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Study of P and S Wave Quality Factor (Q_α and Q_β) Around Mt. Jailolo

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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_α and Q_β), which are inversely proportional to attenuation factor (1/Q). Calculations of Q_α and Q_β 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 $Q_\alpha(f) = 9.61814f^{1.12981}$ 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

Abstrak: Gunung Jailolo merupakan gunungapi tipe B yang belum pernah mengalami eruspi setelah tahun 1600. Aktivitas seismik di sekitar gunung Jailolo belum pernah tercatat hingga terjadinya aktivitas swarm pada November 2015. Beberapa penelitian telah dilakukan untuk mengetahui penyebab dari swarm, namun belum dapat dipastikan apakah kejadian swarm berasal dari aktivitas tektonik atau vulkanik. Penelitian terkait karakteristik atenuasi belum pernah dilakukan di sekitar gunung Jailolo. Karakteristik atenuasi mempunyai peran penting dalam memberikan informasi medium yang dilalui oleh gelombang seismik dan tentunya dapat juga diterapkan pada daerah vulkanik sebagai langkah awal dalam mitigasi bencana gunungapi. Penelitian ini bertujuan untuk menganalisis karakteristik atenuasi menggunakan faktor kualitas gelombang P dan S (Q_α dan Q_β) yang besarnya berbanding terbalik dengan atenuasi (1/Q). Perhitungan Q_α dan Q_β dilakukan menggunakan metode normalisasi koda. Penelitian ini mencakup wilayah di sekitar gunung Jailolo pada koordinat 127,3° - 127,6° BT dan 0,9° - 1,2° LU. Data yang digunakan diperoleh dari hasil rekaman 12 sensor Short Period, yang merupakan kerjasama antara GFZ dan BMKG (Jaringan 7G). Penelitian ini menggunakan 147 kejadian swarm dengan magnitude Mw$< 5,0$ periode April 2017. Penelitian ini memperoleh nilai $Q_\alpha(f) = 9,61814f^{1,12981}$ dan $Q_\beta(f) = 19,10690f^{1,22843}$. Hasil analisis menunjukkan bahwa atenuasi di sekitar gunung Jailolo lebih dekat dengan aktivitas swarm vulkanik yang dapat diakibatkan oleh adanya aktivitas magma di bawah permukaan yang lebih dalam.
Kata kunci: Q-faktor gelombang P dan S, atenuasi, Gunung 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 Guaeria areas with high b-values.

Wulandari (2017) has relocated hypocenters using the

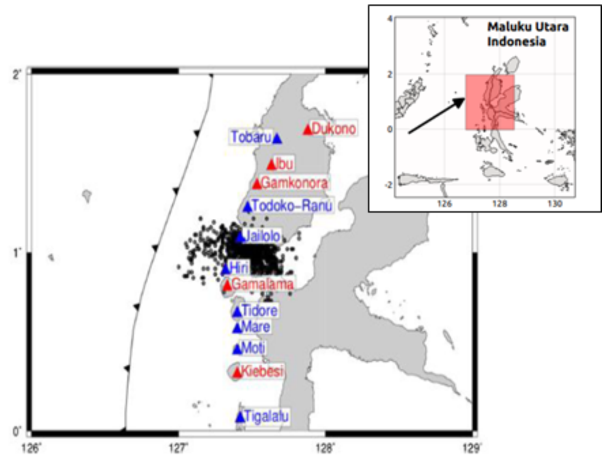

Figure 1. Jailolo swarm activities for the period November-December 2015. The black dots represent the epicenter, while the red and blue triangles show active and inactive volcanoes (Gunawan et al., 2016)

Double Difference method for the period 21 August - 23 October 2016. The results showed that swarm activities were caused by volcanic activities for earthquakes near Mt. Jailolo with shallow depths< 10 km and caused by tectonic activities for earthquakes on the islands of Ternate and Tidore. Passarelli et al. (2018) in their study have stated that the swarm were caused by micro-seismic earthquake activities beneath Mt. Jailolo, the results of the study were more towards magmatic activities despite no indication of magma intrusion was found. Furthermore, Wibowo (2017) with a P wave tomography study has found a low Vp value at a 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 ongoing 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 acitivities.

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

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

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

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 ΔE 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 $Q_\beta/Q_\alpha > 1$, 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_α and Q_β 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_α and Q_β 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 $P(f, t_c)$, site amplification factor $G(f)$, and instrument response $I(f)$. The estimated Q_α and Q_β values have been obtained by normalizing the P wave and the S wave amplitudes from the coda spectra amplitude at a

Table 1. Short period temporary sensor data used in the study.

No.	Sensor Code	Longitude (E)	Latitude (N)	Altitude (m)	Sampling Rate (Hz)	Sensor Location
1	SP04	127.4666	1.0614	20	200	Gufasa
2	SP05	127.4699	1.0841	24	200	Hate Bicara
3	SP06	127.4818	1.1164	26	200	Akediri
4	SP10	127.4921	1.1468	39	200	Aketola
5	SP12	127.4275	1.1098	26	200	Marimabati
6	SP13	127.4141	1,0902	124	200	Idamdehe Gamsungi
7	SP14	127,4276	1.0515	32	200	Payo
8	SP15	127,4989	1,0614	8	200	Todowongi
9	SP16	127,5028	1,0714	31	200	Bukumatiti
12	SP20	127,4899	1,1005	27	200	Tedeng
14	SP27	127.4082	1,0533	11	200	Bobo
15	SP29	127,4199	1,0889	208	200	Idamdehe Gamsungi

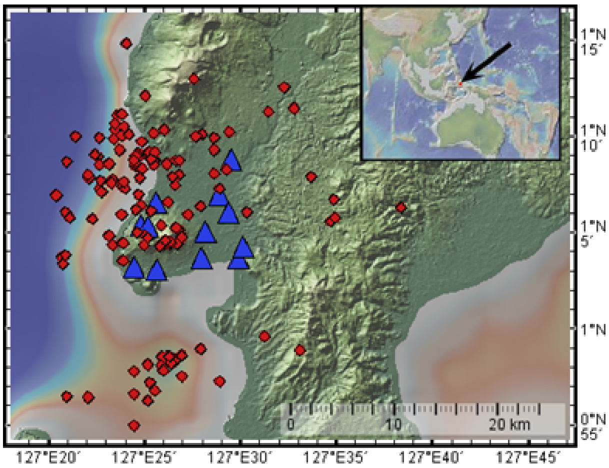

Figure 2. The epicenter distribution of the Jailolo swarm for the period of April 2017. The red circle is the epicenter, while the blue triangle is the temporary short period sensor in collaboration between BMKG and GFZ.

specified 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 wave is shown in Equation 5.

$$A_c(f, t_c) = S(f)P(f, t_c)G(f)I(f) \tag{3}$$

$$\ln\left[\frac{A_p(f,r)r}{A_c(f,t_c)}\right]_{(r\pm\Delta r)} = -\frac{\pi f}{Q_\alpha(f)V_p} r + const(f), \tag{4}$$

$$\ln\left[\frac{A_s(f,r)r}{A_c(f,t_c)}\right]_{(r\pm\Delta r)} = -\frac{\pi f}{Q_\beta(f)V_s} r + const(f), \tag{5}$$

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

Table 2. The components of the bandpass filter center frequency with lower and upper frequency limits

Low cut-off (Hz)	Center frequency (Hz)	High cut-off (Hz)
0.50	1.00	1.50
1.50	3.00	4.50
3.00	6.00	9.00
6.00	12.00	18.00
12.00	24.00	36.00

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 4 and 5). In Equations 4 and 5, by making a linear regression relationship between $\ln\left[\frac{A_p(f,r)r}{A_c(f,t_c)}\right]_{(r\pm\Delta r)}$ with r for P waves and $\ln\left[\frac{A_s(f,r)r}{A_c(f,t_c)}\right]_{(r\pm\Delta r)}$ with r for S waves, we get a slope that represents $-\pi f/(Q_\alpha(f)V_p)$ for P waves and $-\pi f/(Q_\beta(f)V_s)$ for S waves. Thus, calculations of Q_α and Q_β 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, Vp 6.46 km/s and Vs 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).

$$Q_\alpha = -\pi \frac{f}{Slope\, x V_p} \tag{6}$$

$$Q_\beta = -\frac{\pi f}{Slope\, x V_s} \tag{7}$$

$$Q = Q_0 f^n \tag{8}$$

The calculation of Q_α and Q_β with this method has

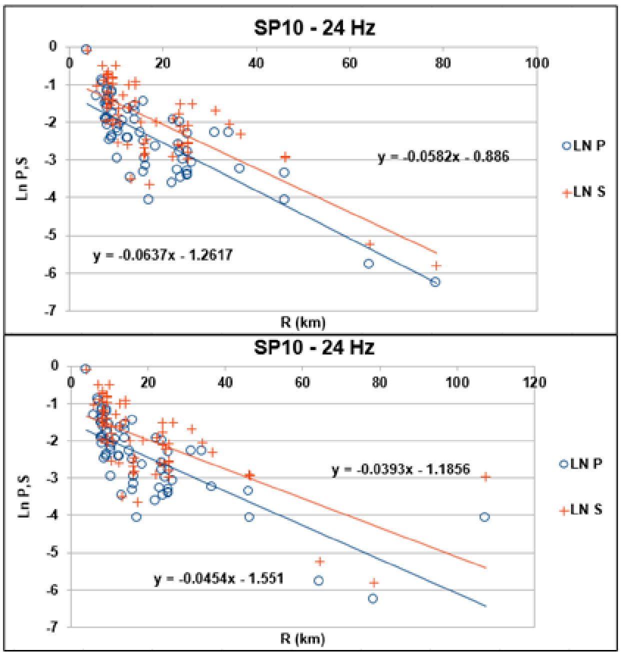

Figure 3. Comparison of Q_α and Q_β for the distance R < 100 km (top) and R> 100 km (bottom) at SP10 station for a frequency of 24Hz. The blue and orange color is the result of normalization for Q_α and Q_β.

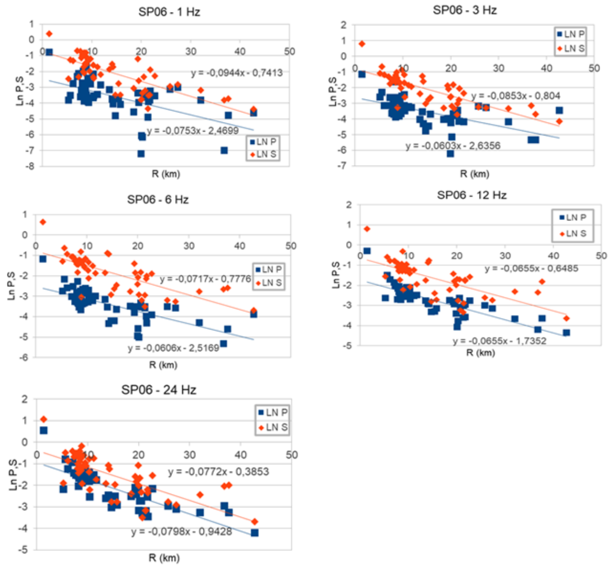

Figure 4. Q-factor versus distance R at SP06 station for 5 center frequencies. All calculations at the center frequencies 1, 3, 6, 12, and 24 Hz, show the same results for association Q_α and Q_β with distance.

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_α and Q_β versus distance graph, dependence Q_α and Q_β to the frequency, ratio and comparison of Q_α and Q_β in high tectonic areas with volcanic areas.

3.1 Q_α and Q_β versus distance

The values of Q_α and Q_β are inversely related to the hypocenter distance. The further away from the source, the smaller the value of Q_α and Q_β 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_α and Q_β are not linear and will affect the regression slope inconsistency.

3.2 Q_α and Q_β versus frequency

The value of Q_α varies from 2.6486 at 1 Hz to 565.3099 at 24 Hz, while Q_β 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_α and Q_β 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_α versus f and 93% for Q_β versus f (Figure 5). These correlation values are strong (Sugiyono, 2014) with Q_β which is always greater than Q_α. The dependence of Q_α and Q_β versus f is assessed using n (Equation 8). The value of n can represent the heterogenity 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_i is independent of frequency, while Q_s is frequency-dependent (Giampiccolo et al., 2007).

Jailolo region has n-value that varies at each station, the variation of n for Q_α(f) ranges from 0.9 to 1.3 and Q_β(f) ranged from 0.89 to 1.6 (Table 4). However, in general n¿ 1 for Q_α(f) and Q_β(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).

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

Freq	1 Hz		3 Hz		6 Hz		12 Hz		24 Hz	
Station	Q_α	Q_β	Q_α	Q_β	Q_α	Q_β	Q_α	Q_β	Q_α	Q_β
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	200.5948	114.6782	198.8020
SP06	6.4562	8.7320	24.1797	28.9962	48.1283	68.9996	89.0818	150.9989	146.2591	256.4265
SP10	8.9626	22.3649	55.5545	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	140.6969	303.7841	266.0560	561.9514
SP13	9.9321	19.6745	31.0082	100.0063	93.9034	257.3234	154.1021	392.0545	252.1933	521.2294
SP14	10.7696	19.5905	25.3566	60.8946	55.3766	115.0786	164.8744	266.8001	243.4497	397.6082
SP15	8.9693	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	184.6065	303.5193	318.1961	478.2494
SP20	13.6188	24.5075	61.3662	177.1301	101.9376	371.5820	180.2228	489.7776	278.4433	529.3255
SP27	15.1027	23.4737	87.2735	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	$6.75656f^{1.01666}$	$17.18692f^{0.89153}$
SP05	$2.64858f^{1.22946}$	$7.06768f^{1.63429}$
SP06	$6.45624f^{1.09028}$	$8.73197f^{1.11416}$
SP10	$8.96261f^{1.30409}$	$22.36488f^{1.16470}$
SP12	$8.56232f^{1.18567}$	$18.12545f^{1.24783}$
SP13	$9.93207f^{1.10281}$	$19.67450f^{1.28752}$
SP14	$10.76961f^{0.94312}$	$19.59051f^{1.00466}$
SP15	$8.96929f^{1.03604}$	$16.37723f^{1.26087}$
SP16	$13.96419f^{1.14835}$	$31.58530f^{1.15128}$
SP20	$13.61880f^{1.12066}$	$24.50745f^{1.37246}$
SP27	$15.10267f^{1.27170}$	$23.47366f^{1.30892}$
SP29	$9.67478f^{1.10883}$	$20.59725f^{1.30287}$
Average	$9.61814f^{1.12981}$	$19.10690f^{1.22843}$

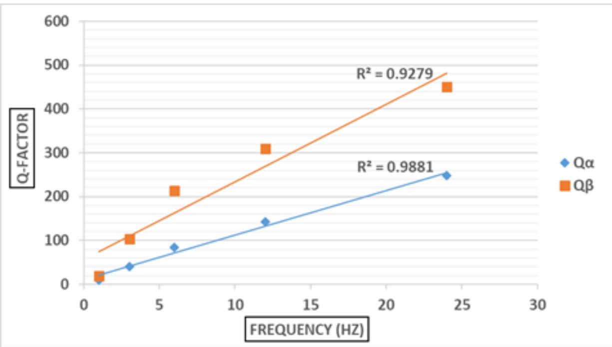

Figure 5. Graph of the correlation between Q_α (blue) and Q_β (orange) versus frequency

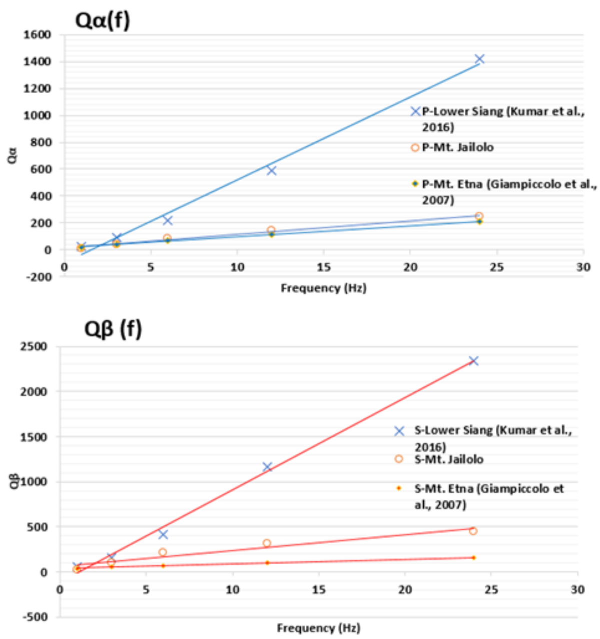

Figure 6. Comparison Q_α(f) and Q_β(f) Jailolo region with tectonic activity areas, Lower Siang (Kumar et al., 2016) and volcanic areas, Mt. Etna (Giampiccolo et al., 2007)

3.3 Ratio and Comparison Q_β/Q_α

Ratios Q_β/Q_α for the Jailolo region at the 12 sensors are greater than 1 (Table 5). Q_β values are higher on all sensors and consistent with the statement that the P wave attenuates faster than the S wave. Giampiccolo et al. (2007) has conducted his research on Mt. Etna with the results indicate $Q_\beta/Q_\alpha > 1$, 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. Wibowo (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_α(f) and Q_β(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 5. Value ratio Q_β/Q_α at each station.

Station	Q_β/Q_α (1 Hz)	Q_β/Q_α (3 Hz)	Q_β/Q_α (6 Hz)	Q_β/Q_α (12 Hz)	Q_β/Q_α (24 Hz)
SP04	2.543737	2.271078574	2.001384358	1.673323054	1.881241488
SP05	2.6684765	7.732721482	10.49826659	2.819412528	1.733564101
SP06	1.3524871	1.1991968	1.433660512	1.695060082	1.753234177
SP10	2.495353	2.075271039	1.790749852	1.882433766	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	1.618202533	1.633225261
SP15	1.8259215	2.366775248	3.639277987	3.54154651	1.894666248
SP16	2.2618779	3.095598129	2.194324197	1.644142465	1.503001916
SP20	1.799531	2.886442914	3.645192532	2.71762222	1.901017045
SP27	1.5542723	2.232895087	1.355470097	1.369603914	1.310885564
SP29	2.1289629	2.790491709	4.037012668	3.108415577	2.271814922
Average	2.052474031	2.556964961	2.859400067	2.095941555	1.783615948

4 CONCLUSION

Jailolo region's Q_α and Q_β decrease with distance and have strong dependency with frequency $n > 1$. The high frequency dependence shows high heterogeneity, indicated with the equations: $Q_\alpha(f) = 9.61814f^{1.12981}$ and $Q_\beta(f) = 19.10690f^{1.22843}$. $Q_\alpha(f)$ 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.

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