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Research Article

# Analysis of Stress Drop Variations in Fault and Subduction Zones of Maluku and Halmahera Earthquakes in 2019

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***Abstract***

*The amount of stress released by an earthquake can be calculated with a stress drop, the stress ratio before and after an earthquake where the stress accumulated in a fault or a subduction zone is immediately released during an earthquake. The purpose of this research is to calculate the amount of stress drop in faults and subduction in Maluku and Halmahera and their variations and relate them to the geological conditions in the area so that the tectonic characteristics in the area can be identified. This research employed mathematical analysis and the Nelder Mead Simplex nonlinear inversion methods. The results show that Maluku and Halmahera are the area with complex tectonic conditions and large earthquake impacts. The Maluku sea earthquake generated a stress drop of 0.81 MPa with a reverse fault mechanism in the zone of subduction, while for the Halmahera earthquake the stress drop value was 52.72 MPa, a typical strike-slip mechanism in the fault zone. It can be concluded that there is a difference in the stress drop between the subduction and fault zones; the stress drop in the fault was greater than that in the subduction zone due to different rock structure and faulting mechanisms as well as differences in the move slip rate that plays a role in the process of holding out the stress on a rock. This information is very important to know the amount of pressure released from the earthquake which has a very large impact as part of disaster mitigation measures.*

**Keywords:** *stress drop, fault, source spectrum, Nelder Mead Simplex method*

# Analisis Variasi Stress Drop pada Zona Sesar dan Subduksi untuk Kasus Gempa Maluku dan Halmahera 2019

***Abstrak***

*Besarnya stress yang dihasilkan oleh gempa bumi dapat dihitung dengan stress drop, yaitu perbandingan stress sebelum dan sesudah kejadian gempa bumi di mana akumulasi stress yang tertimbun dalam suatu patahan maupun subduksi dikeluarkan seketika saat kejadian gempa. Tujuan dari penelitian ini adalah untuk menghitung stress drop daerah sesar, subduksi dan variasinya serta menghubungkannya dengan kondisi geologi di daerah tersebut sehingga kita dapat mengetahui karakteristik tektonik di daerah tersebut, metode penelitian yang digunakan adalah analisis matematika dan metode inversi nonlinear Nelder Mead Simplex. Hasilnya adalah Maluku dan Halmahera dengan kondisi tektonik yang kompleks dan berdampak gempa besar, gempa laut Maluku menghasilkan stress drop 0,81 MPa dengan mekanisme* *patahan naik di zona subduksi sedangkan untuk gempa Halmahera nilai stress drop adalah 52,72 MPa, mekanisme strike-slip di zona sesar, dapat disimpulkan bahwa ada perbedaan stress drop antara subduksi dan zona sesar, stress drop pada sesar lebih besar daripada di zona subduksi karena perbedaan struktur batuan dan mekanisme patahan serta perbedaan slip yang berperan dalam proses menahan tekanan pada batuan. Informasi ini sangat penting untuk mengetahui jumlah tekanan yang dilepaskan sesaat setelah gempa yang memiliki dampak yang sangat besar sebagai langkah mitigasi bencana.*

**Kata Kunci:** *stress drop, spektrum sumber, metode Nelder Mead Simplex*

**PACS:** 91.30.-f, 91.30.Ab, 91.30.Bi, 91.30.Ga, 91.30.Px



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## I. INTRODUCTION

The amount of stress released by an earthquake can be calculated with a stress drop, that is the comparison of stress before and after an earthquake where the accumulated stress accumulated in a fault or subduction is released immediately during the earthquake [1]. The information about earthquake source parameters may use the earthquake teleseismic records, either located far or near the earthquakes depending on the availability of data recorded at the earthquake recording station. One of the important earthquake source parameters is stress drop ($\Delta\sigma$) [2].

Almann and Shearer calculated the global stress drop for earthquakes with the magnitudes greater than five and concluded that earthquakes with a slip strike focus mechanism greater than those are normal [2]. Very low stress drop values occur along the Cocos subduction zone in Central America with an average of under 1 MPa. Very low stress drop values are found in the subduction zone of North Sulawesi, which is an area with very complicated tectonics.

Sunday, July 7, 2019, at 22.08.42 West Indonesia Time, a tectonic earthquake occurred in the North Maluku Sea region with a magnitude of 7.0. The epicenter was located at coordinates of 0.53 North Latitude and 126.18 East Longitude, a depth of 49 km at a distance of 133 km west of Ternate City. This earthquake was categorized as shallow earthquake type with the thrust fault mechanism due to double subduction in the area that triggers a fault under Mayu Ridge. Based on community reports, shocks were felt in Bitung and Manado with IV-V intensity felt by almost all residents, people were awoken, and in Ternate III-IV intensity felt by many people at home [3,4].

The Halmahera Earthquake also occurred on Sunday, 14 July 2019, at 16.10.51 West Indonesia Time, in South Halmahera District with the magnitude of 7.2. The earthquake epicenter was located at coordinates 0.56 South Latitude and 128.06 East Longitude, located on land at a distance of 63 km east of Labuha City, North Maluku Province, at the depth of 10 km. The earthquake that occurred was also categorized as a shallow earthquake type due to the activity of Sorong-Bacan fault. These earthquake shocks were reported to be felt in

Obi district V intensity was felt, Labuha III intensity felt, Ambon II-III intensity felt, Ternate, Namlea, Gorontalo, Sorong, intensity felt, and Bolaang Mongondow II intensity felt [3,4].

The Maluku Sea is located in the convergence area of three major lithosphere plates namely Eurasia, Philippine Sea, and Australia [5]. The extremely high complexity in this region is partly due to the presence of micro plates which are large fragments of the plates or tectonic fragments trapped between the plates that meet each other. Tectonically, this island has many faults which become the source of the earthquakes [6].

The faults include Sula fault, Sorong fault, and North Buru Fault. The location of faults mapped on Maluku Island has been determined and mapped by researchers who were members of the 2017 National Earthquake Study Center shown in Figure 1.

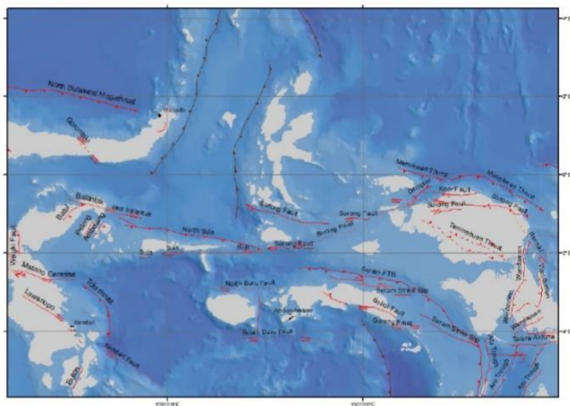

**Figure 1. Map of Fault Locations and Subduction Paths in Maluku [7]**

The tectonic arrangement of the Maluku Sea region is quite unique. This is the only example of a collision between active arcs in the world that are submerged in ocean basins through subduction in two directions. The Maluku Sea Plate has been submerged by two micro tectonic plates, the Halmahera Plate and the Sangihe Plate. Its complexity is now known as the Maluku Sea Collision Zone [8,9].

Data from Indonesian National Board for Disaster Management (known as BNPB) mention that the disastrous impacts of 4 people died, while those who were seriously injured due to the earthquake with the magnitude of 7.2 in South Halmahera 7 on Sunday, July 14, 2019 amounted to 32 people and the other 97 people with minor injuries [10]. Data from Regional Office of Disaster Management (BPBD) of North Maluku Province of July 17, 2019 also noted 13.250 families or 53.076 people were displaced, 1.061 houses were severely damaged, and 1.412 were moderately damaged [10].

Almann and Shearer concluded that very low stress drop values were found in the subduction zone of North Sulawesi, which is an area with very complicated tectonics [2]. They have not discussed the relationship among the tectonic conditions in the region, so it is necessary for more in-depth research in this issue. In this paper stress drop will be calculated in Sulawesi subduction and fault areas to see their relationship with the geological conditions in the Maluku region.

Geological characteristics on the surface usually use conventional geophysical methods, such as passive and active seismic methods. However, the stress drop approach from the source earthquakes to see rock characteristics are unique. The characteristics of rocks below the surface in general can be discovered, which can be seen from the response of these rocks to stress both stress and strain.

The aim of this paper is to calculate the stress drop in faults and subduction areas and their variations and relate them to geological conditions. At the end, the tectonic characteristics in the area can be discovered. Stress drop information is very important to know the amount of stress released from an earthquake that has a large impact as a disaster mitigation measure.

## II. METHOD

The study utilized earthquake waveform data from the IRIS-DMC and Meteorology, Climatology, and Geophysical Agency (BMKG) network. The earthquakes studied were the Maluku Sea earthquake on July 7, 2019, at 22.08.42 West Indonesia Time, with the magnitude of 7.0. The epicenter was located at coordinates 0.53 North Latitude and 126.18 East Longitude, with the depth of 49 km. Another earthquake was the Halmahera earthquake on July 14, 2019, at 16.10.51 West Indonesia Time, with the magnitude of 7.2. The earthquake epicenter was located at coordinates 0.56 South Latitude and 128.06 East Longitude, located on land at a distance of 63 km east of Labuha City, South Halmahera Regency, North Maluku Province at a depth of 10 km, recorded at the TOO, YNG, and ARMA stations in Australia [11].

The tectonic arrangement of the Maluku Sea region is unique as there are subductions in two directions. The Maluku Sea Plate has been submerged by two micro tectonic plates, the Halmahera Plate and the Sangihe Plate. Its complexity is now known as the Maluku Sea Collision Zone, so a stress drop needs to be seen.

In general, the steps for conducting research were divided into 3 parts. First step is the preparation of waveform data, the second was data processing and the last was the interpretation of research results.

The first step was collecting the data related to wave seismograms. The data were obtained from the IRIS-DMC network including downloading data with the criteria for distance data between events to the station from $30^{\circ}$-$100^{\circ}$ recorded at TOO, YNG, and ARMA stations in Australia. The use of stations in Australia was intended to avoid any interference from other wave phases on the recorded waveform seismogram, including refraction which may occur when earthquake waves pass through two different media, diffraction occurs when earthquake waves pass through a narrow gap, interference occurs when two earthquake waves come together to produce maximum and minimum interference patterns [11].

The next step was converting the full wave data format to SAC format with the RDSEED program. After conversion was taken, the P and S waves with the SAC program and 50 seconds were windowed with 2 seconds before the P onset.

After windowing, SNR (signal to noise ratio) was calculated 50 seconds before the onset of P with the frequency band 0.02-0.1 Hz, 0.1-0.4 Hz, and 0.4-2 Hz. SNR is obtained by comparing the spectrum of observational data with noise then averaged. If the SNR ratio is less than three, the signal is not used in data processing (see Figure 2) [12,13].

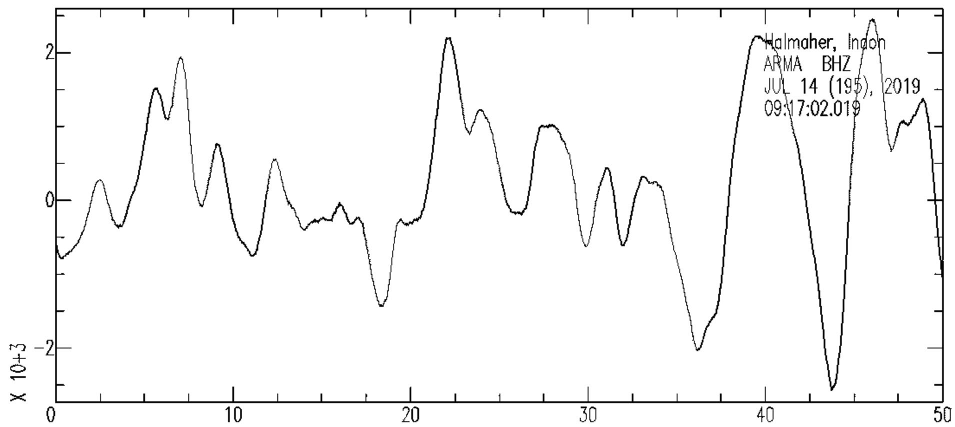


**Figure 2. Windowing [12,13]**

The second step was data processing, starting with instrument and taper correction with multitaper method to eliminate path noise and factors from the tool, after which the waves were integrated from speed to displacement then using Fast Fourier Transform (FFT). The Maluku Sea and Halmahera earthquake displacement spectrum was obtained at the time of the earthquake (see Figure 3) [14-16].

Before this spectrum was analyzed, the deconvolution process was carried out, i.e. releasing the response instrument and path effects (damping and geometric distribution) [17]. The purpose of this deconvolution is to obtain the true spectrum of the earthquake sources. Seismogram signal recording from earthquake events is a combination of some earthquake property information, shown by the following Equation (1).

$$\text{Seismogram}(f) = \text{Source}(f) * \text{Path}(f) * \text{Site}(f) * \text{Instrument}(f) \quad (1)$$

where source ($f$) is the spectrum of source effects associated with parameters such as seismic moments, source radius, stress drop which describe the mechanism at the earthquake source. While the path ($f$) is the spectrum due to the effect of spreading from the source to the recording station which is related to the seismic attenuation parameter ($Q$).

For site ($f$) is the amplification spectrum which contains information about local (geological) influence and the instrument ($f$) is the spectrum caused by the effect of the instrument response [18-20]. For instrument influence ($f$) the station is corrected so that instrument effects can be temporarily eliminated for source ($f$), path ($f$) and site are performed by the inversion method of the Nelder Mead Simplex algorithm [21, 22].

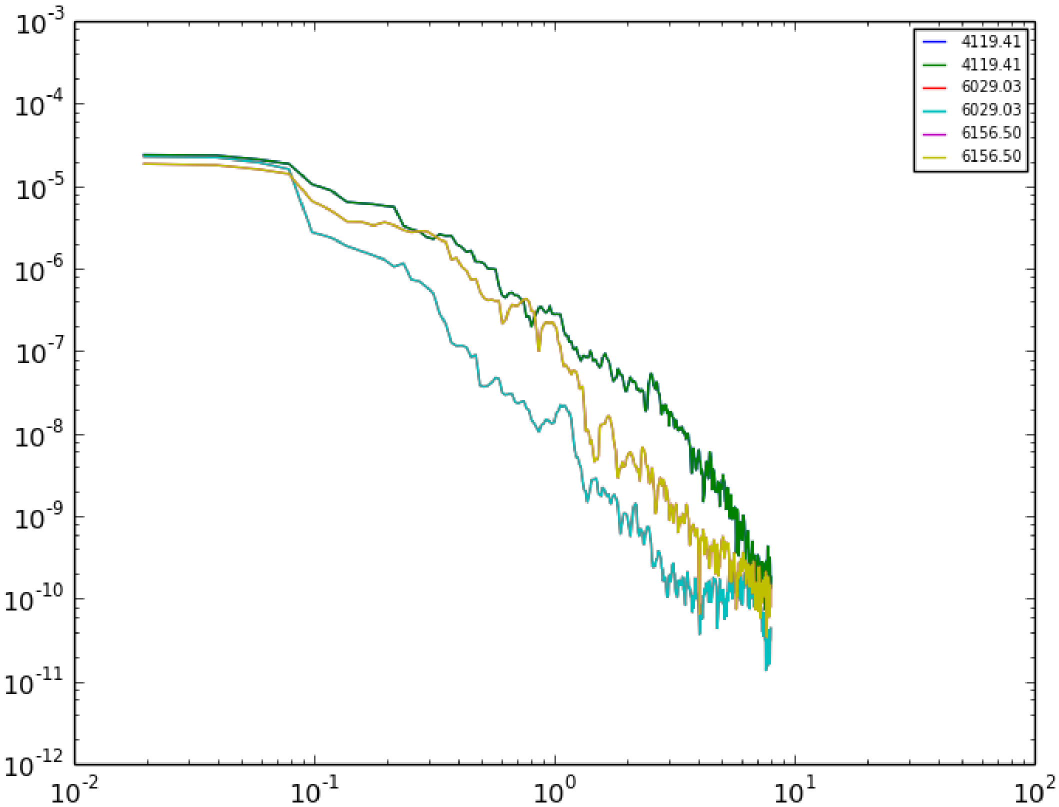


**Figure 3. Observational Displacement Spectrum [14-16]**

The entire inversion process was carried out simultaneously using the Python program [23]. After getting the source spectrum, the calculation of the best angular frequency ($fc$) of the fitting was done as the input in the calculation of stress drop as in the Equation (2).

$$\Delta\sigma = M_0 \left(\frac{f_c}{0.42\beta}\right)3 \tag{2}$$

where $\Delta\delta$ is the stress drop (Mpa), Mo is the moment magnitude (Nm), fc is the angular frequency $\beta$ is the source constant shear source of 3.3 km/s [24,25].

## III. RESULTS AND DISCUSSION

Determination of stress drop from digital seismograms at TOO, YNG, and ARMA stations in Australia was carried out with several stages of data processing as explained in the previous section. The rational of using Australian seismic stations in this study was explained, instead of using the local stations operated by BMKG, because the distance to the earthquake recording station was 30°-100°, to avoid changes from other wave phases such as refraction, diffraction, etc., near short distances. It was confident that the waveform interference would be recorded on a seismogram and would affect the results of data processing.

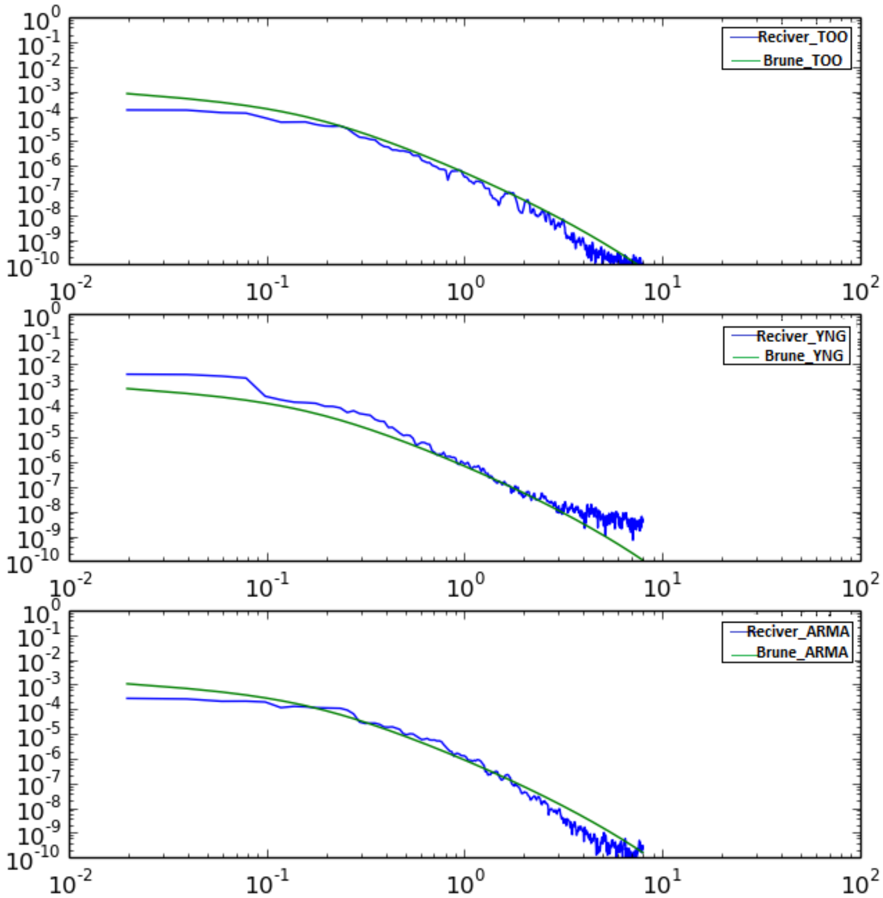


**Figure 4. The Best Fittings with Receiver and Brune Models from TOO, YNG, and ARMA Stations to the Halmahera Earthquake**

The following are the best fitting from TOO, YNG, and ARMA stations from Figures 4 and 5, which can be seen that the receiver spectrum approaches the Brune model, so that the best source spectrum can be seen in Figure 6. The Brune model is manifested by a green curve, while the receiving signal is manifested by a blue signal.

The final result of this study is to determine the stress drop with the Equation (2) that the Maluku earthquake stress drop on 7 July 2019 which was 0.181 MPa, resulted from a fault in the subduction zone. It is common in all subduction zones such as the results of Allmann and Shearer that very low pressure drop values occur along the Cocos subduction zone in Central America with an average value of below 1 MPa [2].

The value of stress drop in subduction areas with 24 earthquake events has a stress drop in the range of 0.17-20.65 MPa. In terms of type of the fault, most of the thrusts that occur in the subduction zone has a relatively small drop stress value. The small value of stress drop is because it mostly occurs in areas with low districts, generally in shallow subduction slab areas [26]. The variation in stress drop is influenced by variations in stiffness, variations in different material plates, as well as variations in the absolute value of the main stress or orientation of the plate boundary in the direction of the main stress [27].

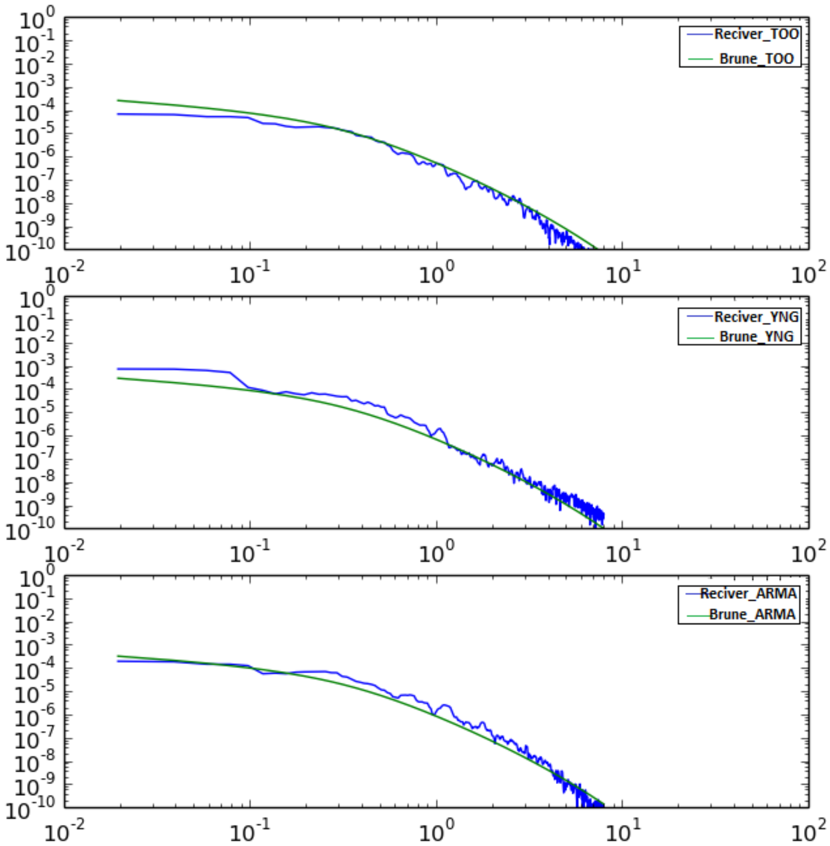


**Figure 5. The Best Fittings with Receiver and Brune Models from ARMA, YNG, and TOO Stations Subduction Earthquake**

Allmann and Shearer revealed that variations in stress drop are influenced by variations in stiffness, variations in different material plates, as well as variations in the absolute value of the main stress or orientation of the plate boundary in the direction of the main stress [2]. Shearer et al revealed that stress drop is sensitive to the tectonic type of the stress regimes [28].

High stress drop values in subduction areas occur in areas with high regimens according to Allmann and Shearer who examined in the Tonga subduction area [2]. The earthquake along the Tonga subduction showed a higher stress drop at the northern end of the subduction zone, the Wadati Beniof zone. Very low stress drop values were found in the subduction zone of Maluku; this is a region with very complicated tectonics.

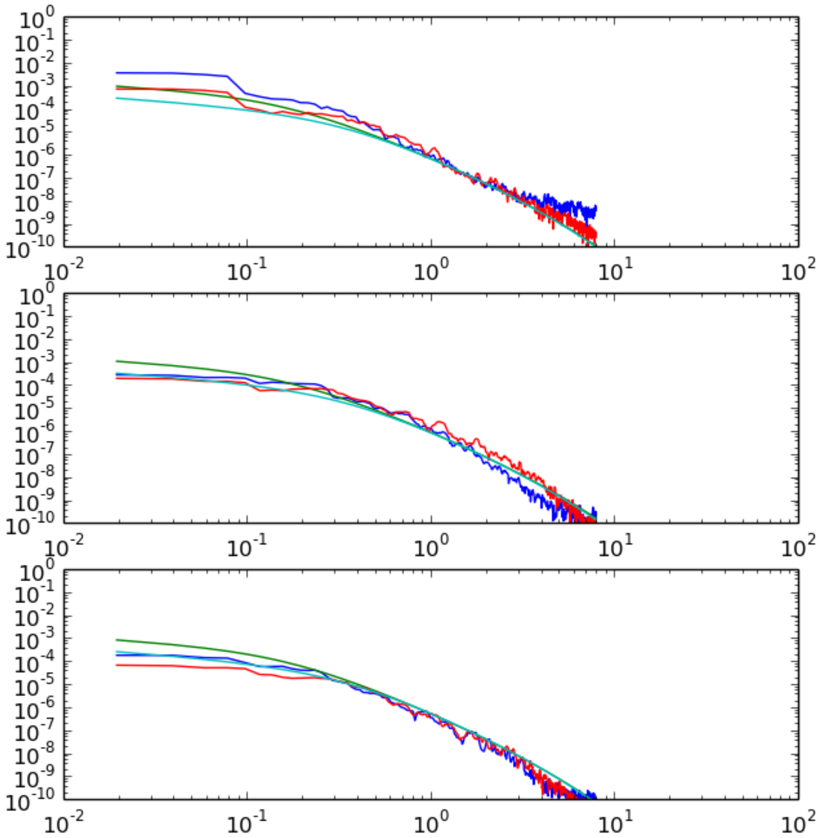


**Figure 6. Source Spectrum**

The stress drop value of the Halmahera earthquake on 14 July 2019 was 52.72 MPa with the type of strike slip mechanism that occurred on land. These results are consistent with Allmann and Shearer who examined the Hindukush region in Central Asia with a value of around 30 MPa in the Hindukush region which is a series of Himalayan Mountains [2]. The result of stress drop in the area of the Earth's crust with earthquake events has a high stress drop value of 39.26 Mpa.

According to Natawidjaya and Triyoso precisely in the Sumatra fault zone in the Siulak segment [29], the type of fault is long segment of 70 km, while the rate of slipping 23 mm/year the geomorphic Siulak segment is the lake of Kerinci volcano and turmeric. Goebel et al concluded that the drop stress is inversely proportional to the slip rate along the San Andreas fault system [30]. A small slip rate results in a higher stress drop value, while a large slip rate results in a small stress drop value the stress drop value of the Halmahera earthquake is very low slip rate results in a higher stress drop value.

There is a difference in the stress drop between the subduction and fault zones. For the Maluku and Halmahera events, the stress drop in the fault was greater than that in the subduction zone. This is due to differences in rock structure and faulting mechanisms as well as differences in the move slip rate that plays a role in the process of holding out the stress on a rock, the same as the conclusion of a study carried by Qimin Wu that the large spatial variability of stress drops reflects strong fault heterogeneity in this area, which is likely influenced by the injection of fluids into the subsurface [31].

The impact of research on stress drop in the field of geophysics is that stress drop is a manifestation of the mechanism of earthquake sources, which is closely related to tectonic conditions in the area around the earthquake. The relationship between the stress drop and tectonic regime upon this phenomenon is an interesting matter for the advancement of geophysical science because it is usually to determine the tectonic conditions through a surface approach rather than at the source of an earthquake.

## IV. CONCLUSION

The Maluku sea earthquake generated a stress drop of 0.81 MPa with a reverse fault mechanism in the zone of subduction, while for the Halmahera earthquake the stress drop value was 52.72 MPa, a typical strike-slip mechanism in the fault zone. There is a difference in the stress drop between the subduction and fault zones. For the Maluku and Halmahera events, the stress drop in the fault was greater than that in the subduction zone. This phenomena is due to differences in rock structure and faulting mechanisms as well as differences in the move slip rate that plays a role in the process of holding out the stress on a rock is very important to know the amount of pressure released from the earthquake which has a very large impact as disaster mitigation measures.

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