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Macroseismic Analysis of the 2023 Earthquakes in Jayapura

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Abstract: On January 2 and February 9, 2023, two significant earthquakes struck Jayapura City, leading to widespread panic, severe damage to buildings and public infrastructure, and multiple casualties. In response, the BBMKG V Earthquake Survey Team conducted a macroseismic study to evaluate the geological impacts, assess community responses, and document the overall effects of the earthquakes. The methodology employed included structured interviews and questionnaires administered to affected residents. The study revealed that soft rock conditions in the area contributed to an MMI scale VI impact, which resulted in extensive damage to public facilities and residential buildings. The insights gained from this study offer valuable information for improving future earthquake mitigation strategies and enhancing preparedness in seismically vulnerable regions.

Keywords: Macroseismic, Earthquake, Jayapura, Local Site Effects, MMI Scale

INTRODUCTION

Indonesia, situated within the Pacific Ring of Fire, is one of the most seismically active regions in the world due to the convergence of several tectonic plates, including the Indo-Australian, Eurasian, and Pacific plates (McCaffrey, 2009; PuSGeN, 2017). The complex interaction of these plates results in frequent seismic activity, making earthquakes a common phenomenon. The tectonic setting of Indonesia is depicted in Figure 1, highlighting the high-risk zones for seismic activity across the region. These seismic events often have devastating consequences, ranging from minor tremors to large-scale destruction that impacts both infrastructure and human lives. The potential hazards include ground shaking, surface rupture, landslides, liquefaction, and, in some cases, the generation of tsunamis (Prawirodikromo, 2012; Sinhval, 2010).

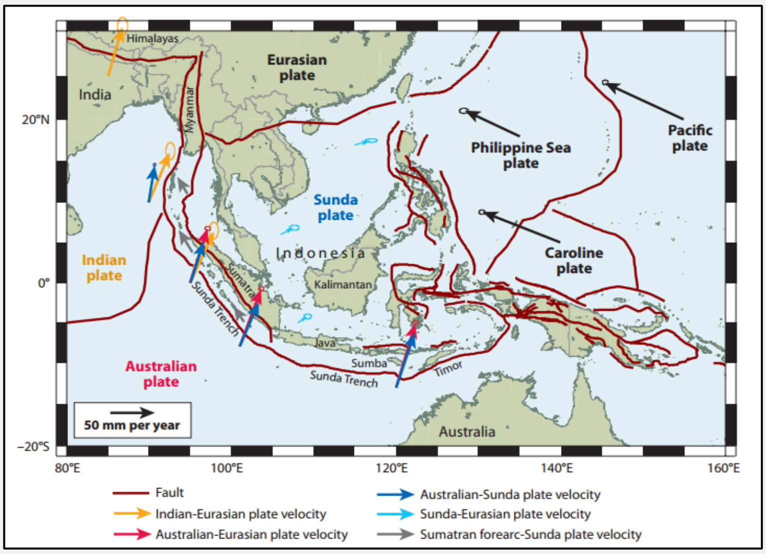

Figure 1. Indonesian Tectonic Setting (McCaffrey, 2009).

In the context of urban centers like Jayapura City, located in Papua, eastern Indonesia, the geological conditions of the region make it particularly vulnerable to earthquakes. The local geology, composed primarily of alluvial sediments and soft rock, exacerbates the intensity of seismic waves, leading to more severe surface impacts during an earthquake. This is especially relevant when considering the macroseismic effects of earthquakes on different soil types, which amplify shaking and result in greater damage to structures in affected areas.

On January 2, 2023, an earthquake with a magnitude of M4.9 (later updated to M5.2) struck Jayapura City, marking the beginning of a seismic sequence that would continue into February. This initial earthquake was followed by another significant event on February 9, 2023. The impacts of these events are visualized in Figure 2 and Figure 3, which show the widespread damage caused by the January 2 and February 9 earthquakes, respectively. The earthquakes triggered widespread panic and caused substantial damage to both public and private infrastructure. The destruction included the collapse of vital government buildings, hotels, residential structures, and roads, severely disrupting the daily life of residents. Additionally, the shaking resulted in neighborhood-wide evacuations as people fled their homes in fear of further tremors (BPBD, 2023).

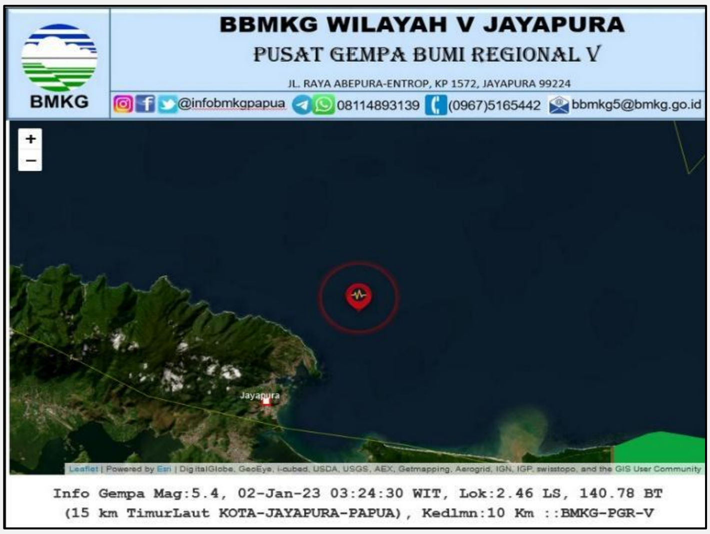

Figure 2. Infographic of the January 2, 2023 earthquake.

Figure 3. Infographic of the February 9, 2023 earthquake.

One of the key factors contributing to the severity of the damage in Jayapura is the nature of the local soil and geological formations. Jayapura's subsurface consists largely of sedimentary layers, which tend to amplify the shaking experienced at the surface, as opposed to more rigid bedrock, which can dissipate seismic energy more effectively. This amplifying effect of the soft ground, coupled with the region's proximity to tectonic activity, has long been recognized as a critical factor in the high vulnerability of Jayapura to seismic events.

In light of these conditions, understanding the macroseismic impacts of the January and February 2023 earthquakes is essential for future earthquake preparedness and mitigation strategies. Macroseismic studies involve the examination of earthquake effects on the Earth's surface, such as building damage, ground deformation, and community response, and offer critical insights for disaster risk reduction. The earthquake intensity scale used in these studies is illustrated in Figure 4, providing a framework for classifying the observed effects. This study, therefore, aims to analyze the macroseismic impacts of these earthquakes, with a focus on geological conditions, community reactions, and the extent of damage to public infrastructure. Through a detailed macroseismic analysis, the study seeks to contribute valuable information that could guide future earthquake mitigation efforts, especially in areas with similar geological conditions and seismic risk.

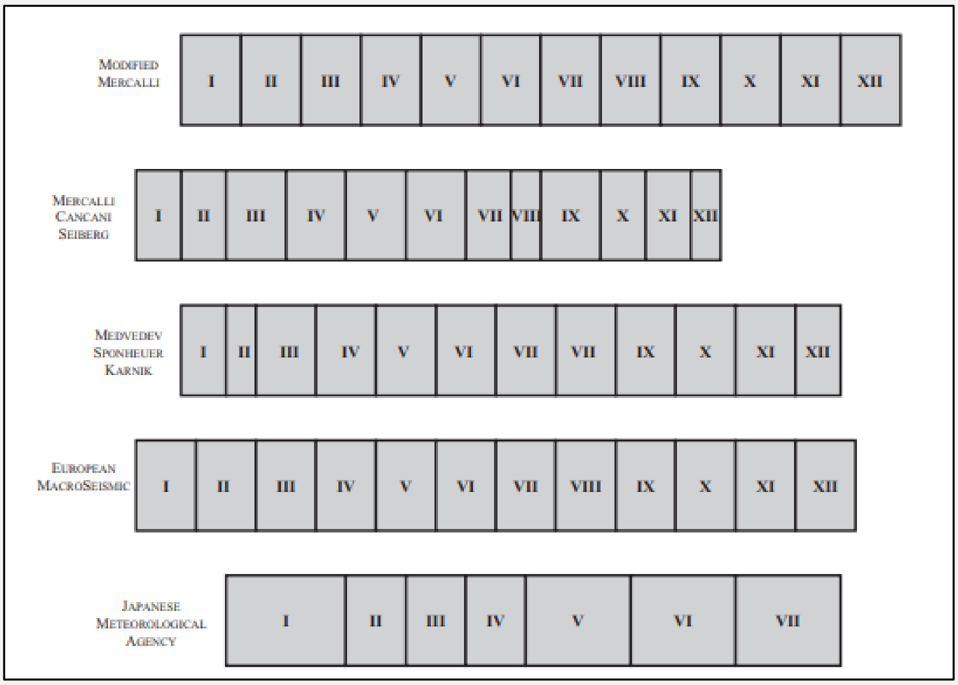

Figure 4. Earthquake Intensity Scale (Elnashai, and Di Sarno, 2008).

Moreover, by examining how Jayapura's geology amplified the seismic effects, this research highlights the need for more rigorous seismic building codes and better land-use planning in earthquake-prone regions of Indonesia. Enhancing earthquake resilience through informed urban planning and engineering practices is critical to minimizing future loss of life and property in cities like Jayapura.

METHOD

An earthquake is defined as the shaking of the Earth's surface, resulting from the sudden release of energy in the Earth's crust due to the fracturing of rocks (Lay & Wallace, 1995; Prawirodikromo, 2012). This release of energy causes seismic waves that propagate through the Earth's surface, leading to various degrees of shaking and potential damage to infrastructure and the environment. The magnitude of an earthquake is a numerical measure of its strength, typically represented by the Richter scale or other magnitude scales. In contrast, the Modified Mercalli Intensity (MMI) scale is used to quantify the effects of an earthquake on the environment, structures, and the population based on observed responses rather than instrumental readings.

The MMI scale classifies earthquake intensity into different levels based on the visible damage to buildings, the movement of objects, and the experiences of people during the quake. This scale is crucial for assessing the severity of an earthquake's impact at specific locations (Mulgaria & Geller, 2003; Shroder & Wyss, 2014; Sucuoğlu & Akkar, 2014). Figure 4 illustrates the earthquake intensity scale and its corresponding impact levels. Additionally, earthquake intensity can be measured by the Peak Ground Acceleration (PGA), which is the maximum shaking experienced at a particular site, as recorded by accelerometers (Mulgaria & Geller, 2003). The PGA value provides a direct measure of the strength of ground shaking, making it a vital parameter in understanding the destructive potential of an earthquake.

Macroseismic Study Approach

Macroseismic studies focus on field surveys conducted at the earthquake-affected location to assess the damage and response of the community. This method allows for a detailed examination of the aftermath of an earthquake, evaluating several factors such as building damage, the extent of environmental disruption, and community reactions (Mulgaria & Geller, 2003; Shroder & Wyss, 2014; Sucuoğlu & Akkar, 2014). Macroseismic data collection is essential in classifying the earthquake's impact on the ground surface and understanding how various factors, such as geological conditions and building structures, influence the degree of damage.

In this study, the primary data collection method involved a combination of on-site surveys and the use of questionnaires designed to gather information about the earthquake's effects. A team of field researchers visited the earthquake-affected areas to observe and record structural damage, while the questionnaire was used to capture community responses to the seismic events. The aim was to gather comprehensive data on how the earthquakes affected different locations and the extent to which local geological conditions exacerbated or mitigated the damage.

Data Collection Techniques

The primary data for this research were gathered through structured questionnaires, which were directly administered to individuals in the earthquake-affected areas. These questionnaires were designed following the standards set by the GFZ German Institute, ensuring consistency and reliability in the data collected (Appendix A). The questions aimed to elicit responses about personal experiences, such as the intensity of shaking, the visibility of damage to buildings, and the overall response of the community. This standardized approach allows for a consistent comparison of results across different locations and demographic groups.

According to Musson (2009), questionnaires for macroseismic studies can be administered to different categories of respondents, including unselected individuals, randomly selected participants, public officials, and volunteers. Each of these respondent categories contributes valuable perspectives on the earthquake's effects. For example:

- *Unselected individuals* provide a broad sample of responses, but their answers may be biased toward more positive assessments due to the convenience sampling method.
- *Randomly selected individuals* offer a more statistically valid dataset, as they are selected through random sampling procedures, such as electoral rolls or direct mailing. This method ensures the representativeness of the population and allows for more generalizable conclusions about the earthquake's impact.
- *Public officials* can provide detailed insights into the infrastructural damage and administrative responses to the earthquake.
- *Volunteers* are typically more motivated to contribute accurate and detailed observations, especially if they have firsthand experience of the event. However, reliance on volunteers may introduce biases, as they might only report extreme cases of damage or community disruption.

Questionnaire Design

The questionnaire used in this study was primarily closed-ended, meaning respondents were asked to select one of the provided answers that best described their experience. This type of questionnaire is particularly effective in macroseismic studies because it reduces ambiguity and ensures that responses can be easily categorized and analyzed (Musson, 2009). The questions were focused on specific indicators of earthquake intensity, such as:

- *Physical responses to the quake:* Did the respondent feel the ground shaking, and if so, how strongly?
- *Damage to the surroundings:* Were there visible signs of damage to buildings, such as cracks in walls or collapsed structures?
- *Community actions:* Did people in the vicinity evacuate buildings, and what was the general reaction to the earthquake?

Respondents were categorized based on their proximity to the earthquake's epicenter, as well as their location within urban or rural areas. This classification allowed for a detailed analysis of how location-specific factors, such as soil conditions and building types, influenced the reported intensity and damage levels.

Data Interpretation

The responses collected through the questionnaires were then used to estimate the MMI scale for each surveyed area. For instance, if respondents reported minor effects, such as a few people feeling the tremor or objects vibrating slightly, the intensity was classified as II-III on the MMI scale. In cases where respondents described more significant experiences—such as body swaying, strong tremors, and people fleeing buildings—the intensity was classified as IV-V MMI.

This structured approach to data collection ensures that the resulting macroseismic study provides an accurate and detailed picture of how the 2023 earthquakes impacted different areas of Jayapura. The combination of survey observations and questionnaire data allowed the research team to develop a comprehensive understanding of the seismic events, offering insights that can inform future disaster preparedness and mitigation strategies.

RESULTS & DISCUSSION

The macroseismic survey conducted in Jayapura in the aftermath of the January and February 2023 earthquakes revealed significant variations in the Modified Mercalli Intensity (MMI) across different locations in both Jayapura Utara and Jayapura Selatan. Table 1 presents the macroseismic survey results, detailing the intensity of ground shaking experienced at specific locations based on observations and community responses.

Table 1. Macroseismic Survey Results

Jayapura Utara	MMI	Jayapura Selatan	MMI
Governor's Office	IV	Hotel Horison Abepura	III
Swiss-Belhotel	IV	Tanah Hitam Complex	III
DPRP Building	IV	Hotel Grand Abe	II-III
GKN Building	IV	TRIA (Tanah Hitam Resident)	III
Hotel Mercure	IV	Hotel Sunny Abepura	IV-V
R.S. Provita	IV	Organda Dalam	III-IV
Mall Jayapura	IV	Danau Kalakote	III
Perumahan Permata Hijau	III	Kios B Sunik	III

The results show that the highest intensities, around IV-V on the MMI scale, were recorded in several key locations such as Hotel Sunny Abepura and Organda Dalam. These findings align with the overall pattern of seismic activity recorded during the earthquake. The MMI scale results obtained from accelerograph recordings (Figure 5) showed that the earthquake reached a maximum intensity of MMI V in certain areas, indicating severe ground shaking that caused significant structural damage. These accelerograph readings were supported by community feedback, where many respondents reported fleeing their homes in panic as buildings shook violently.

Badan Meteorologi Klimatologi dan Geofisika
Laporan Kejadian Gempabumi Bidang Seismologi Teknik

Gempabumi 02 Januari 2023, jam 01:24:33 WIB, Mag:4.9, Lat:2.53°LS, Long:140.74°BT, Kedalaman:10 Km, di darat 14 km Timur Laut Kota Jayap

No	IdSta	Stasiun	Latitude	Longitude	Jarak	MMI	PGA-EW(gal)	PGA-NS(gal)	PGA-UD(gal)
1	JGPI	STA GEOF ANGKASA	-2.515	140.704	4.35	IV	20.5192	21.6678	10.9466
2	JBPI	BALAI BESAR WILAYAH V JAYAPURA	-2.570	140.680	8.01	IV	15.4850	13.9062	7.7969
3	JMPI	STA MET JAYAPURA	-2.576	140.519	25.07	IV	9.4031	12.3745	7.4549
4	ARPI	Arso ,Keerom,Papua	-2.901	140.756	41.34	IV	4.1650	2.9478	2.1609

Figure 5. Accelerograph recording results of the January 2, 2023 earthquake.

The widespread damage caused by the earthquakes can be attributed to the unique geological conditions of Jayapura. The accelerograph data showed that the highest Peak Ground Acceleration (PGA) was recorded at the Space Class 1 Geophysical Station, located near the earthquake epicenter. In contrast, lower PGA values were recorded at stations farther away, such as Arso Keerom. The variation in PGA values is critical in understanding how seismic energy dissipates across different regions, which in turn affects the intensity of the earthquake's impact. Figure 6 shows the MMI scale distribution map based on community responses to the January 2, 2023, earthquake, illustrating the geographical variation in earthquake intensity.

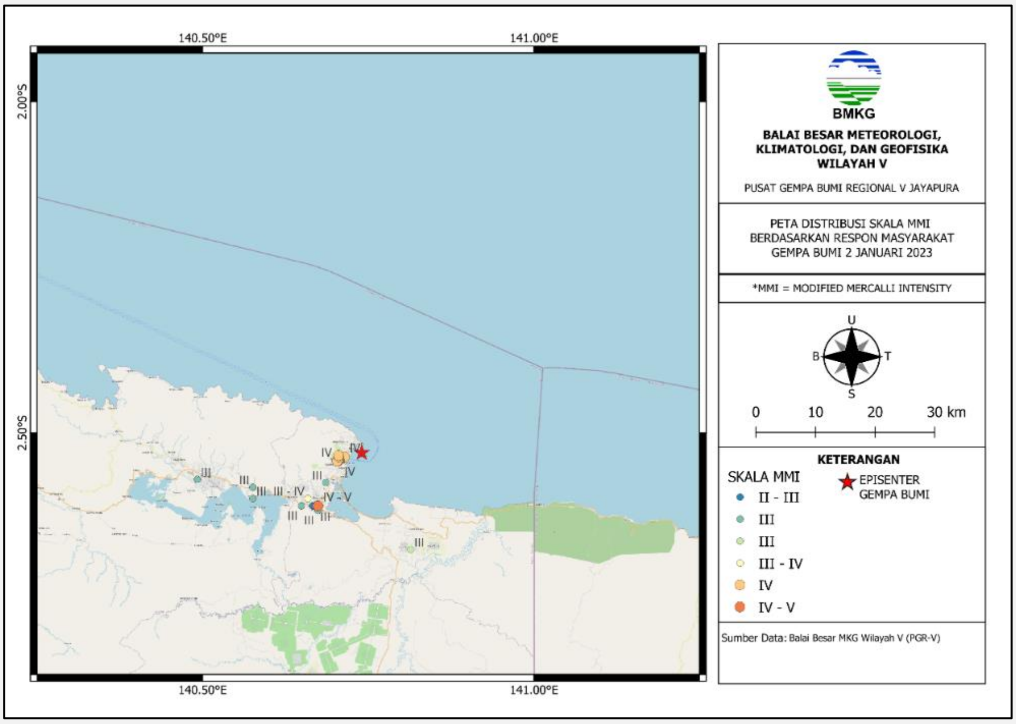

Figure 6. MMI Scale Distribution Map Based on Community Response to the January 2, 2023 Earthquake.

Distribution of Damage

The distribution of damage throughout Jayapura closely followed the variations in PGA and MMI scale intensity. The most significant damage occurred near the epicenter, where the ground shaking was most intense. For instance, the Sunni Abepura Hotel, which experienced substantial damage, is located relatively far from the epicenter. However, its geological setting made it more vulnerable. This hotel is situated on soft, alluvial sedimentary soil, which tends to amplify seismic waves, leading to greater structural damage. The geological map of Jayapura (Figure 7) provides further insight into the distribution of damage by showing the types of rock formations in the region, such as limestone and claystone, which exhibit poor resistance to seismic waves.

This observation is consistent with studies that show how geological conditions play a pivotal role in amplifying or mitigating seismic impacts. Soft soils, like those found in Jayapura, do not attenuate seismic waves effectively. As a result, buildings and infrastructure located on these soils are more likely to experience severe shaking, even when they are relatively far from the earthquake's epicenter (Prawirodikromo, 2012). In contrast, areas with more stable bedrock are less susceptible to amplification and generally experience less severe shaking.

Peak Ground Acceleration (PGA) Analysis

The analysis of PGA values offers critical insights into the mechanics of the earthquake's impact. High PGA values, such as those recorded near the earthquake's epicenter, are associated with strong, high-frequency shaking. This type of shaking can cause extensive damage to buildings, especially if they are not designed to withstand such forces. The data collected from the Space Class 1 Geophysical Station indicates that the proximity to the earthquake's epicenter resulted in high-frequency vibrations, leading to severe ground shaking.

In contrast, lower PGA values were recorded at the Arso Keerom Station, which is located farther from the epicenter. This station recorded low-frequency ground motion, which tends to cause less structural damage, particularly to well-constructed buildings. However, long-distance earthquakes with low-frequency vibrations can still cause significant damage to soft ground or poorly constructed buildings due to the elastic response of the soil. As such, buildings situated on soft ground far from the epicenter, like the Sunni Abepura Hotel, may experience amplified ground motion, leading to greater damage despite the distance from the source of the earthquake.

The interplay between PGA values, soil conditions, and building resilience is evident in the varying levels of damage observed in different locations. Areas with soft soil, such as those on alluvial deposits, experienced higher levels of shaking due to the amplification of seismic waves. The Sunni Abepura Hotel serves as a key example of how geological conditions can exacerbate damage even in areas that are not in close proximity to the epicenter.

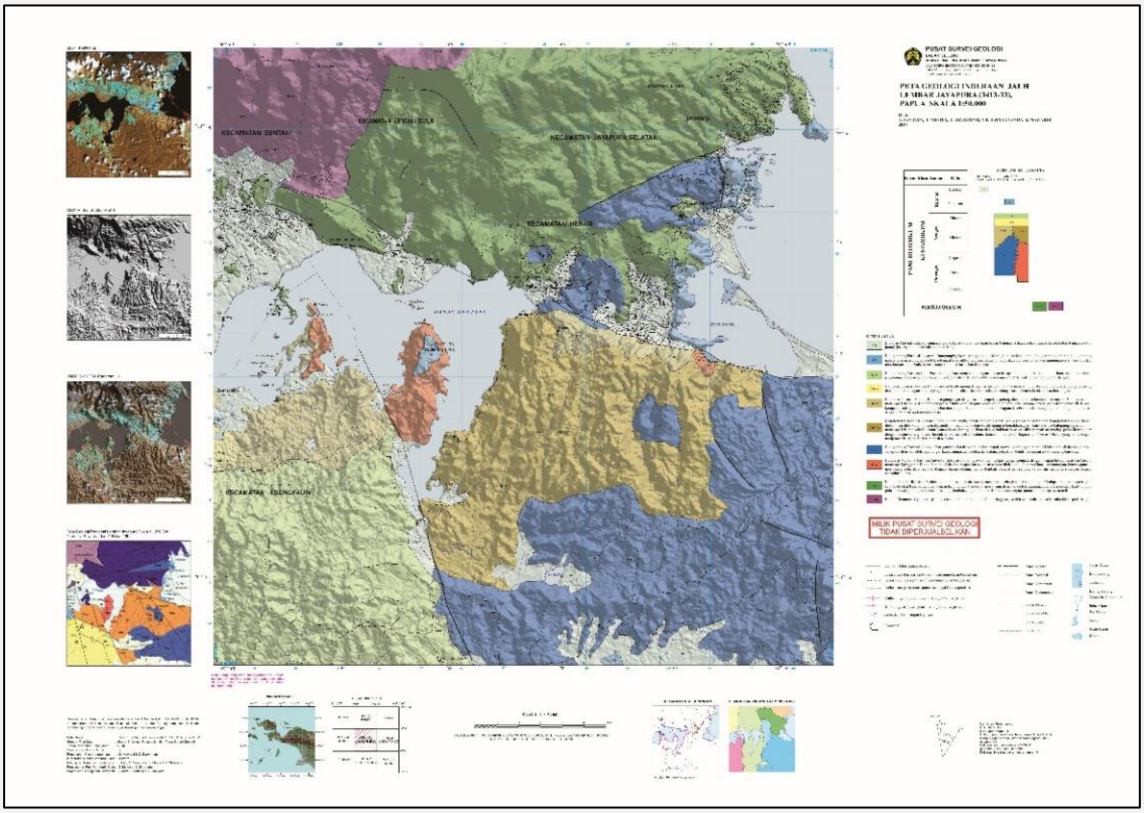

Figure 7. Jayapura Geological Map (Pusat Survei Geologi, 2010).

Geological Impact and Community Response

The geological composition of Jayapura, as depicted in Figure 7, shows a predominance of alluvial sedimentary soils, claystone, and limestone, all of which are particularly vulnerable to seismic shaking. These soils and rock formations have low attenuation properties, meaning they do not effectively reduce the energy of seismic waves. When an earthquake strikes, buildings on these types of soils tend to experience more intense shaking, leading to a higher likelihood of damage or collapse.

Community responses collected through the questionnaire further corroborate the macroseismic data. Many residents reported feeling strong shaking and experiencing structural damage to their homes, particularly in areas with soft soil conditions. The fragility of the local geology was also highlighted by residents living in areas like Organda Dalam and Danau Kalakote, who reported significant disruptions to their daily lives due to the earthquake. This highlights the need for improved disaster preparedness and infrastructure resilience in areas with similar geological vulnerabilities.

Discussion of Findings

The findings of this macroseismic study underscore the critical importance of considering both geological conditions and proximity to the earthquake epicenter when assessing the potential impact of seismic events. While areas close to the epicenter generally experience the strongest shaking, geological factors such as soil composition can greatly influence the severity of the impact. The amplification of seismic waves in soft soil regions, as seen in Jayapura, can lead to disproportionately high levels of damage in areas that would otherwise be expected to experience moderate shaking.

This research highlights the need for stricter building codes in regions with vulnerable geological conditions. By improving the structural resilience of buildings and infrastructure, future damage in earthquake-prone areas can be minimized. Additionally, the findings point to the importance of disaster preparedness programs that take into account local geology and the specific vulnerabilities of different communities. Areas like Jayapura, which are situated on soft soils, require particular attention in disaster risk reduction planning.

CONCLUSION

The findings of this study highlight the critical influence of both geological conditions and proximity to the epicenter on the severity of earthquake impacts. Respondents located close to the epicenter reported significant experiences, such as strong shaking, structural damage, and environmental disruptions. However, the study also reveals that the condition of local soils and rock formations plays an equally important role. Even in areas farther from the epicenter, the presence of soft, sedimentary rocks such as alluvial soils, claystone, and limestone amplified the shaking, leading to extensive damage, as observed in the Sunni Abepura Hotel and other locations.

This research underscores the need for a more comprehensive approach to earthquake mitigation and preparedness, particularly in regions with vulnerable geological conditions. Areas built on soft soils are more susceptible to seismic wave amplification, resulting in greater damage than regions with more stable bedrock. Therefore, stricter building codes, tailored to the specific geological characteristics of earthquake-prone areas, are essential to minimizing future damage. This includes the reinforcement of structures, improved land-use planning, and the application of seismic-resistant construction techniques.

Furthermore, the results emphasize the importance of ongoing public education and preparedness programs in communities vulnerable to seismic activity. Ensuring that residents are aware of the risks associated with their local geology and equipped with knowledge on how to respond effectively during an earthquake is crucial for reducing casualties and property loss in future seismic events.

The macroseismic analysis of the 2023 Jayapura earthquakes provides valuable insights into the complex interplay between geological conditions and seismic impacts. These findings can inform future urban planning and infrastructure development, helping to build more resilient communities in regions with high seismic risk. Special attention should be given to areas like Sunni Abepura, where soft geological conditions contribute to disproportionate damage, making them prime candidates for targeted mitigation efforts.

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