Study of P and S Wave Quality Factor ($Q_\alpha$ and $Q_\beta$) Around Mt. Jailolo

Emi Ulfiana1,*, Wandono2, Dimas Sianipar2 and Nova Heryandoko3

1Stasiun Geofisika Denpasar, Badan Meteorologi Klimatologi dan Geofisika, Denpasar, Indonesia
2Sekolah Tinggi Meteorologi Klimatologi dan Geofisika, Badan Meteorologi Klimatologi dan Geofisika, Badan Meteorologi Klimatologi dan Geofisika, South Tangerang, Indonesia
3Pusat Gempabumi dan Tsunami, Badan Meteorologi Klimatologi dan Geofisika, Jakarta, Indonesia
*Email: emi.ulfiana@bmkg.go.id

Abstract: Mt. Jailolo is a B type volcano that has never erupted after 1600. Seismic activities around Mt. Jailolo have never been recorded until the swarm in November 2015. Several studies have been done to determine the cause of the swarm, but it is not certain whether the cause of the swarm is tectonic or volcanic activities. The study of attenuation characteristics has never been carried out in the area around Mt. Jailolo. Attenuation characteristics are important to provide the medium information which seismic waves pass through and it can also be applied to the volcanic areas as preliminary disaster mitigation. The main objective of this study is to analyze attenuation characteristics often expressed by Quality factor (Q-factor) of P and S seismic wave ($Q_\alpha$ and $Q_\beta$), which are inversely proportional to attenuation factor (1/Q). Calculations of $Q_\alpha$ and $Q_\beta$ are obtained using coda normalization method. The study area location is around Mt. Jailolo at 127.3° - 127.6°E and 0.9° - 1.2° N. Data have been collected with 12 Short Period temporary 7G sensors network belongs to GFZ and BMKG. This study uses 147 swarm events from the sensors with a threshold magnitude of Mw< 5.0, during April 2017. The study obtains $Q_\alpha(f) = 9.61814f^{1.22843}$ and $Q_\beta(f) = 19.10690f^{1.22843}$. The current analysis concludes that the attenuation beneath Mt. Jailolo corresponds to the volcanic swarms which may have been triggered by its deeper layer’s magmatic activity.

Keywords: Q-factor of P and S wave, attenuation, Mt. Jailolo

1 INTRODUCTION

The tectonic of Halmahera is affected by the double subduction of the Maluku Sea, which is a coalition area between the Halmahera Arc and the Sangihe Arc-North Sulawesi (Hamilton, 1979). The complex tectonic conditions cause Halmahera Island to be included in an area with high seismicity activities. Halmahera Island is surrounded by many volcanoes, including Mt. Jailolo which is located in the middle of the Halmahera volcanic arc. Mt. Jailolo is a B type volcano that has not yet experienced a magmatic eruption after 1600, but is having symptoms of activities such as solfatara. Even though it has been categorized as an inactive volcano, this volcano has the potential to erupt. There are no further records of seismic activities around Mt. Jailolo for the period of 40 years until the swarm activities in November 2015 (Figure 1). Swarm activities have been dormant since February 2016, then it has fluctuated again from 2017 to the present.

Several studies about the Jailolo’s swarm activities have been done previously. Putri et al. (2016) have relocated and calculated the b-value of 96 earthquakes that occurred around the Jailolo area for the period November - December 2015. The results showed that volcanic activities were indicated by the b-value ± 1. The results are supported by field observations of several fractures in the Galala and Gueria areas with high b-values.

Wulandari (2017) has relocated hypocenters using the
A describes an amplitude spectrum the medium of the wave passes through. Bath (1974) de-
propagation. The attenuation depends on the source and the tectonic or volcanic acitivities.
understand about its swarm’s origin, whether it comes from ticular Mt. Jailolo attenuation characteristics study aims to going magma intrusion from the upper mantle pushed the face that interpreted as the remnant of magma intrusion. The study concludes that the swarm’s origin was the on-
certain depth, which is considered a magma chamber in the volcanic areas. Low Vp values were also found on the surface that interpreted as the remnant of magma intrusion. The study concludes that the swarm’s origin was the on-
going magma intrusion from the upper mantle pushed the weak patches of igneous rock in the lower crust. This particular Mt. Jailolo attenuation characteristics study aims to understand about its swarm’s origin, whether it comes from the tectonic or volcanic activities.

Attenuation is the seismic wave energy loss during wave propagation. The attenuation depends on the source and the medium of the wave passes through. Bath (1974) describes an amplitude spectrum $A_{ij}(f)$ observed at station $j$ for event $i$ in Equations 1 and 2

$$A_{ij}(f) = G_{ij}K_i(f)S_j(f)I_j(f)\exp(-\pi f t^*_{ij})$$  \hspace{1cm} (1)$$

$$t^*_{ij} = D_{ij}/Q_v$$  \hspace{1cm} (2)

Where :
$G_{ij}$ : parameter of geometrical spreading on a medium with 1/$D_{ij}$
$D_{ij}$ : distance between events $i$ with station $j$.
$K_i(f)$ : source event $i$
$S_j(f)$ : site response
$I_j(f)$ : instrument transfer function
$t^*_{ij}$ : amount of attenuation during propagation along the propagation $i - j$

$Q$ : average quality factor at propagation $D_{ij}$
$v$ : average wave velocity.

Attenuation decay is inversely proportional to the Q-factor. Q-factor is a dimensionless parameter used to measure attenuation in an area (Knopoff, 1964). Q-factor $2\pi/Q = -\Delta E/E$ where $\Delta E$ is the energy loss in one cycle, while $E$ is the total energy in a harmonic wave. Attenuation is directly related to the composition of the earth’s layers. The Q-factor value can identify variations in the rock properties and also provide information on the fluid content or permeability variation. Higher porosity and Vp/Vs exhibit greater attenuation or lower Q-factor value. P waves attenuate faster than S waves because of the difference in absorption between longitudinal and transverse waves by the geological medium factor. Therefore, the Q-factor of P wave is generally smaller than S wave, or $Q_p/Q_s > 1$, which is common in areas with complex tectonics (Kumar et al., 2016). The seismic wave attenuation in volcanic area on the other hand is influenced by the degree of melting and fractures (caused by thermal cracking), as well as critical or super critical hydro thermal fluid conditions. Low Q-factor value is usually associated with systems of fluid filled fractures or partial melts and magma chambers. The high rate of cracking, i.e. the presence of melt or fluid in the fractures will create lower $Q_a$ and $Q_b$ values, or attenuation will occur more quickly (Giampiccolo et al., 2007).

Attenuation characteristics studies have the potential to improve the understanding of the physical properties of layered medium through which have been passed through by the seismic waves. Such understanding can also be applied to the volcanic areas, where rock’s elasticity changes significantly before the volcanic eruption (Bianco et al., 1999). The attenuation study in the area around Mt. Jailolo is therefore carried out as a first step in mitigating volcanic disasters.

2 DATA AND METHODS

2.1 Data

This study area is located around Mt. Jailolo at 127.3° - 127.6° E and 0.9° - 1.2° N. The data are collected from 12 Short Period temporary sensors (Table 1), which have been deployed by the collaboration between GFZ and BMKG (7G Network). This study uses only 147 swarm events with a magnitude of Mw< 5.0 recorded during April 2017 (Figure 2).

2.2 Normalization method

Calculation of $Q_a$ and $Q_b$ is based on the coda normalization method by Aki (1979) and Yoshimoto et al. (1993). This method has been applied by Sharma et al. (2008), Kumar et al. (2016), and Predein et al. (2017). The amplitude of the coda wave spectra recorded on a seismogram is represented by Equation 3 (Aki, 1979). The coda spectra amplitude is a combination of the source spectra amplitude $S(f)$, coda excitation factor $P(f,t_e)$, site amplification factor $G(f)$, and instrument response $I(f)$. The estimated $Q_a$ and $Q_b$ values have been obtained by normalizing the P wave and the S wave amplitudes from the coda spectra amplitude at a
specifying lapse time. For the local earthquakes recorded at a distance of R < 100 km, the amplitude of the coda spectra at the lapse time (calculated from the origin time) which is greater than 2 times the travel time of the S wave is proportional to the amplitude of the S wave spectra. Thus, the normalization of the S-wave spectra by the coda wave, allows elimination of the effects of source, site, and instrument responses (Yoshimoto et al., 1993; Sharma et al., 2016). The normalization of the S wave spectra amplitude by the coda spectra is shown in Equation 5.

\[ A_c(f, t_c) = S(f)P(f, t_c)G(f)I(f) \]  

\[ \ln \left\{ \frac{A_p(f, r)}{A_c(f, t_c)} \right\}_{(r \pm \Delta r)} = -\frac{\pi f}{Q_p(f)V_p} r + \text{const}(f), \]  

\[ \ln \left\{ \frac{A_s(f, r)}{A_c(f, t_c)} \right\}_{(r \pm \Delta r)} = -\frac{\pi f}{Q_s(f)V_s} r + \text{const}(f), \]  

Where:
- \( A_{p,s}(f, r) \) : amplitude spectra of P and S waves at a distance \( r \)
- \( Q_{p,s} \) : Q-factor of P and S waves
- \( V_{p,s} \) : average velocity of the P and S waves

Yoshimoto et al. (1993) have applied similar way for the P wave. The first assumption of coda normalization states that the energy of the coda wave is uniformly distributed around the source. The second assumption states that the coda is the result of the scattering of the S wave (Kumar et al., 2016; Predein et al., 2017). With this first assumption, P and S wave radiations have the same spectra ratio in a certain magnitude range and/or frequency range (Predein et al., 2017; Kumar et al., 2016). This allows for the same normalization of the P-wave spectra amplitude. The amplitude of the P and S wave spectra (\( A_p \) and \( A_s \)) is divided by the amplitude of the coda spectra \( A_c \) (Equations 6 and 5). In Equations 4 and 5, by making a linear regression relationship between \( \ln \left\{ \frac{A_p(f, r)}{A_c(f, t_c)} \right\}_{(r \pm \Delta r)} \) with \( r \) for P waves and \( \ln \left\{ \frac{A_s(f, r)}{A_c(f, t_c)} \right\}_{(r \pm \Delta r)} \) with \( r \) for S waves, we get a slope that represents \(-\pi f/(Q_p(f)V_p)\) for P waves and \(-\pi f/(Q_s(f)V_s)\) for S waves. Thus, calculations of \( Q_p \) and \( Q_s \) can be estimated according to Equations 6 and 7. The P and S wave velocity values use the 1-Dimensional local velocity model of the Halmahera region, with an average velocity of up to a depth of 60 km. \( V_p \) 6.46 km/s and \( V_s \) 3.81 km/s (Sipayung et al., 2017). Through Equation 8 for each station, the dependence of Q-factor on frequency can be estimated, where \( Q_0 \) is Q-factor at f 1 Hz and \( n \) is the frequency dependence factor (Sharma et al., 2016).

\[ Q_\alpha = -\frac{\pi f}{\text{Slope} \times V_p} \]  

\[ Q_\beta = -\frac{\pi f}{\text{Slope} \times V_s} \]  

\[ Q = Q_0 f^n \]  

The calculation of \( Q_\alpha \) and \( Q_\beta \) with this method has
been using one of the 3 components of the seismogram; vertical (Z), horizontal N-S, or horizontal E-W. The value of Q-factor will be almost the same for the 3 components, and this study using the horizontal E-W component. The filter used in this study is Butterworth band-pass at 5 center frequencies (Table 2) which is obtained from a specified lower and upper frequency limit (Low cut-off and High cut-off). The choice of frequency limit value depends on the type of sensor type. This study uses a Short Period sensor with a sampling rate of 200 Hz.

3 RESULTS AND DISCUSSIONS

The results of processing using CodaNorm software which will be explained with various analysis, including: $Q_\alpha$ and $Q_\beta$ versus distance graph, dependence $Q_\alpha$ and $Q_\beta$ to the frequency, ratio and comparison of $Q_\alpha$ and $Q_\beta$ in high tectonic areas with volcanic areas.

3.1 $Q_\alpha$ and $Q_\beta$ versus distance

The values of $Q_\alpha$ and $Q_\beta$ are inversely related to the hypocenter distance. The further away from the source, the smaller the value of $Q_\alpha$ and $Q_\beta$ or the attenuation will be greater (Figure 4). This statement applies to the distances $<100$ km (Figure 3), consistent with the statement of Yoshimoto et al. (1993). Therefore, in this study only earthquakes with a distance of $R<100$ km are used. The results of using $R>100$ km in the calculation of $Q_\alpha$ and $Q_\beta$ are not linear and will affect the regression slope inconsistency.

3.2 $Q_\alpha$ and $Q_\beta$ versus frequency

The value of $Q_\alpha$ varies from 2.6486 at 1 Hz to 565.3099 at 24 Hz, while $Q_\beta$ variation is between 7.0677 at 1 Hz to 898.8078 at 24 Hz. The Q-factor value is closely related to frequency. Higher frequency exhibits higher Q-factor or smaller attenuation. The results of Q-factor calculations based on the 12 sensors are shown in Table 3. The estimated values of $Q_\alpha$ and $Q_\beta$ at varying frequencies indicate increase with the increasing frequency. The results of the study are consistent with the $Q(f)$ of the other seismically active areas, such as those in Kanto, Japan (Yoshimoto et al., 1993), Garda, Italy (Castro et al., 2008), France (Campillo and Plantet, 1991), and the Lower Siang region, India (Sharma et al., 2016). The analysis indicates 99% correlation for $Q_\alpha$ versus $f$ and 93% for $Q_\beta$ versus $f$ (Figure 5). These correlation values are strong (Sugiyono, 2014) with $Q_\beta$ which is always greater than $Q_\alpha$. The dependence of $Q_\alpha$ and $Q_\beta$ versus $f$ is assessed using $n$ (Equation 8). The value of $n$ can represent the heterogeneity and elasticity of a rock or medium through which the waves pass. The higher $n$ values, the higher frequency dependencies. In this case, the scattering attenuation has been dominant compared to the intrinsic attenuation because $Q_\alpha$ is independent of frequency, while $Q_\beta$ is frequency-dependent (Giampiccolo et al., 2007).

Jailolo region has $n$-value that varies at each station, the variation of $n$ for $Q_\alpha(f)$ ranges from 0.9 to 1.3 and $Q_\beta(f)$ ranged from 0.89 to 1.6 (Table 4). However, in general $n_\alpha$ 1 for $Q_\alpha(f)$ and $Q_\beta(f)$, only $Q_\alpha(f)$ at SP14 and $Q_\beta(f)$ at SP04 which has a value of $n<1$, it was 0.9 and 0.89. However, the smallest $n$ in SP04 and SP14 is still close to 1. This illustrates that the Jailolo region is an area with high heterogeneity, which is likely to be dominated by scattering attenuation, as a result of the complex tectonic arrangement in the area, including volcanic areas composed of high heterogeneity structure (Giampiccolo et al., 2007).
results have not provided evidence of the magma or fluid intrusion. Mt. Jailolo’s case has been related with the Mt. Etna eruption activity areas, Lower Siang (Kumar et al., 2016) and volcanic areas, Mt. Etna (Giampiccolo et al., 2007).

In this study, a comparison of $Q_\alpha(f)$ and $Q_\beta(f)$ for the Jailolo region with tectonic activity areas, Lower Siang (Kumar et al., 2016) and volcanic areas, Mt. Etna (Giampiccolo et al., 2007) has conducted his research on Mt. Etna with the results indicated $Q_\beta/Q_\alpha > 1$, as well as $Q_\beta/Q_\alpha < 1$ for several sensors from summit crater where magma is present. The latter case has been related with the Mt. Etna eruption activities during 2001 and 2002-2003. Mt. Jailolo’s $Q_\beta/Q_\alpha > 1$ results have not provided evidence of the magma or fluid presence at the shallow depth. Large attenuation in the S wave or $Q_\beta/Q_\alpha < 1$ would indicate fluid-filled fractures. Wirbo (2017) explains that magma intrusion could occur at a deeper level resulting lower Vp value. Meanwhile, higher Vp values were found at shallow depths near the surface could be related with the igneous rocks from the previous magma intrusion.

In this study, a comparison of $Q_\alpha(f)$ and $Q_\beta(f)$ was also carried out for the study area with the Mt. Etna volcanic area and the Lower Siang tectonic area. The results of the comparison show that $Q_\alpha(f)$ and $Q_\beta(f)$ for the area around Mt. Jailolo are similar to Mt. Etna (Figure 6). $Q_\alpha(f)$ and $Q_\beta(f)$ were lower for volcanic areas compared to tectonic areas. $Q_\alpha(f)$ and $Q_\beta(f)$ values are approaching Mt. Etna’s.

### Table 3. Q-factor of P and S wave at the center frequency for each station.

| Station | $Q_\alpha$ | $Q_\beta$ | $Q_\alpha$ | $Q_\beta$ | $Q_\alpha$ | $Q_\beta$ | $Q_\alpha$ | $Q_\beta$ | $Q_\alpha$ | $Q_\beta$ |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| SP04    | 6.7566    | 17.1869   | 17.5718   | 39.9070   | 35.3277   | 70.7042   | 111.0228  | 185.7770  | 258.6853  | 486.6495  |
| SP05    | 2.6486    | 7.0677    | 9.2719    | 71.6972   | 25.6577   | 269.3616  | 71.1477   | 206.5948  | 114.6782  | 198.8020  |
| SP06    | 6.4562    | 8.7320    | 24.1797   | 28.9662   | 48.1283   | 68.9966   | 89.0818   | 150.9989  | 146.2591  | 256.4265  |
| SP10    | 8.9626    | 22.3649   | 55.4554   | 115.2906  | 115.4859  | 206.8063  | 141.1143  | 265.6382  | 229.1707  | 427.9944  |
| SP12    | 8.5623    | 18.1255   | 35.7621   | 91.4641   | 78.0894   | 187.1519  | 140.6096  | 303.7841  | 266.0560  | 561.9514  |
| SP13    | 9.9321    | 19.6745   | 31.0082   | 100.0063  | 93.9034   | 257.3234  | 154.1021  | 392.1003  | 258.3103  | 489.4117  |
| SP14    | 10.7696   | 19.5905   | 25.3566   | 60.8946   | 55.3766   | 115.0786  | 164.8744  | 266.8001  | 243.4497  | 397.6082  |
| SP15    | 8.9603    | 16.3772   | 28.9895   | 68.6116   | 54.2006   | 197.2510  | 111.7211  | 395.6656  | 258.3103  | 489.4117  |
| SP16    | 13.9642   | 31.5853   | 64.3204   | 199.1103  | 115.7752  | 254.0483  | 184.6965  | 303.5193  | 318.1961  | 478.2494  |
| SP20    | 13.6188   | 24.5075   | 61.3662   | 177.1301  | 101.9376  | 371.5820  | 205.9727  | 489.7776  | 278.4433  | 529.3255  |
| SP27    | 15.1027   | 23.4737   | 87.2375   | 194.8726  | 212.0059  | 287.3677  | 205.9727  | 282.1009  | 323.4802  | 424.0456  |
| SP29    | 9.6748    | 20.5973   | 34.2188   | 95.4872   | 69.7384   | 281.5347  | 156.9704  | 487.9292  | 282.4914  | 641.7681  |
| Average | 9.6181    | 19.1069   | 39.5728   | 103.6223  | 83.8022   | 213.9341  | 142.6278  | 310.3867  | 247.6178  | 451.1218  |

### Table 4. $Q_\alpha(f)$ and $Q_\beta(f)$ at each station.

| Station | $Q_\alpha(f)$ | $Q_\beta(f)$ |
|---------|---------------|--------------|
| SP04    | 6.7566f1.44686 | 17.1869f0.89103 |
| SP05    | 2.6486f1.22496 | 7.0678f0.63429 |
| SP06    | 6.4562f1.10028 | 8.73197f0.11416 |
| SP10    | 8.9626f1.13049 | 22.36489f0.16470 |
| SP12    | 8.5623f1.18567 | 18.12545f0.24783 |
| SP13    | 9.93207f1.10281 | 19.6745f0.28752 |
| SP14    | 10.76961f0.94312 | 19.59051f0.0466 |
| SP15    | 8.96029f1.03604 | 16.37723f0.26087 |
| SP16    | 13.96419f1.14835 | 31.58530f0.515128 |
| SP20    | 13.61880f1.12066 | 24.50745f0.37246 |
| SP27    | 15.10267f1.27770 | 23.47376f0.30952 |
| SP29    | 9.67478f1.12981 | 20.59735f0.30287 |
| Average | 9.61814f1.12981 | 19.10696f0.22843 |

### Figure 5. Graph of the correlation between $Q_\alpha$ (blue) and $Q_\beta$ (orange) versus frequency

### Figure 6. Comparison $Q_\alpha(f)$ and $Q_\beta(f)$ Jailolo region with tectonic activity areas, Lower Siang (Kumar et al., 2016) and volcanic areas, Mt. Etna (Giampiccolo et al., 2007)
4 CONCLUSION

Jailolo region’s \(Q_\alpha\) and \(Q_\beta\) decrease with distance with high frequency dependence with frequency \(n \geq 1\). The high frequency dependence shows high heterogeneity, indicated with the equations: 

\[ Q_\alpha(f) = 9.61814f^{-0.12981} \]  

and 

\[ Q_\beta(f) = 19.10690f^{-1.2843} \] 

\( Q_\alpha(f) \) and \( Q_\beta(f) \) in this study have close proximity to the volcanic area, such as Mt. Etna. The attenuation in the area around Mt. Jailolo is almost close to the volcanic area of Mt. Etna and has a greater value than the tectonic area. This can be explained by the increasing pressure of fluid or magma which may have been triggered by its deeper layer’s magmatic activity. Further interpretation of Q-factor variation with depth has been recommended to complement this study to support Wibowo (2017)’s Vp tomography study, which results a lower Vp at the deeper level would indicate magma intrusion-related swarms.

ACKNOWLEDGMENTS

The authors thank GFZ and BMKG for the waveform data. We thank you Predein et al. for providing the CodeNorm software (Predein et al., 2017) and we also thank the reviewers for their comments and suggestions that helped the authors to improve the quality of this work.

References

Aki, K. (1979): Attenuation of shear waves in the lithosphere for frequencies from 0.05 to 25 Hz. Physics of the Earth and Planetary Interiors, 21, 50–60.

Bath, M. (1974): Spectral Analysis in Geophysics: Developments in Solid Earth Geophysics. Elsevier Science Publishing Co.

Bianco, F., Castellano, M., Pezzo, E.D. and Ibanez, J.M. (1999): Attenuation of short-period seismic waves at mt vesuvius, italy. Geophysical Journal International, 138, 67–76.

Campillo, M. and Plantet, J. (1991): Frequency dependence and spatial distribution of seismic attenuation in France: experimental results and possible interpretations. Physics of the earth and planetary interiors, 67(1-2), 48–64.

Castro, R.R., Massa, M., Auglieri, P. and Pacor, F. (2008): Body-wave attenuation in the region of Garda, Italy. Pure and applied geophysics, 165(7), 1351–1366.

Giampiccolo, E., D’Amico, S., Patané, D. and Gresta, S. (2007): Attenuation and source parameters of shallow micro-earthquakes at Mt. Etna volcano, Italy. Bulletin of the Seismological Society of America, 97, 184–197.

Gunawan, E. et al. (2016): Field investigation of the november to december 2015 earthquake swarm in west Halmahera, Indonesia. Geotechnical and Geological Engineering, 35, 425–432.

Hamilton, W.B. (1979): Tectonics of the Indonesian region. Tech. rep., doi:10.3133/pp1078.

Knopoff, L. (1964): Q. Review of Geophysics, 2, 625–660.

Kumar, R., Gupta, S., Singh, S.P. and Kumar, A. (2016): The attenuation of high-frequency seismic waves in the lower siang region of arunachal himalaya: \(q_\alpha\), \(q_\beta\), \(\beta\), and \(\alpha\). Bulletins of the Seismological Society of America, 106, 1407–1422.

Passarelli, L. et al. (2018): Magmatic or Not Magmatic? The 2015-2016 Seismic Swarm at the Long-Dormant Jailolo Volcano, West Halmahera, Indonesia. Frontiers in Earth Science, 6, 79.

Predein, P.A., Dobrynina, A.A., Tubanov, T.A. and German, E.I. (2017): Codanorm: A software package for the body-wave attenuation calculation by the codanormalization method. SoftwareX, 6, 30–35, ISSN 2352-7110, doi:https://doi.org/10.1016/j.softx.2016.12.004.

Putri, Y.T. et al. (2016): Relokasi dan Distribusi b-Value Gempabumi Swarm Jailolo-Halmahera Barat. Jurnal Meteorologi dan Geofisika, 17, 199–206.

Sharma, B., Gupta, A.K., Devi, D.K., Kumar, D., Teotia, S. and Rastogi, B. (2008): Attenuation of high-frequency seismic waves in kachchh region, gujarat, india. Bulletin of the Seismological Society of America, 98(5), 2325–2340.

Sharma, K., Bala, R., Kumar, A. and Kumar, R. (2016): Matlab codes (q body) to study attenuation of seismic body-waves. International Journal of Advance Research, 4, 107–117.

Sipayung, R., Sianipar, D., Agus, R.N. and Sriyanto, S.P.D. (2017): Estimasi model kecepatan lokal gelombang p dan s satu dimensi (1-d) wilayah Halmahera. Physics and its Applied National Conference 2017.

Sugiyono (2014): Metode Penelitian Pendidikan dan Penelitian. Kualitatif, Kuantitatif, and R&D. Alfabeta.

Wibowo, B.A. (2017): Tomografi Struktur Kecepatan Gelombang Seismik Menggunakan Data Gempabumi Swarm di Wilayah Jailolo, Halmahera Barat. Ph.D. the-

Table 5. Value ratio \(Q_\beta/Q_\alpha\) at each station.

| Station | \(Q_\beta/Q_\alpha\) (1 Hz) | \(Q_\beta/Q_\alpha\) (3 Hz) | \(Q_\beta/Q_\alpha\) (6 Hz) | \(Q_\beta/Q_\alpha\) (12 Hz) | \(Q_\beta/Q_\alpha\) (24 Hz) |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|
| SP04    | 2.534737        | 2.279378475     | 2.601384358     | 1.673230554     | 1.88124188     |
| SP05    | 2.6884765       | 7.732721482     | 10.49826659     | 2.819412528     | 1.733564101    |
| SP06    | 1.3324871       | 1.1991968       | 1.43660512      | 1.695060982     | 1.75234177     |
| SP10    | 2.495353        | 2.075271039     | 1.790749852     | 1.882437666     | 1.867579458    |
| SP12    | 2.1168844       | 2.557572683     | 2.396635336     | 2.159139179     | 2.112154651    |
| SP13    | 1.9809066       | 3.225159906     | 2.740298366     | 2.544120789     | 2.066785033    |
| SP14    | 1.8190553       | 2.401525178     | 2.078108068     | 1.86205253     | 1.633225261    |
| SP15    | 1.8259215       | 2.366775248     | 3.639277987     | 3.54156151      | 1.894666248    |
| SP16    | 2.2618779       | 3.095596129     | 2.194324197     | 1.644142465     | 1.5039001916   |
| SP20    | 1.799531        | 2.86442914      | 3.645192532     | 2.717622222     | 1.901074054    |
| SP27    | 1.5542723       | 2.2326959287    | 1.355470079     | 1.36903914      | 1.310885564    |
| SP29    | 2.1289629       | 2.790491709     | 4.037126685     | 3.108415577     | 2.271814922    |
| Average | 2.052474031     | 2.556964961     | 2.859400067     | 2.095941555     | 1.783615948    |
sis, Universitas Indonesia.
Wulandari, A. (2017): Relokasi Hiposenter Gempabumi Mikro di Wilayah Jailolo, Halmahera Barat. Ph.D. thesis, Sekolah Tinggi Meteorologi Klimatologi dan Geofisika.
Yoshimoto, K., Sato, H. and Ohtake, M. (1993): Frequency-Dependent Attenuation of P and S Waves In the Kanto Area, Japan, Based On the Coda-Normalization Method. *Geophysical Journal International*, **114**(1), 165–174.