Application of multichannel seismic reflection method to measure temperature in Sulawesi Sea

R Fajaryanti[1]*, H M Manik[1]*, C Purwanto[2]

[1]Department of Marine and Science Techology, Bogor Agricultural University
Gedung Marine Center Jl. Agatis, No.1, FPIK, IPB Bogor 16680
[2]Marine Geological Institute of Indonesia
Jl. Dr. Djunjunan No.236 Pasteur- Bandung 40174
*e-mail : rinafajaryanti@gmail.com; henrymanik@ipb.ac.id

Abstract. Seismic oceanography is integrated discipline between seismology and physical oceanography that can be used to investigate phenomenon in water column. Seismic oceanography displays fine structure of water column seismically and in wide range. The aim of this research was to measure temperature in Sulawesi Sea with CTD and seismic data. The benefits of this research were to create integrity and effectiveness in seismic and oceanographic surveys as well as to help develop OTEC (Ocean Thermal Energy Conversion) studies in Indonesia. The acquisition of seismic and CTD data in line 17 Sulawesi Sea conducted by P3GL on Mei-Juni 2016. Data processing was conducted in Februari-April 2017 and divided into three processes: seismic data processing using ProMax 2D software, synthetic seismogram processing using Hampson-Russell software, and mapping temperature using Ocean Data View software. The results showed that temperature in Sulawesi Sea based on CTD data ranged 4.7-30.3 ℃, and temperature based on the sesimic data ranged 4.49-30.29 ℃. This difference occured due to difference in vertical sampling between CTD and sound velocity *semblance*. Acoustic impedance in Sulawesi Sea ranged 1.529-1.578 MRy. Vertical and horizontal resolution of seismic data in this research were 6.3 m and 93.5 m, respectively. It's well established that sound velocity the main contribution to acoustic impedance. Correlation between seismic field with synthetic seismogram from CTD data is 0.7.

1. Introduction

The information about physical oceanography can be obtained by satellite imagery, ground check, and acoustic survey. Thermohaline circulation is the primary forcing mechanism that keeps the ocean conveyor belt in perpetual motion, regarding ocean processes helps build a comprehensive understanding of the ocean's role in the distribution of heat around the planet and thereby affecting climate. Seismic oceanographer investigate oceanic thermohaline finestructure based on temperature and salinity profiles [1].

Seismic method is one of sea exploration method based on measurement of sound waves propagating on earth layer medium then reflected and refracted [2]. Seismic method has three application with different requirements for band-width and depth-width; engineering seismology, exploration seismology, and earthquake seismology. Engineering seismology is used to derive a velocity-depth model for near surface with bandwidth 1000 Hz and depth down to 1 km. *Exploration seismology* is used to derive an image of subsurface with bandwidth 100 Hz and depth of interest down to 10 km. Earthquake seismology is used to investigate oceanic and continental crust with bandwith 10 Hz and depth of interest down to 100 km [3].

Seismic oceanography is recently developed approach for investigating water column using seismic reflection method. This method utilizies vibration source from *air gun* and fired to water, the waves are exposed to the medium and energy. This propagation will be influenced by many factors, such as offset, attenuation, and other disturbances. Seismic waves are reflected and refracted by the boundary layer of the rock and received by the receiver. The recorded seismic data is data based time domain that is consisting of reflection waves, direct waves, and noise [2].

Over the past few years, multichannel seismic reflection method is used in petroleum industry to describe subsurface geological structure [4]. This method can be used to image oceanic termohaline finestructure as a reflection process in underwater that called seismic oceanography. [5] simulated seismic reflection and observation of physical oceanography in Norwegia Sea and established that this method have temperature sensitivity 0.03°C. In the same region, [6] demonstrated seismic reflection to express internal wave spectrum. This method provide great potential in ocean imaging and be able to observe ocean termohaline structure in great detail [7].

Seismic oceanography utilizes low-frequency sound waves (1-100 Hz) emitted by air gun to the water column then reflected by water column sturcture and received by the hydrophone to image internal oceanic structure. This work illustrates the great potential of multichannel finestructure of meddies with exceptional vertical resolution 10 m and horizontal resolution 100 m [8]. Several studies of seismic oceanoprahy have demonstrated the ability of seismic imaging to detect and map major features in the ocean, including thermohaline finestructure and water mass front [9], *internal waves* [5], currents [10], *eddies* in Cadiz Bay [10], and *boundary mixing* [6]. In Indonesia, this study was conducted by Wirda (2016) in detecting structure of water column in East Waigeo, Papua.

The aim of this research is to measure temperature in Sulawesi Sea using seismic data and Conductivity Temperature Depth (CTD) data. Seismic oceanography displays fine structure of water column seismically and in wide range. The application of seismic reflection is possible to create integrity and effectiveness in seismic and oceanographic surveys as well as help to develop OTEC (Ocean Thermal Energy Conversion) studies in Indonesia. Seismic oceanography in Indonesia has not been widely known. Through this research, it is expected to introduce and encourage the development of seismic oceanography in Indonesia.

2. Material and methods

The research area was located in Sulawesi Sea at line 17 (figure 1). Multichannel seismic and CTD data were acquired during May 2nd-June 3rd 2016 by Marine Geological Institute Indonesia in Sulawesi Sea. Air gun of 880 Cu.Inch were used for seismic source. A 900 m long streamter with 72 channels at an interval 12.5 m was used to receive the seismic signal. The near offset distance is 160 m and the data was recorded with a 2 ms sampling rate. The CTD data was collected in seicmic line is CTD 17 and CTD 20. The observed temperature and salinity profiles from CTD data were used to estimate the sound speed and density profiles which in turn are used for reflectivity modelling to generate synthetic seismogram.

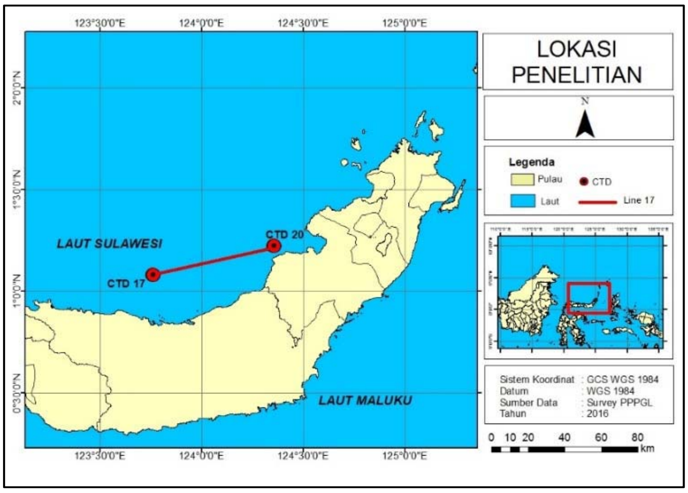


Figure 1. Location of seismic line 17 and CTD data in Sulawesi Sea.

Seismic data was processed wiith *ProMax 2D Version 5000.0.0.0 ©Landmark Graphic Corporation 1989-2008 All Right Reserved.* The process include input seismic data line 17 *.SEG-D into ProMax database. Subsequently, geometry assignment is performed to fit the field geometry into digital data. Information on geometry is the identity of seismic trace and becomes a vital attribute for the next process. Bandpass filter was used in this data using frequency 3-10-80-100 Hz to increase SNR. Trace muting is used to maximize observation of water column structure, by removing noise from direct wave and seafloor. In seismic oceanographic study, basin reflectors must be removed to improve the visibility of the water column reflector. Noise signals that cannot be seen periodically is separated using F-K filters, and convert time-distance domains (T-X) into frequency-waves number (F-K). The result is water column reflector in the form of a hyperbolic curve under direct arrival. Velocity analysis was processed to eliminate time lags due to separation of source and receiver on the surface and correct the speed of sound. Velocity analysis was performed every 100 CDP (CDP space is 6.25 m) with semblance method in each 8 points of picking velocity and extracted every 10 m depth. The resulting rms velocity is used for NMO (normal moveout) correction, ie the correction of travel time to eliminate the distance factor between the source and the receiver in one CDP and carry reflection waves from a dip reflection to a normal reflection. The next process is the stack by combining multiple traces into one trace. The result is a seismic cross-section of water column in the time domain. Seismic profiles are converted to depth using velocity estimated from CTD. Resolution of seismic profile can be estimated as :

$$L = \frac{c}{4\,f_o} \quad \text{and } R = \sqrt{\lambda h/2} \qquad (1)$$

where L represent vertical resolution (m), R represent horizontal resolution (m), c represent sound velocity (m/s), fo represent dominant frequency in seismic data (Hz), h represent depth of reflector (m), and λ represent wave length (m).

Synthetic seismogram was processed with *Hampson-Russel Software* (HRS). Generating synthetic seismogram from sonic and density log helps understanding the observed reflections in seismic data. The established empirical relationship are used to compute soundspeed from CTD data which are turn used to generate impedance (reflectivity) log. The impedance log is convolved with ricker wavelet to produce synthetic seismogram. Sound velocity varies with temperature, salinity, and depth and usually it ranges between 1490-1540 m/s (Sinha *et al.,* 2016). The empirical relationship by Wilson (1960) was used to calculate sound velocity from observed salinity and temperature profiles.

$$c = 1492.9\ + 3\,(T-10) - 0.006\,(-10)^2\ 0.04\ \ (T-18)^2 +\ 1.2\,(S-35)\ 0.01\,(T-18)\ (S-35)\ \ +\ d/61 \qquad (2)$$

where c represent sound velocity (m/s), T represent temperature (°C), S represent salinity (psu), and d represent depth (m).

As sound wave travels through water column, it refracts and reflects from layers of different acoustic impedances. This layer property (i.e. acoustic impedance, Z) is calculated by multiplying density with soundspeed, $Z = \rho\, c$. The amplitude of reflected sound waves from different impedance layers is directly proportional to the reflection coefficient or reflectivity, determined by the impedance contrast between the two layers. For an incident normal sound wave, reflection coefficient is expressed as:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad (3)$$

Correlation was processed with *eLog* program in HRS using seismic stack data *.SEG Y to adjust CTD location (CTD 17 in CDP 8751 and CTD 20 in CDP 1751). The right wavelet phase in CTD data was processed by extracting statistical wavelet so that zero phase wavelet has the same amplitud with seismic data. A good correlation between synthetic seismogram and seismic reflection was 0.7.

Water mass in Sulawesi Sea can be observed by T-S diagram. T-S diagram was processed with *Ocean Data View* (ODV) 4. The spreadsheet file consist of ocean parameters like depth, temperature, salinity, latitude, and longitude was imported to ODV database then source variable is associated with meta variable. Salinity and Potential Temperatur profile is used to generate T-S diagram.

3. Result and discussion

Ocean imaging using reflection seismic method produce seismic profile whose quality depends on data processing, particularly sound velocity. Seismic oceanography is optimally obtained from sound velocity data approaching the actual conditions at sea. Reflection in water column is a manifestation of the difference in acoustic impedance generated by thermohaline structure. Accuration of sound velocity data means easily to interpret seismic profile.

According to [10], sound velocity in the sea ranged from 1490-1540 m/s and it decreases to depth relatively. Velocity analysis show that the sound velocity in Sulawesi Sea ranges from 1470-1540 m/s. Sound velocity profile shows the water column structure stratified into 3 layers (figure 2). The upper layer is red at 0-300 m depth has sound velocity of 1515-1540 m/s, the green middle layer at depth 310-550 m has sound velocity of 1495-1515 m/s, and the bottom layer is blue at depth 560-1050 m has sound velocity of 1470-1485 m/s. The sound velocity is used for NMO correction until the seismic profile is obtained in figure 3.

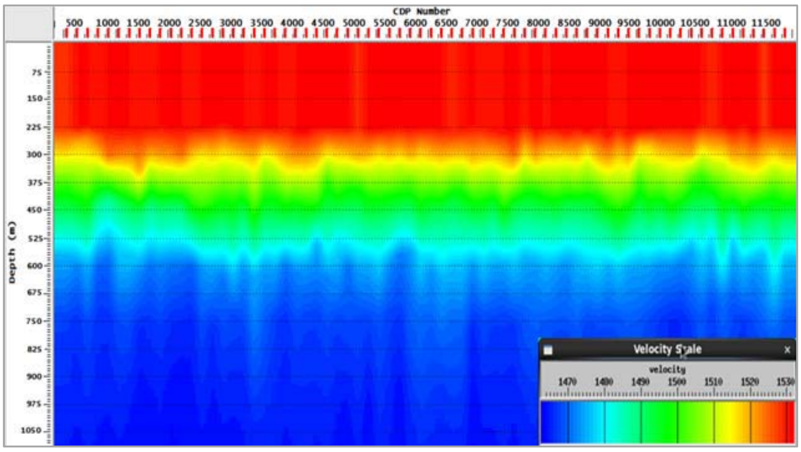


Figure 2. Sound velocity profile derived from semblance analysis shows stratification in Sulawesi Sea.

The maximum depth in Sulawesi Sea was varied from 1200-1400. Seafloor reflector is removed by trace muting process. figure 3 shows that stratification in water column formed by presence reflected seismic waves. The seismic waves are reflected by water column layers which is formed by difference in acoustic impedance. Those layers were recorded as reflectors depicted in red and blue seismic profil. The red reflector represent negative amplitude while the blue one represent positive amplitude. The lighter color represent the greater reflector amplitude value.

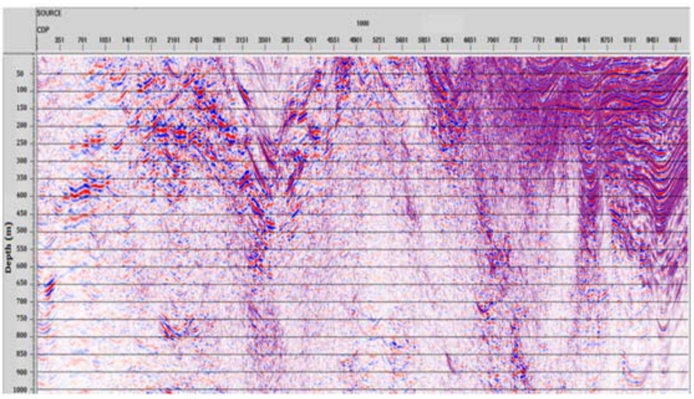


Figure 3. Seismic profile derived from semblance velocity analysis.

Acoustic reflector was clearly observed at 50-700 m depth. Most of the strong and continuous reflectors are confined in CDP 1401-4551 at 100-450 m depth and CDP 5951-9801 depth 50-550 m. Blur reflectors were confined in CDP 1-6301 at 500-700 m depth, CDP 1-6301 at 750-1000 m depth along the seismic line. Strong reflectors represent a relatively large acoustic impedance contrast. This difference is assumed due to significant changes in temperature and salinity [10].

Seismic profile can also be obtained from other sound velocity data. [11] made the seismic profile of Norwegia Sea derived from constant sound velocity (1500 m/s), sound velocity form Levitus database, sound velocity of CTD, and sound velocity from semblance analysis. [10] made seismic profile of Teluk Bengal using sound velocity obtained from CTD. In this research, seismic profile is derived from semblance sound velocity and CTD data. Seismic profile derived from sound velocity of CTD is shown in figure 4.

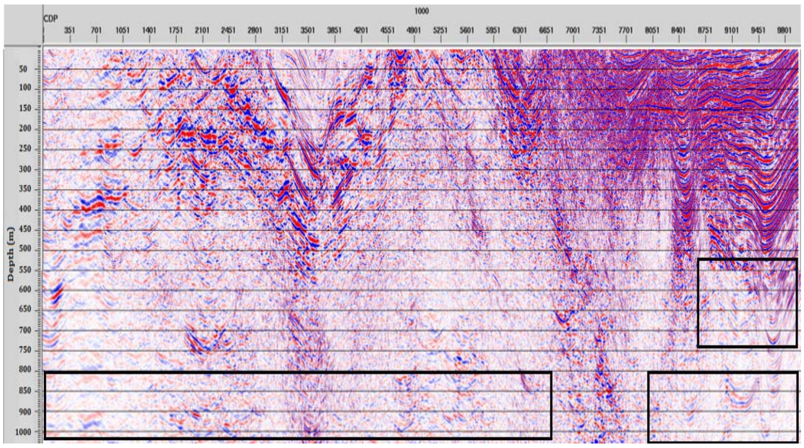


Figure 4. Seismic profile derived from sound velocity of CTD.

Seismic profile derived from sound velocity of CTD data is able to show the stratifictaion in Sulawesi Sea similar to the seismic profile in figure 3. However, in figure 4 shows blur reflector (black polygon area) so that the number of observed reflector decreases, ie CDP 8401-9801 at 500-750 m depth, CDP 1-6851and CDP 8051-9801 at 800-1000 m depth. According to [11], the decrease number reflectors are influenced by the lateral sampling of sound velocity profil. Sound velocity picked line wth lateral spacing ~8 km. Therefore, the seismic profile derived from semblance sound velocity is better and more clear in describing lateral variations more subtly that sound velocity of CTD data.

Seismic profile generated in this study has a horizontal resolution of 93.5 m and a vertical resolution of 6.3 m. The dominant frequency of seimic data is 60 Hz and the reflector is still clearly observed at 700 m depth. At a depth more that 700 m, the reflector blurred.

Seismic stratification in Sulawesi Sea is related to the temperature profile [1]. The sudden change in temperature and sound velocity (spike) has correlation to the layers in water column. According to [5], reflector arise when temeprature gradien is 4-8 4-8 °C. In Sulawesi Sea, spike at 100-200 m depth represent reflector occured in the same depth of seismic profile (figure 6).

Figure 5 shows the internal wave phenomenon at 100-450 m depth (black polygon area) with a flat reflector turns slightly wider with a high vertical displacement. Internal wave is ocean interior wave due to changes in hydrostatic balance [13]. Internal waves are generated when interfaces between layers of different water densities are disrupted, usually due to differences in temperature and/or salinity [12]. In addition, tilted reflector is observed at 150-500 m depth (black ellips area). Tilted reflectors arise from water *mass front*, *eddy*, *upwelling*, *downwelling*, etc. The tilted reflector that found in Sulawesi Sea is thought to be a water mass front that denotes two water masses distinct meet clearly.

Based on figure 7, salinity value in Sulawesi Sea from CTD ranged from 34.3-34.6 psu. Salinity profile shows that Sulawesi Sea divided into 3 layers, ie mixed layer, halocline layer, and deep layer. In the mixed layer at 0-40 m depth is 34.3 psu. In halocline at 50-450 m depth is 34.6 psu. Halocline is area within a body of water that marks a drastic change in salinity. Maximum salinity water from *North Pacific Subtropical Water* (NPSW) and minimum salinity water from *North Pacific Intermediate Water* (NPIW) meet within the body water of Sulawesi Sea [13]. In the deep layer, salinity ranged 34.5 psu and tends to increase slowly to the bottom of the water.

Based on figure 7, temperature in Sulawesi Sea from CTD ranged from 4.7-30.3 °C. Temperature profile shows that Sulawesi Sea divided into 3 layers, ie mixed layer, thermocline layer, and deep layer. Temperature in mixed layer at 0-50 m depth is 30 °C and tends to be homogeneous due to the mixing of water mass influenced by winds, currents, and tides. Salinity in thermocline at 50-250 m depth is 18 °C. In the deep layer, temperature ranged from 4.7 °C and tends to decrease slowly to the bottom of the water. Figure 8 shows the temperature stratification occured to 700 m depth and the rest relatively homogeneous. Reflector in seismic profile can be observed to a maximum depth of 700 m. Small gradient of temperature and relatively uniform temperature distribution at depths >700 m resulted blur reflector on seismic profile.

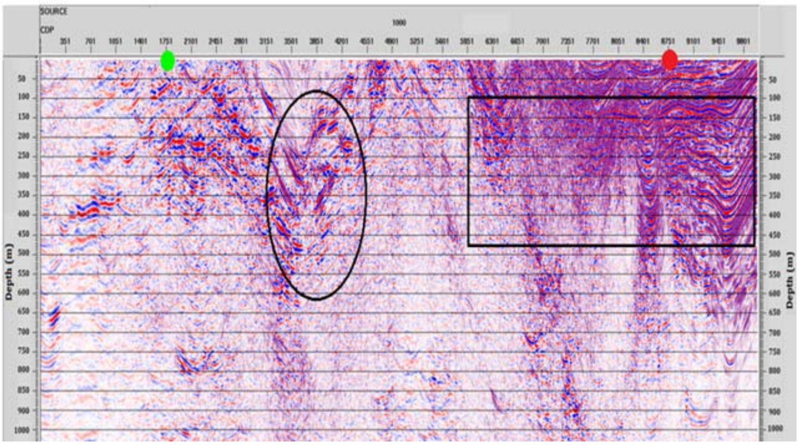


Figure 5. Seismic profil of Sulawesi Sea shows internal wave (black polygon area) and water mass *front* (black ellips area). Green symbol is CTD 20 site and the red one is CTD 17 site.

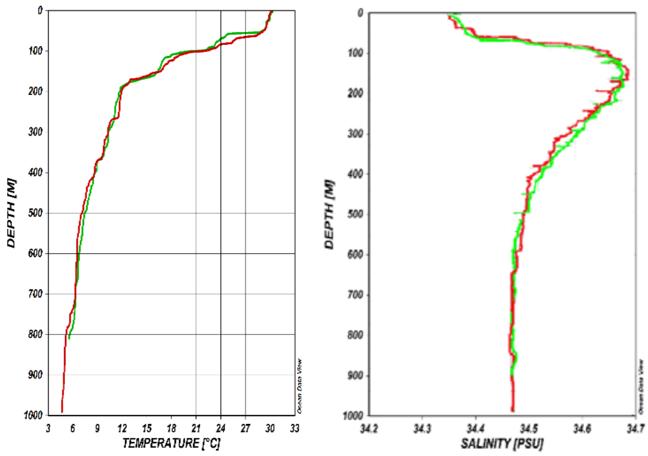


Figure 6. Temperature and salinity profile derived from CTD 17 (red) and CTD 20 (green).

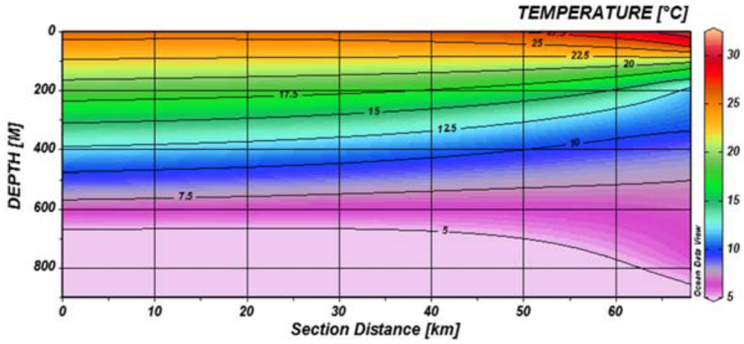
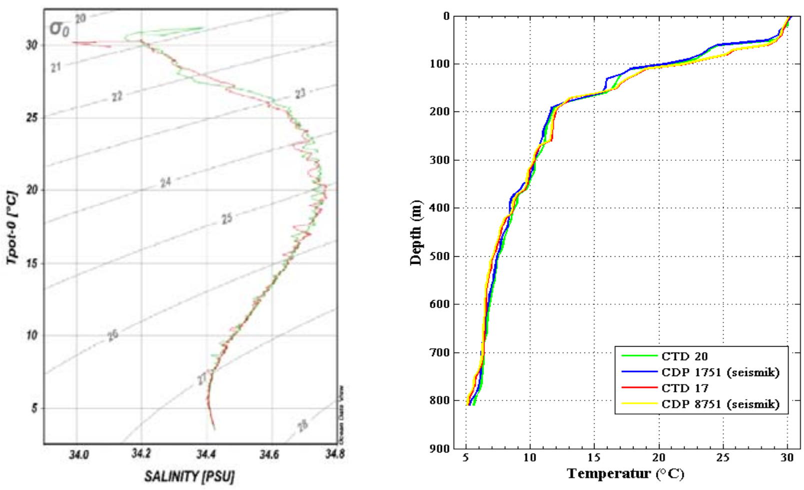


Figure 7. Temperature lateral profile of Sulawesi Sea derived from CTD data.

The properties of sea water can be plotted in one diagram to describe the characteristic of water mass. According to figure 8a, water mass of Sulawesi Sea derives from North Pacific Ocean and fills the upper thermocline layer, ie NPSW and NPIW. This water mass carried by Northern Equatorial Flow to eastern waters of Indonesia. The water current moves toward Phillipines and branches north into Kurushio current and south into Minandao stream. Some Minandao current move towards Sulawesi Sea and Makassar Strait, carrying NPSW with salinity 34.6-34.8 psu and temperature 15.79-23.83 ℃ at 120-200 m depth. At the bottom layer, NPIW with salinity 34.4-34.5 psu and temperaturr 5-7 ℃ at 250-400 m depth is transported [13]. Sulawesi sea is the part of Indonesia Through Flow (ITF), which is carry warm water from Pacific Ocean to cooler water from Indian Ocean. [13] states that during eastern monsoon Souther Equatorial Flow carried water mass along the northern Papua to the western and join the water mass that carried by Northern Equatorial Flow from north coastal of Sulawesi. Water mass characteristic in Sulawesi Sea during eastern monsoon is salinity of 33.8–34.4 psu and temperature 30 ℃, while during western monsoon the salinity is 33 psu and temperature is lower. This changes is due to changes of surface current. Some of Sulawesi Sea current flowed into Sulu Sea and partly into the Makassar Strait.



(a) (b)

Figure 8. (a) T-S diagram Sulawesi Sea from CTD data; (b) temperature profile for CTD and seismic data.

Temperature data can also be obtained from seismic sound velocity data using empirical relationship stated by Wilson that is calculated with Matlab *software*. Temperature was derived from seismic data ranged from 4.49-30.29 °C. Temperature profile derived from CTD and seismic data can be seen at figure 8b. According to figure 8b, temperature profile derived from seismic data is relatively similar to the temperature profile based on CTD data. Temperature from seismic data is smaller than CTD with the difference is 0.19 °C. This difference was caused by vertical sampling, CTD data was sampled each 1 m depth, while the sound velocity by seismic data is extracted by 10 m. According to [14], reflection seismic method is sensitive to the vertical sound velocity rather that the value of sound velocity itself. The propagation time is sensitive to average sound velocity but reflection amplitude is sensitive to vertical changes. Synthetic seismogram is used to see the correlation between CTD and seismic data. Density and sound velocity form the function of reflection coefficient to be convolved with wavelet. Density of Sulawesi Sea was 1021-1031 kg/m^3 and does not vary much to depth. Acoustic impedance in Sulawesi Sea is more influenced by sound velocity, while the sound velocity is more influenced by temperature. According to figure 10, salinity changes affect the change of synthetic seismogram character at 100-200 m depth, while temperature changes affect the change of synthetic seismogram character at 100-600 m depth. [15] estimates that reflection seismic derived from 90-95% sound velocity and 5-10% density and the contribution of temperature is 80% while salinity is 20%. [8] is also mention that the contribution of temperature is 83% and salinity is 17%.

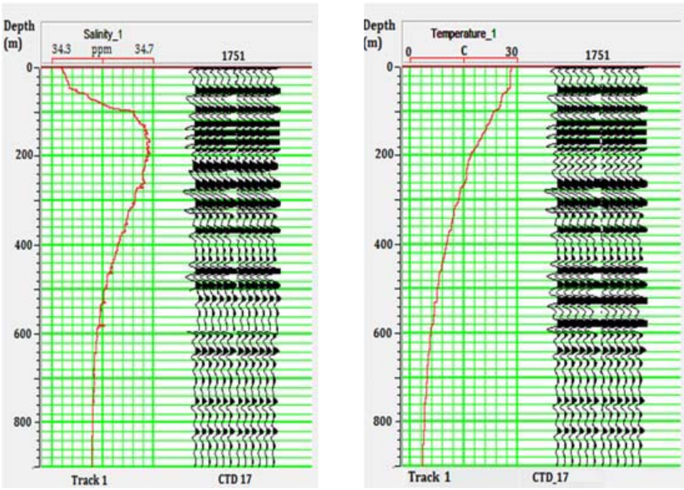


Figure 9. Synthetic trace of CTD data based on temperature and salinity profile.

Acoustic impedance profile is obtained by seismic inversion using seismic data as an input and log CTD data as control to invert into reflectivity data [16]. The impedance layers are essentially describe the thermohaline structures. Acoustic impedance is Sulawesi Sea ranged from 1.529-1.578 MRy. In figure 11, acoustic impedance at 0-400 m depth is relatively high that is characterized by blue-purple impedance color, while in the deeper layer (>500 m depth) the acoustic impedance weakens that is characterized by yellow impedance color. The layers with weak acoustic impedance is caused by a decrease in temperature and salinity [10].

The function of the reflection coefficient is convolved with the wavelet to form a synthetic seismogram. According to [3], wavelet consists of many components including source signature, recording filter, surface reflection, and geophone response. In this research, wavelet is formed from zero phase wavelet corrected their amplitude against seismic data. The resulting wavelet has length of 200 ms, taper length of 25 ms, sample rate of 2 ms, phase rotation 00 and constant phase. This synthetic seismogram is matched wth seismic data or composite trace to obtain good correlation. The final synthetic seismogram has length wavelet of 150 ms, taper length of 20 ms, and sample rate of 2 ms (figure 12). Synthetic seismogram is represent by red trace over seismic trace around the CDT location. The correlation between field seismic and synthetic seismic using CTD 17 and CTD 20 respectively is 0.731 and 0.72. This value indicateds a good or close relationship.

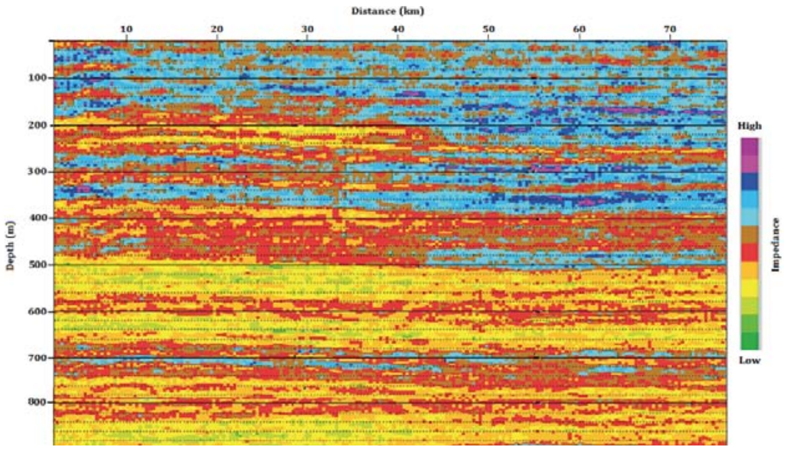
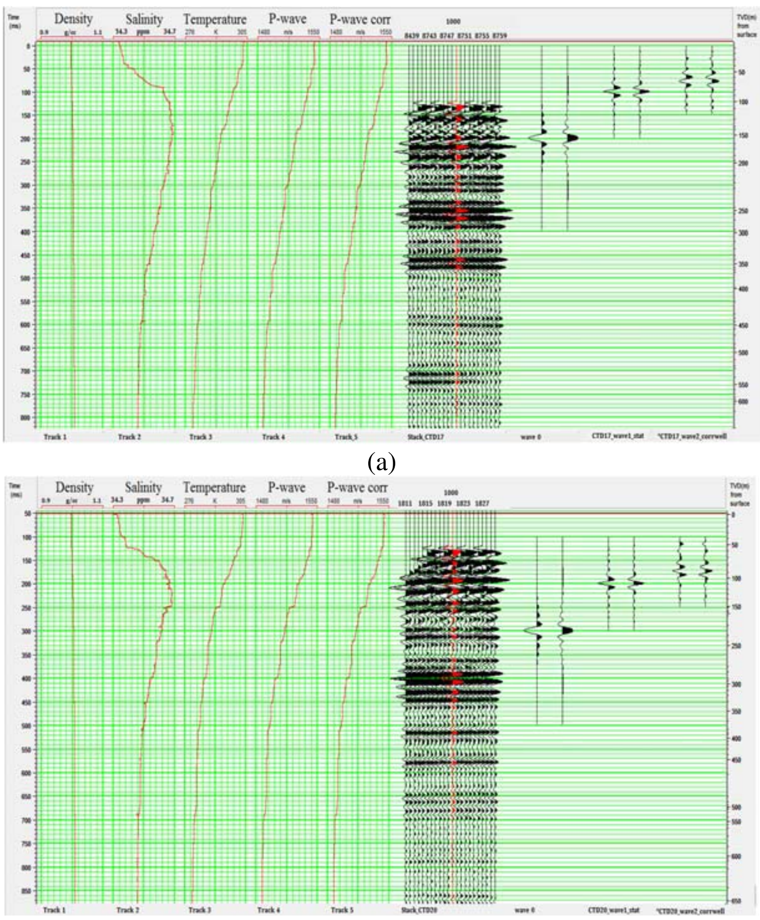


Figure 10. Acoustic impedance in Sulawesi Sea.



(a)

(b)

Figure 11. Synthetic seismogram (red curve) overlaid over seicmic data and log CTD data in Sulawesi Sea derived from (a) CTD 17; and (b) CTD 20.

4. Conclusion

Seismic reflection method was used to identify water column stratification. The seismic profile indicate the presence of internal wave and water mass front caused by encountering of two water mass with temperature and salinity distinc. Temperatur Sulawesi based on CTD data is ranged 4.7-30.3 °C while the temperature derived from seismic data is 4.49-30.29 °C. Correlation between syntetic seismogram of CTD data and seismic data is 0.7.

Acknowledgement
Acknowledgement delivered to Marine Geological Institute of Indonesia in Bandung for the data access and data processing permission in Seismic Laboratory.

References

[1] Nakamura Y T, Noguchi T, Tsuji S, Itoh H, Niino and Matsuoka 2006 Simultaneous seismic reflection and physical oceanographic observations of oceanic fine structure in the Kuroshio extension front *Geophys. Res. Let*. **33** L23605
[2] Hasanudin M 2005 Teknologi seismik refleksi untuk eksplorasi minyak dan gas *Oceana* **30** 1-11
[3] Yilmaz Q 2001. *Seismic Data Analysis: Processing, Inversion, and Interpretation of Seismik Data Vol I, Invest. Geophys 2nd ed.* (Tulsa: Society of Exploration Geophysis)
[4] Song H, Pinheiro L M, Ruddick B and Huang X 2012 Seismic oceanography: a new geophysical tool to investigate the thermohaline structure of the oceans, In: Marcelli, M., editor. *Oceanography*; 2012 Maret 23; Rijeka, Croatia (Rijeka: Intech) p 113-128
[5] Nandi P, Holbrook W S, Piramo S, Pearse and Schmitt R W 2004 Seismic reflection imaging of water as boundaries in the Norwegian Sea *Geophys. Res. Lett.* **31** L23311
[6] Holbrook W S, Fer I and Schmitt R W 2009 Images of internal tides near the Norwegian continental slope *Geophys. Res. Let.* **36** L00D10 doi: 10.1029/2009GL038909
[7] Buffett G G 2011 Seismic Oceanography: a new tool to characterize physical oceanographic structures and processes [tesis] (Barcelona: Universitat de Barcelona)
[8] Ruddick B, Song H B, Dong C Z and Pinheiro L 2009 Water column seismic image as maps of temperature gradient *Oceanography* **22**(1) 192-205
[9] Holbrook W S, Parametero P, Pearse S and Schmitt R W 2003 Thermohaline fine structure in an oceanographic front from seismic reflection profiling *Science* **301** 821-824
[10] Sinha S K, Dewangan P and Sain K 2016 Acoustic reflections in the water column of Krishna-Godavari offshore basin, Bay of Bengal *J. Acoust. Soc. Am.* **139** 2424-2431
[11] Fortin F J W and Holbrook W S 2009 Sound speed requirements for optimal imaging of seismic oceanography data *Geophys. Res. Let*. **36** 1-6 doi: 10.1029/2009GL038991
[12] Holbrook W S, and Fer I 2005 Ocean internal wave spectra inferred from seismic reflection transects. *Geophysical Research Letters* **32** L023733
[13] Wyrtki K 1961 *Physical Oceanography of Southeast Asian Waters. Naga Report 2* (La Jolla: University of California)
[14] Fer I, and Holbrook W S 2008 Seismic reflection methods for study of the water column. *Encyclopedia of Ocean Sciences* **00799** 1-11
[15] Biescas B, Sallares V, Pelegri J L, Machin F, Carbonell R, Buffet G, Andobeitia J J and Calahorrano A 2008 Imagine meddy finestructure using multichannel seismic reflection data *Geophys. Res. Lett*. **35** L11609 doi:10.1029/ 2008GL033971
[16] Sukmono S 2007 *Advance Seismic Methods for Field Exploration & Developments.* (Bandung: Institut Teknologi Bandung)