalization was performed so that the root mean square amplitude of each trace was fixed within limits that maintain a fixed amount of overall energy at each common receiver gather in order to compensate for cases where the amplitude scale of the acquired seismic data varies over time for reasons such as changes in weather conditions, sea conditions, or mechanical settings for each survey line. Finally, a process was performed that adjusts and balances the signal through a time–power amplitude gain function ($g(t) = t^{\alpha}$; α is calculated empirically, and in this study α = 1) to compensate for the decrease in trace amplitude as energy is lost due to scattering attenuation in the underground medium and geometrical spreading as the seismic wave travels further from the transmission source. Fig. 5 shows a common receiver gathering which has undergone initial data processing.

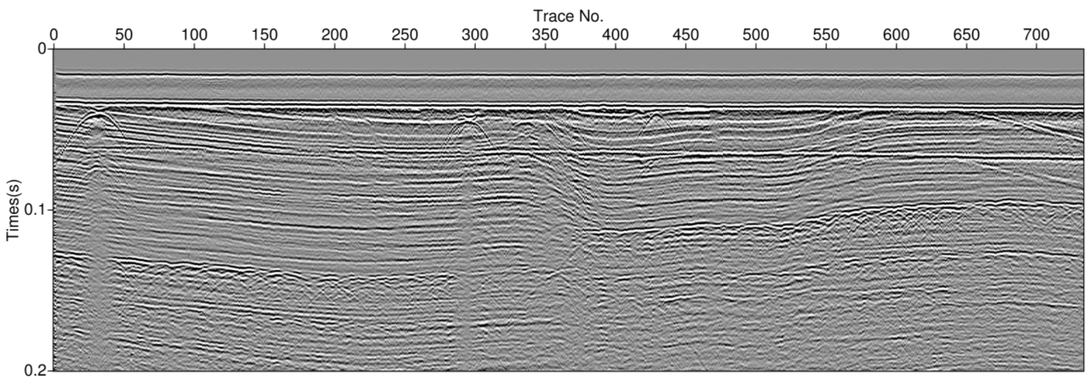


Fig. 5. Common-receiver gather (Channel 1) after going through the initial data processing steps.

A differential GPS system, which performs corrections and reduces the error at individual receiving points by precision measurements at reference stations, was used to record the source and receiver position information in the EOS3D−Streamer. However there is the possibility that positioning errors of several meters will occur due to the distance from the reference station, radio wave interruption, or radio wave interference. Even an error of several meters may possibly have a negative effect on UHR seismic survey data processing which uses such a small scale. To mitigate this problem, a moving average method was used to smoothly interpolate the coordinates of the mid-points between the source and the receiver in order to better estimate the coordinates where the actual system was positioned.

To make the acquired data into a 3D seismic cube, a process is needed which creates a computational 3D grid and moves each seismic trace to the grid cell corresponding to the source-receiver midpoint and stacks them. This process is called 3D binning. The size of the grid cells used in binning is often set at less than half of the dominant wavelength. A 1-m grid was used to process the survey data, which has a central frequency range of around 300 Hz. Figs. 6a and 6b are the inline and time sections of the channel 1 data with the traditional nearest binning method applied, and it can be seen that it results in gaps in many places. This is a problem that occurs as a consequence of an insufficient number of survey lines because of scheduling and cost limitations, difficulties with detailed steering because of the sea conditions, and changes in survey lines due to external factors (marine buoys, fishing nets, etc.). To resolve this problem, this study used a bilinear interpolation method, the radial basis function (RBF), in the 2D grid to create signals in grid cells where signals did not exist. RBF interpolation is a method that maps out the field strengths at all points that were actually measured in a given dimensional space and multiplies them by appropriate weights and adds them to supplement the measured values and to predict values for the desired points (Fornberg and Flyer, 2005). RBF interpolation in a 2D space is most often used in the image processing field for restoring lost images, but it can also be used in the field of geostatistics which includes seismic data processing (Hale, 2009; Zhang and Liu, 2017). RBF interpolation is best suited to a smoothly changing surface so it was repeatedly applied along the time axis to a time slice, rather than an inline section or crossline section. In RBF interpolation, matrix-type linear equations must be solved to find the weights which are multiplied by the field strength. This process requires computer calculations proportional to $O(n^3)$ (n being the number of measured values), so it is difficult to calculate the prediction values for the entire grid all at once using the observation values acquired from 92,199 source positions. Therefore, a method was chosen that applies the interpolation by selecting 100 adjacent measurement values for each grid cell. Figs. 6c and 6d show inline and time sections in which the RBF interpolation has been applied to the channel 1 data and it can be seen that the gaps have been filled reasonably.

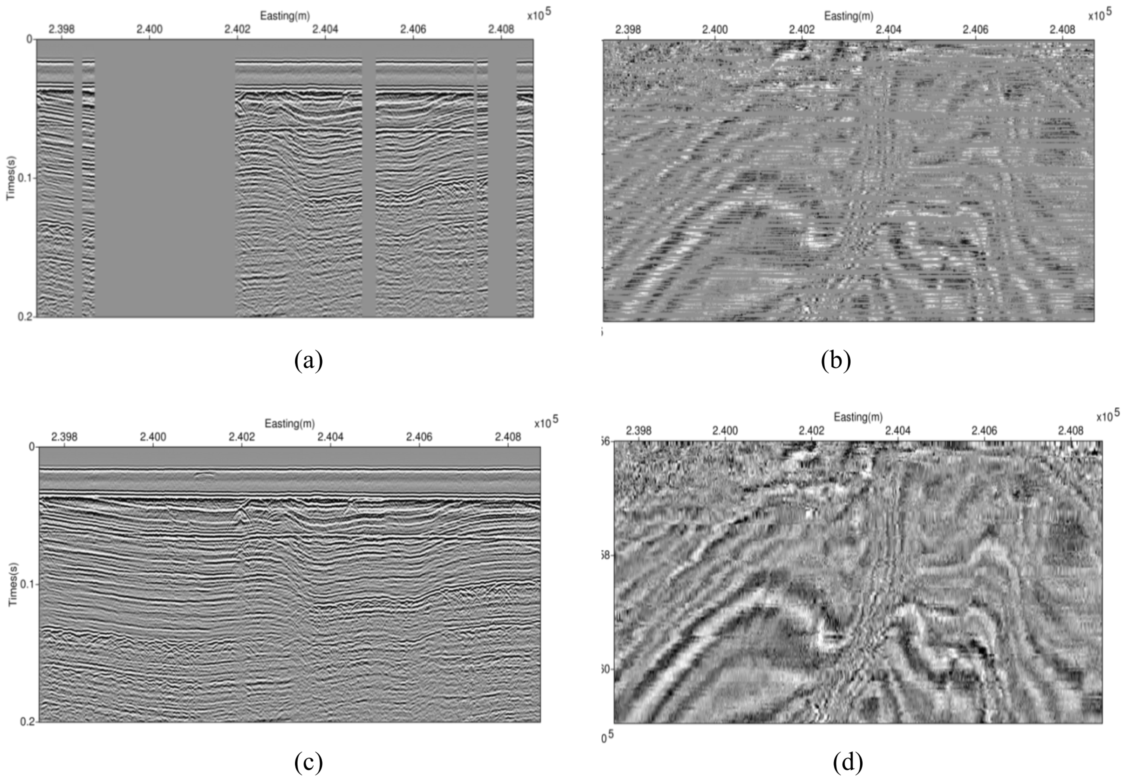
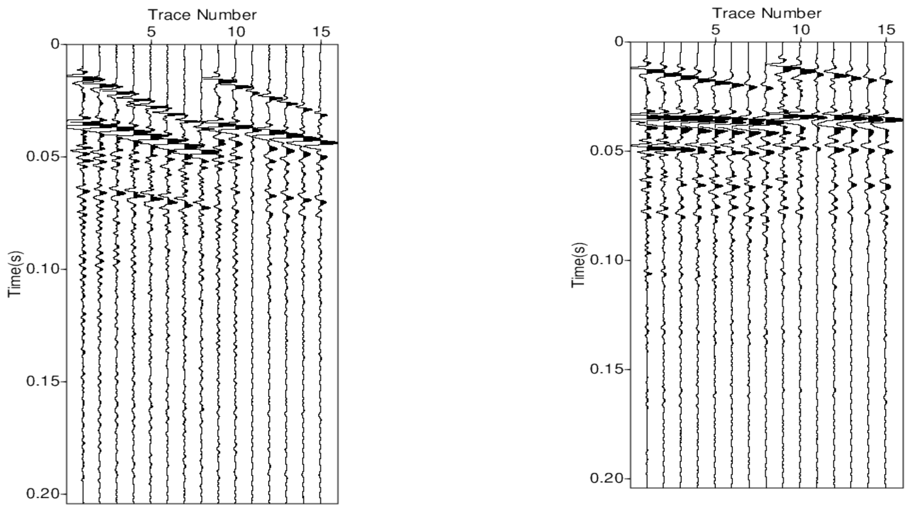


Fig. 6. (a) Inline and (b) time sections with conventional nearest binning applied. (c) Inline and (d) time sections with RBF-based flexi-binning applied.

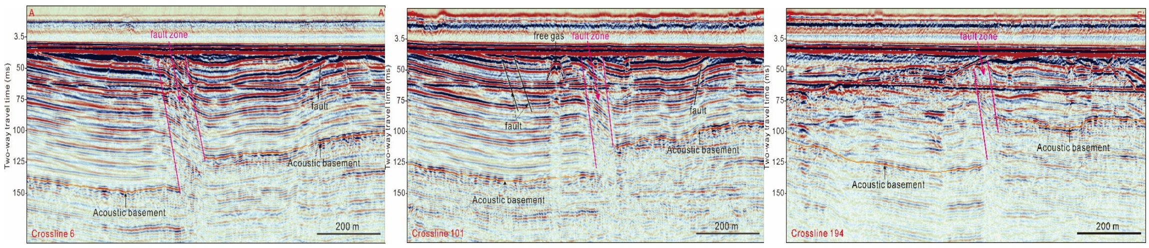
When creating a common midpoint gather at a given point, the reflected waves experience a time delay according to offsets that differ for each channel. In this case, it is not possible to properly stack the seismic wave cubes that were found for each receiving channel. The task of compensating the normal move-out, which is the change in the reflected wave's arrival time due to the offset between the source and the receiver, is called the normal move-out (NMO) correction, and a NMO velocity model is needed to apply the correction. If an accurate NMO velocity is used in the correction, the time-offset curve in the common midpoint gathering becomes clearly aligned with the horizontal axis (offset). When this is stacked, the signal to noise ratio improves and more accurate data can be obtained (Yilmaz, 1987). The most difficult part of this process is estimating an accurate NMO velocity. Traditionally during the data processing, a semblance panel is created and stacked, and then the velocity with the maximum energy is picked to estimate the velocity model. However, in the case of the data acquired in this study, the maximum offset is even shorter than maximum imaging depth, and expected velocity variation in the shallow sedimentary layers is moderate. Therefore, a method was used that assumes a reasonable one-dimensional velocity to perform the NMO correction and estimates the optimal velocity model empirically.

After correction, the surface reflected waves are arranged in a series (Fig. 7), and a high-resolution 3D seismic wave cube with an improved signal to noise ratio was found through the stacking process (Fig.8).

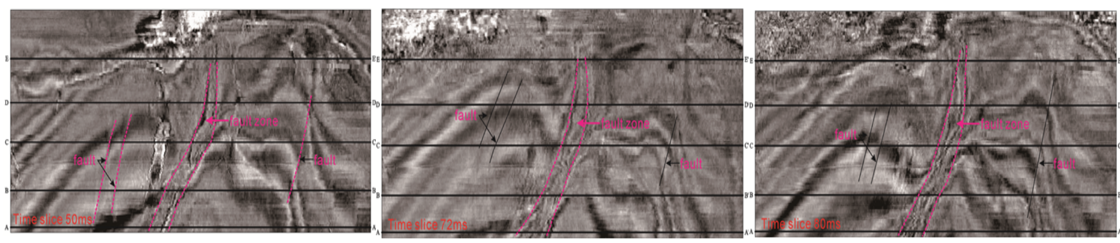


(a) (b)

Fig. 7. Example of common midpoint gather (a) before NMO correction and (b) after NMO correction.



(a) (b) (c)



(d) (e) (f)

Fig. 8. Inline (a, b, and c) and time (d, e, and f) sections incorporated with seismic interpretation process from the final 3D seismic cube.

Interpretation

The derived 3D seismic cube was used to perform an analysis of the shallow subsurface. Fig. 8 is an image of the inline sections of crossline numbers 6, 101, and 194, out of the total of 248 grid points (smaller numbers mean a more southern area), as well as time sections for 50 ms, 72 ms, and 80 ms. By observing the inline sections, it can be seen that many shallow faults were discovered in the entire area, and a fault zone has developed in which several faults are gathered in the middle part of the survey lines. Also, it can be seen that there is an unconformity that becomes deeper from south to north that is interpreted as indicating that there were temporal gaps in the sedimentation process. The survey also discovered the entire area's acoustic basement where the seismic signals stop penetrating, and the part that is split by the fault has a vertical offset of over 20 m. Finally, the survey discovered acoustic blanking which is interpreted as shallow gas. These features also appeared clearly in the time section which can be seen through the 3D processing. Several fault indicators going from the southern part to the north-northeast direction were seen, and shallow free gas anomaly zones with strong negative amplitude in the southern and northern areas were seen more clearly.

CONCLUSIONS

Seismic surveys are generally the most widely used technique for imaging of reservoirs at a depth of several kilometers to improve the success rate of petroleum and natural gas drilling. Seismic surveys that use higher frequency sound sources are being used in coastal areas, and there is an increasing demand for such surveys for scientific and engineering purposes, rather than resource exploration. Therefore, researchers are currently developing multi-channel, wide azimuth angle 3D digital data acquisition systems that diverge from existing single channel analog data acquisition methods. However, most of these studies require a special-purpose vessel for seismic survey systems, and generating high-resolution seismic cubes is still a difficult technology.

The goals of this study were to develop an optimal data processing flow and a survey system that uses any ordinary small vessel rather than a special-purpose vessel to minimize the costs required to perform 3D seismic surveying and increase its effectiveness. The study was successful in developing a 3D seismic survey system that consists of a portable air-gun sound source system, 8-channel streamer 3D receiving system, and compact seismic data recording system. In addition, the study proved that it is possible to economically and efficiently acquire data in a test survey covering the ocean offshore of Pohang City in the southeast part of Korea. Initial data processing (frequency filtering, normalization, and gain recovery) which was divided by channel number and intensive data processing (GPS smoothing, flexi-binning, dynamic correction, stacking) were used to successfully produce a high-resolution seismic cube for a 1400 x 500 m survey area. Lastly, the study proved that it is possible to use this cube to perform analysis of geological structures such as shallow fault and free gas.

Despite the successful test survey, this system needs to be tested and verified in a sea with a wider variety of topographical features to expand the system's usefulness. In particular, it has been decided that the most important task of all is to study the optimal air gun capacity and firing time interval according to the bottom material conditions and provide guidelines to the end user. In addition, it is also necessary to develop optimized data processing techniques for small-scale seismic survey data, including noise removal, velocity analysis, trace interpolation, etc. in order to produce a high-quality seismic cube.

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