http://journal.uir.ac.id/index.php/JGEET

E-ISSN : 2541-5794
P-ISSN : 2503-216X

Journal of Geoscience,
Engineering, Environment, and Technology
Vol 9 No 2 2024

RESEARCH ARTICLE

Relocation Study of Flores Sea Hypocenter (Mw = 7.3) Based on Single Station Estimation Using ObsPy

Azmi Khusnani[1,*], Ade Anggraini[2], Adi Jufriansah[1], Zulfakriza[4], Yudhiakto Pramudya[5], Margiono[6], Konsenius Wiran Wae[1]

[1]*Physics Education, Universitas Muhammadiyah Maumere, Maumere, Indonesia*
[2]*Geoscience Research Group, Universitas Gadjah Mada, Yogyakarta, Indonesia*
[4]*Global Geophysics Research Group, Institut Teknologi Bandung, Bandung, Indonesia*
[5]*Master of Physics Education, Universitas Ahmad Dahlan, Yogyakarta, Indonesia*
[6]*Geophysics Station, Meteorological, Climatological, and Geophysical Agency, Kupang, Indonesia*

* Corresponding author : husnaniazmi@gmail.com
Tel.:+62-823-256-635-37
Received: Oct 6, 2023; Accepted: May 22, 2024.
DOI: 10.25299/jgeet.2024.9.2.14503

Abstract

One area in Indonesia that is prone to disasters is the Flores Sea area, which has the potential for earthquakes to trigger tsunamis. This is due to the location of Flores, which is in a subduction zone that originates from the collision of the Indo-Australian (South) and Eurasian plates. Inaccuracies in earthquake locations are influenced by differences in residual travel time values, mathematical solutions to location problems, and inaccuracies in the seismic velocity model used. The accuracy of determining the hypocenter of an earthquake influences the location of the earthquake source, which will later be used as a reference in appropriate earthquake disaster mitigation planning. Based on this, an analysis of earthquake hypocenter data is needed, so it is important to carry out research. This research aims to relocate the hypocenter using ObsPy with a single station. The results obtained show that the Python package, namely ObsPy, can carry out data retrieval commands through filtering, detrending, normalisation, and determining data request parameters, such as the start and end times of the desired data, location, network, and data type. This research contributes to the field of seismology because the process of determining the hypocenter requires a relatively short time. Apart from that, the accuracy obtained also provides accurate values.

Keywords: Hypocenter; Flores Sea; ObsPy; Single Stasiun; IRIS

1. Introduction

Flores Island is part of East Nusa Tenggara Province, Indonesia, which is highly prone to earthquakes. This is so because the Indo-Australian (South) and Eurasian (North) tectonic plates collided to create a subduction zone (Ramdhan et al., 2021; Rosid et al., 2020; Sasmi et al., 2020). In addition, the Flores thrust zone, the back-arc thrust that extends from North Flores to West Nusa Tenggara via Bali, is one of the causes of earthquake activity in the region (Felix et al., 2022; Jufriansah et al., 2021; Lythgoe et al., 2021).

Based on historical records, the Flores region also has the potential for tectonic earthquakes that can result in tsunamis (Khusnani et al., 2023, 2022). Meanwhile, the Flores region has experienced several earthquakes with a magnitude >7 (Beckers and Lay, 1995; Handayani, 2020; Jufriansah et al., 2023b, 2023a). However, seismic research in the Flores region is still limited (Maneno et al., 2019).

The determination of the earthquake hypocenter can be carried out by optimizing the accuracy of the earthquake hypocenter, as it has the potential to enhance the effectiveness of earthquake disaster mitigation efforts. This is crucial, considering that the earthquake hypocenter provides essential data such as the depth of the earthquake and location coordinates (Cihad et al., 2023). In order to achieve this, the analysis of earthquake hypocenter data can be a highly useful step (Daniels and Peng, 2023; Jafari et al., 2023).

Considering that the Flores Sea has a high seismic hazard potential, identifying earthquake source mapping based on hypocenter data is very important. Accurate identification of the hypocenter can be done by relocating the hypocenter (Lomax and Savvaidis, 2022; Mousavi et al., 2023).

This approach is used to recalculate or correct the position of the earthquake hypocenter better and more accurately. The relocation analysis process is carried out by adding information by using absolute positioning (earthquake signal capture stations) and algorithms (Cihad et al., 2023). Steps that can be implemented are to choose the closest station to the earthquake event; this can reduce the effect of noise, which can affect the calculation of the P wave arrival time and the S wave arrival time. (Kiswanti et al., 2021; Lomax and Savvaidis, 2022; Priyambada et al., 2022). By determining the arrival time of the P and S waves, the correct hypocenter value for the earthquake will be found. The Flores Sea Earthquake is an unusual series of earthquakes (Supendi et al., 2022). So it requires tools for processing recorded seismic data. Utilization of computing technology is a necessity to optimize seismic data analysis. One particularly useful tool in this context is ObsPy, a Python software library designed specifically for seismic data processing. Python is the most popular programming language, where it can be used for more complex programs, and provides the Python Package Index (Megies et al., 2011). Based on this, this research aims to determine the location of the hypocenter of the December 14 2021, earthquake with the ObsPy package in Python.

2. Methods

The data utilised in this research comprises single-event data from the KAPI station (latitude: 119.7517, longitude: -5.0142) corresponding to the Flores Sea earthquake on

December 14, 2021. This data was sourced from the IRIS (Incorporated Research Institutions for Seismology) web service, utilising the primary data accessible on Service Implementations FDSNWS (Figure 1). In addition, the obtained seismogram data was analysed using the Seismic Analysis Code (SAC) and Python (according to the research flow depicted in Figure 2). At the data analysis stage, Python libraries, including NumPy, SciPy, CartoPy, and ObsPy, were utilised. ObsPy is designed specifically for reading, analysing, and displaying seismological data, while NumPy and SciPy handle the mathematical and scientific operations required to manipulate data (Krischer et al., 2015). The Python programming language has a module called CartoPy that is used to make theme maps. CartoPy makes use of Matplotlib, a well-known data visualisation library, and adds more features to make creating maps easier. Python is utilized to execute commands for processing earthquake data, encompassing the waveform of each seismic event, the arrival times of primary (P) and shear (S) waves on the seismometer, the duration of each event in seconds, the RMS amplitude of each event, as well as the average frequency and maximum frequency per event. To determine the effective amplitude of seismic waves during an event, the Root Mean Square amplitude, or RMS amplitude, is a quantity used in seismic data processing.

A seismograph will record the vibration that results from a fissure shifting and causing an earthquake (Hadi et al., 2018). A spectrogram illustrates how frequency changes over time are depicted by different colours (Yin et al., 2018). Calculating the spectrogram involves partitioning the seismic signal into multiple window functions, which are then converted to the frequency domain. This analysis employs two programmes, namely SAC and Python.

At the stage of analysis, the data is filtered to eliminate extraneous noise, such as background seismicity, tidal noise, or human activity (Rincon-Yanez et al., 2022). Bandpass filters were once used to remove data with a frequency between 0.5 Hz and 10 Hz. This limit was chosen to distinguish between events with a very short period and those with a very long period, and by analysing the unfiltered frequency content of the two sample events, it was revealed that most of the frequencies contained by those events fell within the range of 0.5–10 Hz.

The next step is to calculate the P-arrival (alpha) polarization angle between the two horizontal components. Additionally, we will retrieve station metadata (component azimuth, slope, and location). Create a model of the crustal velocity in half-space that the seismic station will use to calculate the earthquake hypocenter. We presume that the half-space velocity model is along the back-azimuth profile from the station.

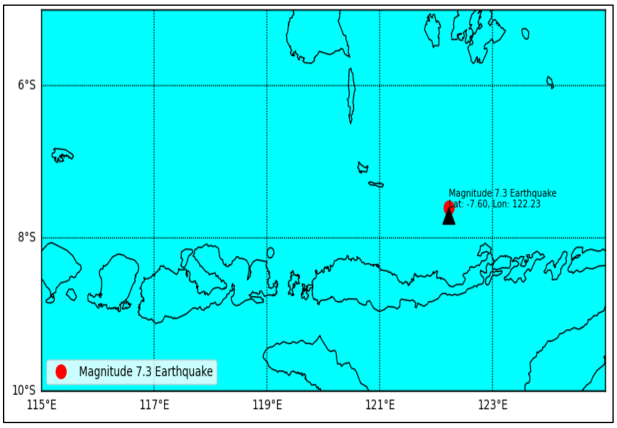

Fig 1. The location of the incident using the CartoPy package

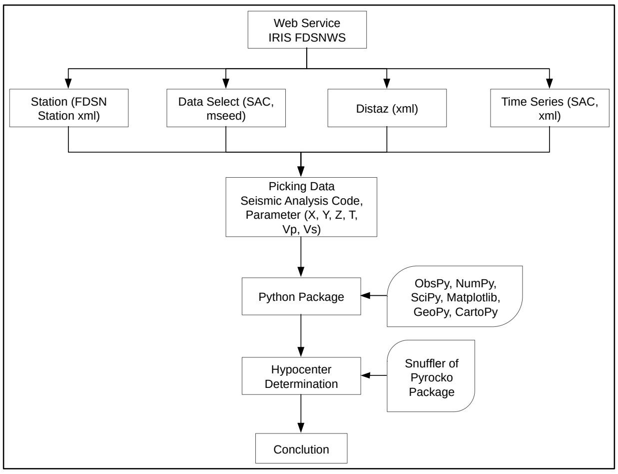

Fig 2. The Research flow

3. Result & Discussion

This research employs the ObsPy library as a client to request and download seismic data from the IRIS server for the retrieval of IRIS seismic data. The acquired data is downloaded for the KAPI station, followed by the removal of responses and trends and writing to an MSEED file. Subsequently, the data is filtered to generate a waveform plot and saved to a file. ObsPy offers an intuitive interface for accessing seismic data from diverse sources, including IRIS, utilising the data structure depicted in Figure 3.

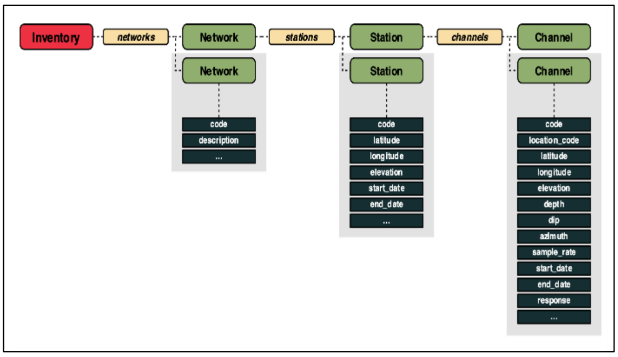

Fig 3. IRIS Web Service data structure

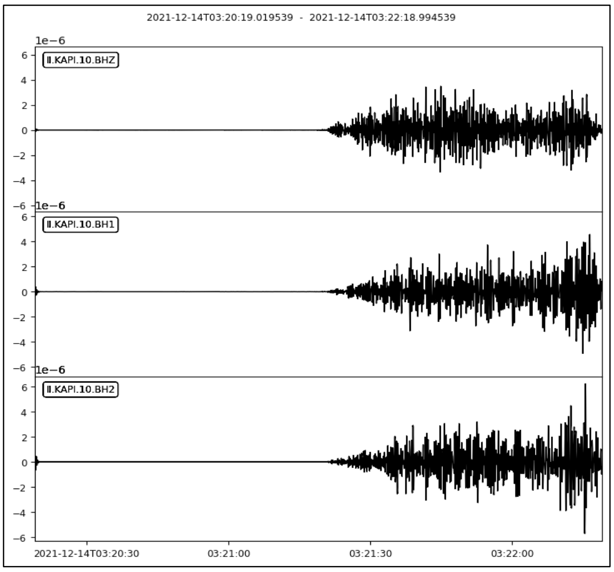

Fig 4. Records of data obtained from KAPI stations

In this section, the network data is encoded with the value II to indicate that it pertains to KAPI stations in South Sulawesi. The subsequent phase is to specify the data request parameters, such as the start and end times, location, network, and data type. The following phase is to preprocess the data using ObsPy's functions, such as detrending, filtering, and normalisation (Hosseini and Sigloch, 2017). The objective of detrending is to centralise data so that it focuses more on the actual seismic signal and eliminates extraneous trending components. Typically, linear or polynomial-based regression methods are used in the detrending procedure. The subsequent phase involves the retrieval of data in various formats, including MiniSEED and Seismic Analysis Code (SAC). Figure 4 illustrates the outcomes of the data downloads that were successful.The subsequent phase is filtering. Filtering is the process of removing undesirable frequencies from seismic data while retaining relevant frequencies. Filtering can assist in amplifying the earthquake signal and removing noise that interferes with the analysis. In this study, two filtering processes are presented, including High-pass filtering, which concentrates on reducing low-frequency components while preserving high-frequency components, making it suitable for identifying earthquakes and high-energy events. Meanwhile, band-pass filtering eliminates high-frequency components while preserving low-frequency components, making it suitable for identifying distant earthquake waves and analysing small-magnitude earthquakes (Burud and Kishen, 2021; Foti et al., 2018).

Seismic data filtering has several essential applications in the analysis and interpretation of seismic data. Among its primary benefits is noise filtering. Numerous forms of noise, such as environmental noise, instrument noise, and human noise, are commonly present in seismic data and can impede analysis. By employing filtering techniques, it is possible to reduce or eradicate irrelevant noise, thereby enhancing the quality of the desired seismic signal. Filtering techniques can increase the amplitude of crucial seismic earthquake signals by removing frequency components that are not relevant. This improves the detection and analysis of earthquake events, particularly in circumstances where noise may mask the seismic signal.

Identify wave types that can be used to distinguish specific wave types in seismic data. Low-pass filtering, for instance, can help identify P (primary or compressive waves) and S (secondary or shear waves), whereas high-pass filtering can concentrate on high-energy waves such as surface waves (Salvermoser et al., 2017; Saygin et al., 2017). Our findings displays ground acceleration data in three directions (vertical, north-south, and east-west) as well as earthquake acceleration data gathered by seismic stations. Higher acceleration levels are indicated by thicker lines in the original image (Figure 6(a)), which represent the acceleration data. Establishing the cutoff frequency, that is, the frequency above which the filter will eliminate the signal, is essential to putting high-pass filtering into practice. The goal of setting the cutoff frequency in this situation is to exclude any signals that have frequencies lower than about 0.5 Hz. The Figure 6 (a) is then subjected to a filter, which lowers the amplitude of the lines that indicate signals with frequencies below the cutoff. Consequently, high-pass filtered pictures exhibit notable modifications, including enhanced visualisation of undesired noise signals and shorter lines for signals with frequencies below the cutoff. Since earthquake signals typically have higher frequencies than noise, high-pass filtering can be employed to separate them in the context of earthquakes. When a signal's frequency falls below the cutoff frequency value, it is passed via the low-pass filter (Figure 6(b)) when its frequency rises beyond the cutoff frequency value, it is attenuated and appears as a dotted line. The filter will pass waves with frequencies below the cutoff value, which is placed below the dotted line, and reduce the amplitude of waves with frequencies over the cutoff value, which is positioned above the dotted line. It is evident that the dotted line's waves are larger in amplitude than those above it, suggesting that the filter is successful in attenuating high-frequency sounds.

Filtering frequency analysis can aid in the study and analysis of the frequency properties of seismic signals, which are crucial in the modelling and understanding of earthquake sources as well as the study of the geology and structure of the earth. Comparisons and comparisons. In some instances, it can be useful to compare seismic data from various locations or events. Filtering data helps to equalise instrument sensitivity and eradicate frequency differences resulting from varying distances or station conditions (Gao et al., 2021). The use of data processing techniques, such as filtering, to pinpoint particular wave types in seismic data is emphasised in this context. P waves and S waves can be distinguished, for instance, using low-pass filtering, whereas surface waves, or high-energy waves, can be the focus of high-pass filtering. In the meantime, the normalisation phase concentrates on adjusting the amplitude of seismic data to a uniform value (Earle and Shearer, 1994).

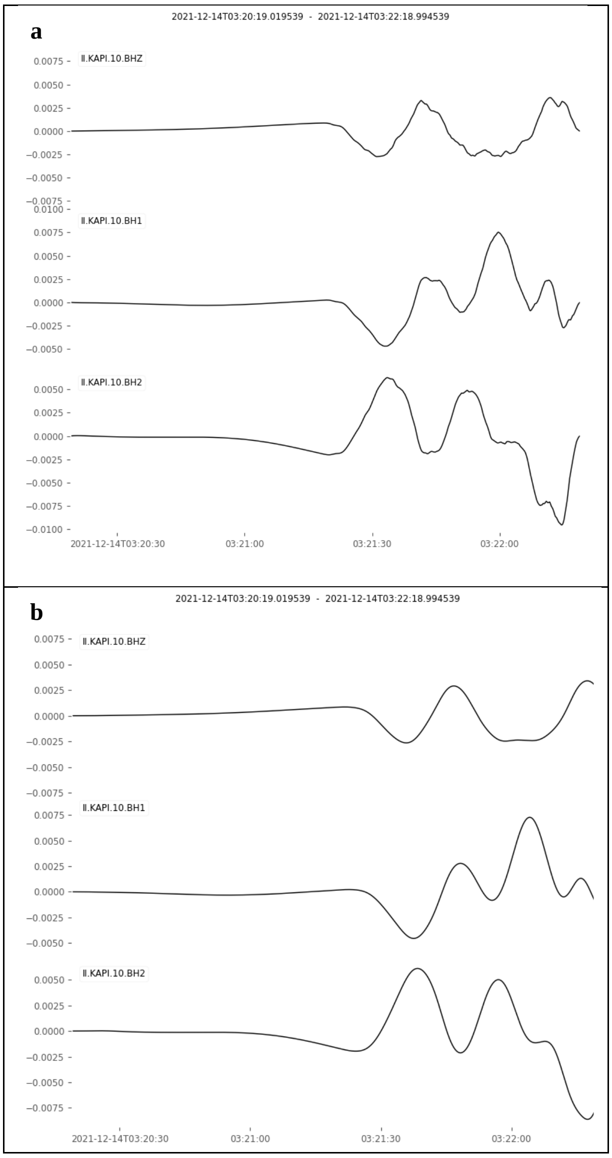

Fig 5. (a) Process prior to filtering; (b) Process subsequent to filtering

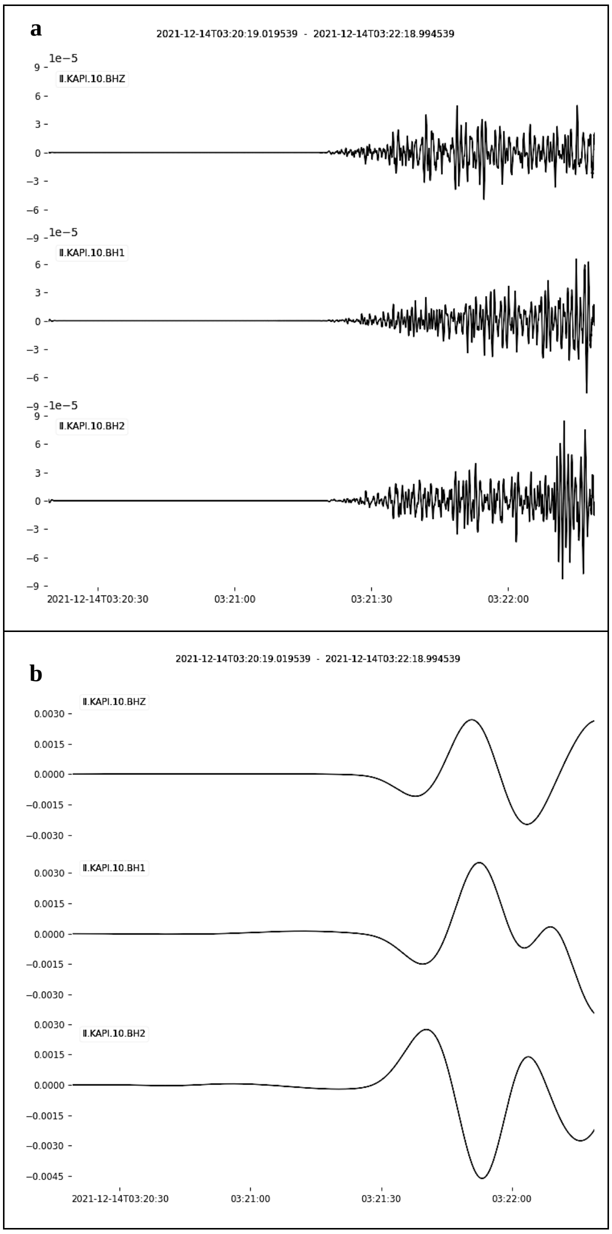

Fig 6. (a) High-pass, (b) Band-pass

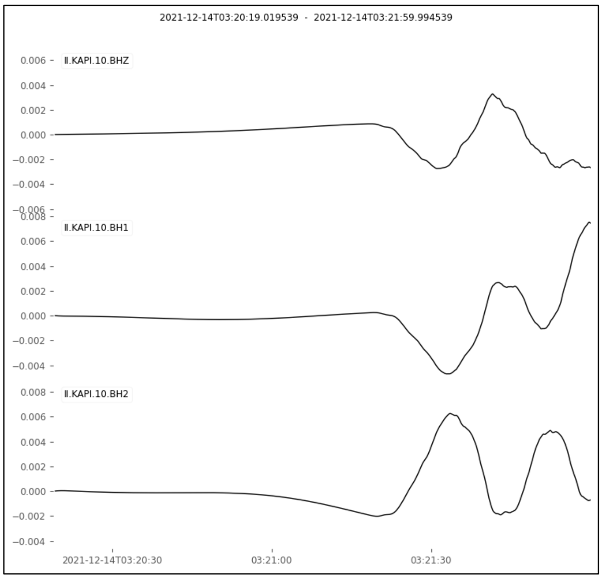

Fig 7. Trimming streams and trace results

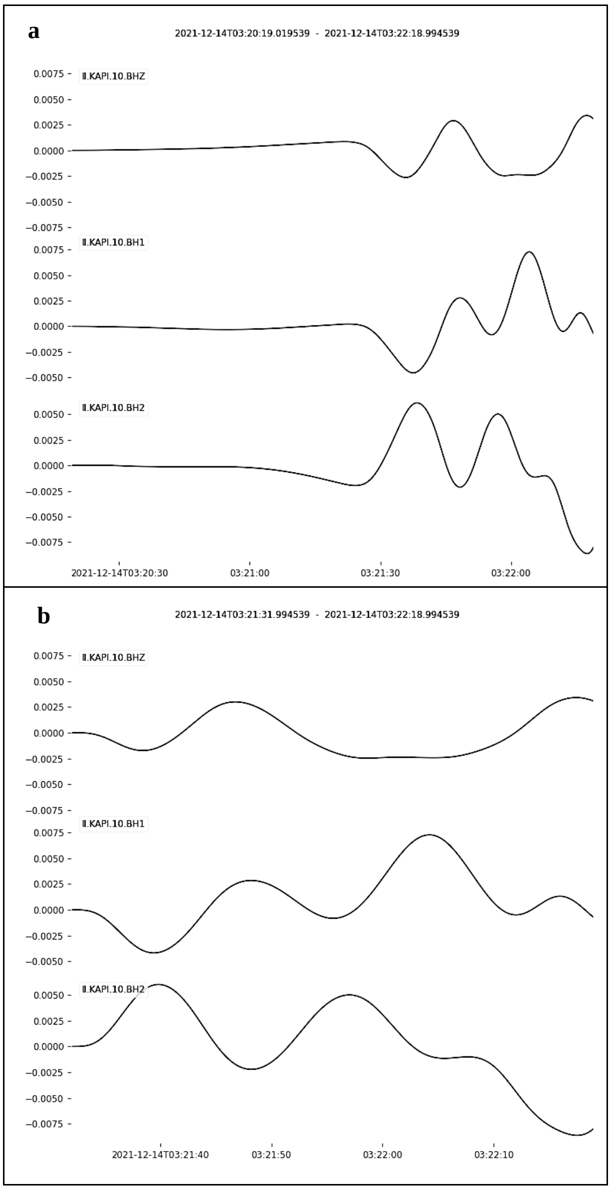

Fig 8. Determination of the arrival time of (a) P-wave and (b) S-wave

The following step is to terminate the earthquake recording feed. This procedure plays a role in isolating or segregating portions of seismic data (e.g., specific times) that are of interest for subsequent analysis. It is common practise to isolate time periods in the seismic record by focusing on earthquake events, i.e., the arrival times of P waves and S waves. A "stream" in ObsPy is a collection of seismic traces originating from various stations and/or networks (Chamberlain et al., 2018; Megies et al., 2011; Turner et al., 2021). Figure 7 depicts the clip of the earthquake recording stream with the subsequent trace results.

In order to determine the arrival time of the P wave and S wave according to Figure 8, the peak amplitude of the vertical component at the arrival time of the P wave is determined. The peak amplitude indicates the arrival time of the P wave. In contrast, the S wave is generated after the P wave has been determined. The S wave typically arrives a few seconds after the P wave. It is obtained automatically by ObsPy.

The analysis reveals that the KAPI station for wave P (KAPI_P) is obtained at 2021-12-14T03:21:19 (UTC), and the KAPI station for wave S (KAPI_S) is obtained at 2021-12-14T03:22:02 (UTC). The selection of the KAPI station was based on its proximity to the earthquake source. The majority of the timing corresponds to the theoretically calculated travel time trajectory for the primary seismic phases based on the

IASP91 model. From the P and S wave travel time curves (Figure 9). In determining the speed of P waves at varying epicentral distance, this curve illustrates how wave velocity varies with depth and rock type beneath the Earth's surface. There exists a critical distance at which the longest P or S wave can reach the station. After this distance, seismic stations are unable to detect P or S waves because their angle of arrival is too acute.

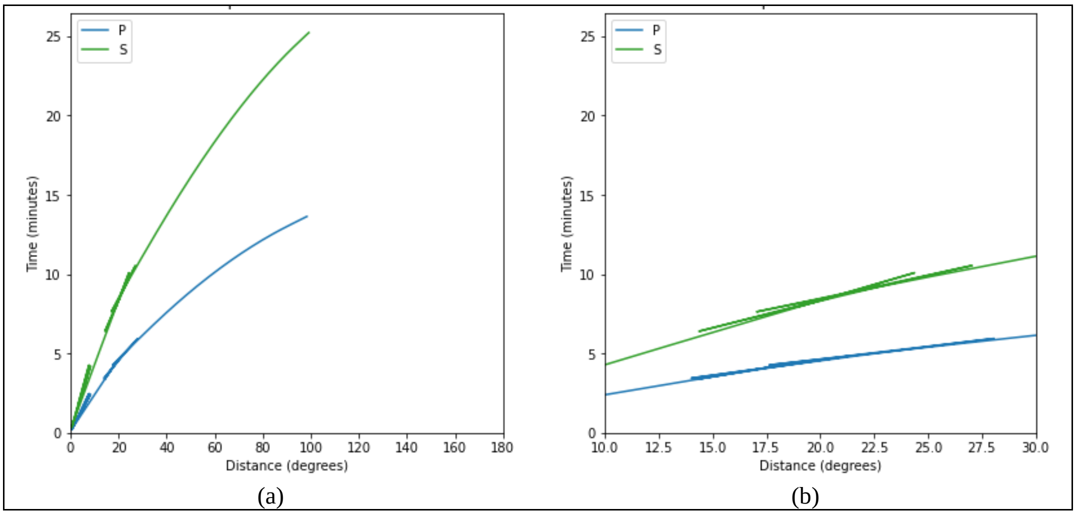

Fig 9. P-wave and S-wave travel time curves at a depth of 10 km

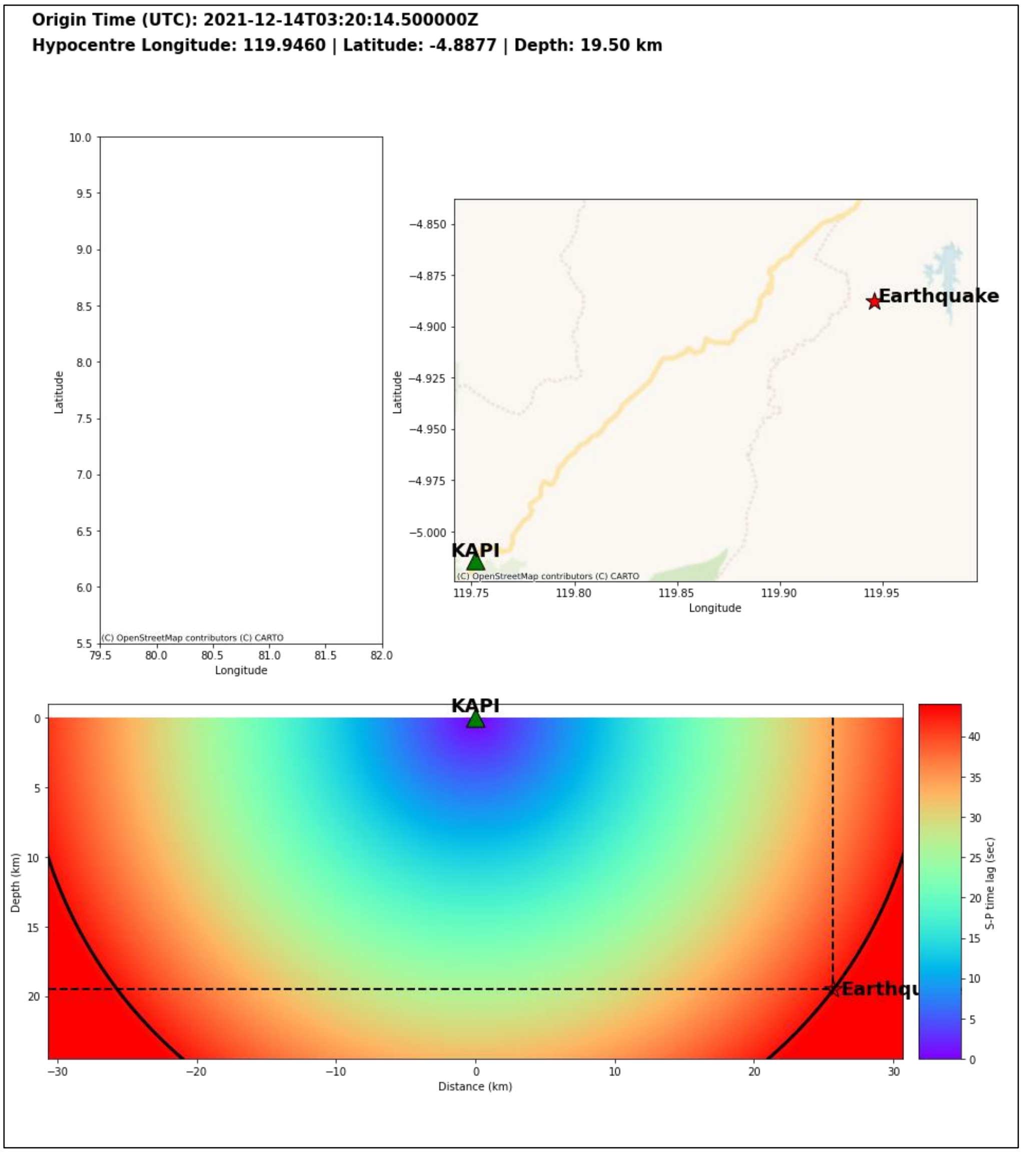

Fig 10. Visualization of hypocenter results with ObsPy

If the arrival times of P and S were determined using the Snuffler module of the Pyrocko package (Braun et al., 2020), the next stage is to read the data in Pyrocko format, followed by a time difference analysis using ObsPy. In the event of a Mw 7.3 earthquake, the difference between the onset times of P and S waves is 43 seconds. Calculating the polarisation angle (alpha) of arrival P between the two horizontal components is the next step. This requires seismic data from the two selected horizontal components and the arrival time of the P waves. In addition, KAPI station metadata, including component azimuth, slope, and station location, is required.

The next stage is to create a model of the half-space crustal velocity obtained from the seismic station in order to calculate the hypocenter of the earthquake. This research presents a half-space velocity model along the profile of the station's rear azimuth with Vp = 0.5 m/s and Vs = 0.3 m/s. Because the travel time selection error for calculating the tsp time contour on the half-space velocity model is 0.02, the results obtained are as follows:

```
Origin time (UTC): 2021-12-14T03:20:14.500000Z | Hypocenter longitude: 119.94600, latitude: -4.88774, depth: 19.50 km
```

with the hypocenter visualization presented in Figure 10.

The data displayed is based on earthquakes that occurred in the Flores Sea area. The determined earthquake origin time (UTC) was 2021-12-14T03:20:14.500000Z, and the corresponding hypocenter coordinates were 119.94600 latitude, -4.88774, and a depth of 19.50 km. This location has a high potential for seismic danger, so researchers launched research to relocate the hypocenter data. Relocating the hypocenter is a crucial component of this inquiry since it facilitates pinpointing the precise epicentre of the earthquake. Using absolute location determination from the earthquake signal capturing station the KAPI station and an algorithm created with ObsPy to offer further information, this process entails recalculating or correcting the hypocenter. Noise can be reduced in the P wave and S wave arrival times computation by using the station nearest to the earthquake occurrence. Furthermore, the timing of the primary earthquake and its aftershocks is examined in relation to the BMKG location criteria, the source mechanisms of the earthquake, and changes in pressure error values. The major goal is to categorise measurement discrepancies related to the main earthquake's hypocenter. The procedure for drawing this conclusion mostly depends on gathering information about the arrival times and velocities of the P and S waves. Nonetheless, there are difficulties in moving the hypocenter in the Flores region. First of all, it is difficult to maintain the seismograph network due to the lack of infrastructure in remote locations, which affects the coverage and accuracy of seismic data as well as the expiration of many stations' usage periods. Second, several kinds of earthquakes are introduced by the intricate subduction zone in the Flores region, where the Indo-Australian and Eurasian continents meet, making the relocation process much more difficult. These comprise pull-apart earthquakes caused by complex continental interactions, subduction earthquakes, and shallow tectonic earthquakes.

4. Conclusion

Determining the location of the earthquake source is the basis for preparing the most effective earthquake disaster mitigation plan. This is, of course, greatly influenced by the accuracy of identifying the hypocenter. Due to the high earthquake activity in the Flores Sea region, this research discovered a Seismic Analysis Code (SAC) command execution technique based on the ObsPy Python package running on Linux. Even though it is straightforward, the resulting algorithm value is still accurate. ObsPy can execute commands for data collection by filtering, reducing trends, and normalising data. It can also ascertain data request parameters, including start and end time, location, network, and type of data required. The main contribution of this research lies in simplifying the occurrence time of the hypocenter. In addition, the level of accuracy obtained offers precision value.

Acknowledgements

The researcher would like to express gratitude to the Indonesian Ministry of Education, Culture, Research, and Technology for funding research through the 2023 Beginner Lecturer Research Grant Scheme (PDP). This investigation required access to waveform data, which was provided by the IRIS Data Management Centre (http://ds.iris.edu/ds/nodes/dmc/; accessed on February 20, 2023).

References

Beckers, J., Lay, T., 1995. Very broadband seismic analysis of the 1992 Flores, Indonesia, earthquake (Mw = 7.9). J Geophys Res Solid Earth 100, 18179–18193. https://doi.org/10.1029/95JB01689

Braun, T., Frigo, B., Chiaia, B., Bartelt, P., Famiani, D., Wassermann, J., 2020. Seismic signature of the deadly snow avalanche of January 18, 2017, at Rigopiano (Italy). Sci Rep 10, 18563. https://doi.org/10.1038/s41598-020-75368-z

Burud, N., Kishen, J.C., 2021. Damage detection using wavelet entropy of acoustic emission waveforms in concrete under flexure. Struct Health Monit 20, 2461–2475. https://doi.org/10.1177/1475921720957096

Chamberlain, C.J., Hopp, C.J., Boese, C.M., Warren-Smith, E., Chambers, D., Chu, S.X., Michailos, K., Townend, J., 2018. EQcorrscan: Repeating and Near-Repeating Earthquake Detection and Analysis in Python. Seismological Research Letters 89, 173–181. https://doi.org/10.1785/0220170151

Cihad, S., Al-Heety, E., Abdulnaby, W., 2023. Relocation and Magnitude for Earthquakes in the Outer Arabian Platform of Iraq. Iraqi Geological Journal 56, 198–215. https://doi.org/10.46717/igj.56.1B.15ms-2023-2-23

Daniels, C., Peng, Z., 2023. A 15-year-Long catalog of seismicity in the Eastern Tennessee Seismic Zone (ETSZ) using matched filter detection. Earthquake Research Advances 3, 100198. https://doi.org/10.1016/j.eqrea.2022.100198

Earle, P.S., Shearer, P.M., 1994. Characterization of global seismograms using an automatic-picking algorithm. Bulletin of the Seismological Society of America 84, 366–376. https://doi.org/10.1785/BSSA0840020366

Felix, R.P., Hubbard, J.A., Bradley, K.E., Lythgoe, K.H., Li, L., Switzer, A.D., 2022. Tsunami hazard in Lombok and Bali, Indonesia, due to the Flores back-arc thrust. Natural Hazards and Earth System Sciences 22, 1665–1682. https://doi.org/10.5194/nhess-22-1665-2022

Foti, S., Hollender, F., Garofalo, F., Albarello, D., Asten, M., Bard, P.-Y., Comina, C., Cornou, C., Cox, B., Di Giulio, G., Forbriger, T., Hayashi, K., Lunedei, E., Martin, A., Mercerat, D., Ohrnberger, M., Poggi, V., Renalier, F., Sicilia, D., Socco, V., 2018. Guidelines for the good practice of surface wave analysis: a product of the InterPACIFIC project. Bulletin of Earthquake Engineering 16, 2367–2420. https://doi.org/10.1007/s10518-017-0206-7

Gao, D., Kao, H., Wang, B., 2021. Misconception of Waveform Similarity in the Identification of Repeating Earthquakes. Geophys Res Lett 48. https://doi.org/10.1029/2021GL092815

Hadi, A., Brotopuspito, K., Pramumijoyo, S., Hardiyatmo, H., 2018. Regional Landslide Potential Mapping in Earthquake-Prone Areas of Kepahiang Regency, Bengkulu Province, Indonesia. Geosciences (Basel) 8, 219. https://doi.org/10.3390/geosciences8060219

Handayani, L., 2020. Seismic Hazard Analysis of Maumere, Flores: a Review of the Earthquake Sources, in: Proceedings of the Proceedings of the 7th Mathematics, Science, and Computer Science Education International Seminar, MSCEIS 2019, 12 October 2019, Bandung, West Java, Indonesia. EAI. https://doi.org/10.4108/eai.12-10-2019.2296247

Hosseini, K., Sigloch, K., 2017. ObspyDMT: a Python toolbox for retrieving and processing large seismological data sets. Solid Earth 8, 1047–1070. https://doi.org/10.5194/se-8-1047-2017

Jafari, M., Aflaki, M., Mousavi, Z., Walpersdorf, A., Motaghi, K., 2023. Coseismic and postseismic characteristics of the 2021 Ganaveh earthquake along the Zagros foredeep fault based on InSAR data. Geophys J Int. https://doi.org/10.1093/gji/ggad127

Jufriansah, A., Anggraini, A., Zulfakriza, Z., Khusnani, A., Pramudya, Y., 2023a. Forecast earthquake precursor in the Flores Sea. Indonesian Journal of Electrical Engineering and Computer Science 32, 1825. https://doi.org/10.11591/ijeecs.v32.i3.pp1825-1836

Jufriansah, A., Khusnani, A., Pramudya, Y., Afriyanto, M., 2023b. Comparison of aftershock behavior of the flores sea 12 december 1992 and 14 december 2021. Journal of Physics: Theories and Applications 7, 65-74. https://doi.org/https://doi.org/10.20961/jphystheor-appl.v7i1.71609

Jufriansah, A., Pramudya, Y., Khusnani, A., Saputra, S., 2021. Analysis of Earthquake Activity in Indonesia by Clustering Method. Journal of Physics: Theories and Applications 5, 92. https://doi.org/10.20961/jphystheor-appl.v5i2.59133

Khusnani, A., Jufriansah, A., Afriyanto, M., 2022. Utilization of Seismic Data as a Tsunami Vulnerability Review. Indonesian Review of Physics 5, 66–72. https://doi.org/https://doi.org/10.12928/irip.v5i2.6706

Khusnani, A., Jufriansah, A., Welly, O., Thalo, J., 2023. Tsunami event in Flores: literature review. Journal of Physics: Theories and Applications J. Phys.: Theor. Appl 7, 139–151. https://doi.org/10.20961/jphystheor-appl.v7i2.74625

Kiswanti, S., Palupi, I.R., Raharjo, W., Arwa, F.Y., Dwiyanti, N.E., 2021. The Study of Automatic Picking of P and S Wave Arrival and Identification of Earthquake Sequence Pattern using Scalogram in Obspy (Python). IOP Conf Ser Earth Environ Sci 873, 012014. https://doi.org/10.1088/1755-1315/873/1/012014

Krischer, L., Megies, T., Barsch, R., Beyreuther, M., Lecocq, T., Caudron, C., Wassermann, J., 2015. ObsPy: a bridge for seismology into the scientific Python ecosystem. Comput Sci Discov 8, 014003. https://doi.org/10.1088/1749-4699/8/1/014003

Lomax, A., Savvaidis, A., 2022. High-Precision Earthquake Location Using Source-Specific Station Terms and Inter-Event Waveform Similarity. J Geophys Res Solid Earth 127. https://doi.org/10.1029/2021JB023190

Lythgoe, K., Muzli, M., Bradley, K., Wang, T., Nugraha, A.D., Zulfakriza, Z., Widiyantoro, S., Wei, S., 2021. Thermal squeezing of the seismogenic zone controlled rupture of the volcano-rooted Flores Thrust. Sci Adv 7. https://doi.org/10.1126/sciadv.abe2348

Maneno, R., Sentosa, B.J., Rachman, G., 2019. Relocation Of Earthquake Hypocenter In The Flores Region Using Hypo71. IPTEK The Journal of Engineering 5. https://doi.org/10.12962/j23378557.v5i2.a5024

Megies, T., Beyreuther, M., Barsch, R., Krischer, L., Wassermann, J., 2011. ObsPy – What can it do for data centers and observatories? Annals of Geophysics 54. https://doi.org/10.4401/ag-4838

Mousavi, S., Hejrani, B., Miller, M.S., Salmon, M., 2023. Hypocenter, Fault Plane, and Rupture Characterization of Australian Earthquakes: Application to the September 2021 Mw 5.9 Woods Point Earthquake. Seismological Research Letters. https://doi.org/10.1785/0220220348

Priyambada, F.R., Nugraha, A.D., Supendi, P., 2022. Hypocenter Determination using a Non-Linear Method in Bali, Lombok, and Nusa Tenggara Regions: Preliminary Result. J Phys Conf Ser 2243, 012008. https://doi.org/10.1088/1742-6596/2243/1/012008

Ramdhan, M., Priyobudi, Mursityanto, A., Palgunadi, K.H., Daryono, 2021. Analysis of M 5.3 Sumbawa, Indonesia earthquake 2020 and its aftershocks based on hypocenter relocation from BMKG seismic stations. IOP Conf Ser Earth Environ Sci 873, 012070. https://doi.org/10.1088/1755-1315/873/1/012070

Rincon-Yanez, D., De Lauro, E., Petrosino, S., Senatore, S., Falanga, M., 2022. Identifying the Fingerprint of a Volcano in the Background Seismic Noise from Machine Learning-Based Approach. Applied Sciences 12, 6835. https://doi.org/10.3390/app12146835

Rosid, M.S., Widyarta, R., Karima, T., Wijaya, S.K., Rohadi, S., 2020. Fault Plane Estimation Through Hypocentres Distribution of the July-August 2018 Lombok Earthquakes Relocated by using Double Difference Method. IOP Conf Ser Mater Sci Eng 854, 012053. https://doi.org/10.1088/1757-899X/854/1/012053

Salvermoser, J., Hadziioannou, C., Hable, S., Krischer, L., Chow, B., Ramos, C., Wassermann, J., Schreiber, U., Gebauer, A., Igel, H., 2017. An Event Database for Rotational Seismology. Seismological Research Letters 88, 935–941. https://doi.org/10.1785/0220160184

Sasmi, A.T., Nugraha, A.D., Muzli, M., Widiyantoro, S., Zulfakriza, Z., Wei, S., Sahara, D.P., Riyanto, A., Puspito, N.T., Priyono, A., Greenfield, T., Afif, H., Supendi, P., Daryono, D., Ardianto, A., Syahbana, D.K., Husni, Y.M., Prabowo, B.S., Narotama Sarjan, A.F., 2020. Hypocenter and Magnitude Analysis of Aftershocks of the 2018 Lombok, Indonesia, Earthquakes Using Local Seismographic Networks. Seismological Research Letters 91, 2152–2162. https://doi.org/10.1785/0220190348

Saygin, E., Cummins, P.R., Lumley, D., 2017. Retrieval of the P wave reflectivity response from autocorrelation of seismic noise: Jakarta Basin, Indonesia. Geophys Res Lett 44, 792–799. https://doi.org/10.1002/2016GL071363

Supendi, P., Rawlinson, N., Prayitno, B.S., Widiyantoro, S., Simanjuntak, A., Palgunadi, K.H., Kurniawan, A., Marliyani, G.I., Nugraha, A.D., Daryono, D., Anugrah, S.D., Fatchurochman, I., Gunawan, M.T., Sadly, M., Adi, S.P., Karnawati, D., Arimuko, A., 2022. The Kalaotoa Fault: A Newly Identified Fault that Generated the Mw 7.3 Flores Sea Earthquake. The Seismic Record 2, 176–185. https://doi.org/10.1785/0320220015

Turner, R.J., Latto, R.B., Reading, A.M., 2021. An ObsPy library for event detection and seismic attribute calculation: preparing waveforms for automated analysis.

Yin, J., Denolle, M.A., Yao, H., 2018. Spatial and Temporal Evolution of Earthquake Dynamics: Case Study of the Mw 8.3 Illapel Earthquake, Chile. J Geophys Res Solid Earth 123, 344–367. https://doi.org/10.1002/2017JB014265