Surface Rupture and Fault Characteristics Associated with the 2020 Magnitude ($M_W$) 6.6 Masbate Earthquake, Masbate Island, Philippines

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Abstract

The magnitude ($M_W$) 6.6 earthquake that struck Masbate Island on 18 August 2020 offers a unique opportunity to investigate the slip and seismic behavior of the Philippine Fault in the Masbate region. In this study, we employ InSAR, seismicity analysis, and field investigations to comprehensively characterize the coseismic and postseismic slip associated with the event. Our findings reveal a 50-km-long fault rupture along the Masbate segment of the Philippine Fault, with ~23 km surface rupture mapped onshore, despite the occurrence of interseismic creep. The slip distribution demonstrates decreasing displacements northwestward towards the creeping section, with a maximum left-lateral displacement of 0.97 m near the epicenter. Toward the southeast offshore, the rupture terminates at a fault left stepover. While the surface rupture appears relatively straight and narrowly concentrated, the secondary ruptures and mapped offshore faults reveal a more complex transtensional fault structure in the vicinity of Cataingan Bay. This fault complexity represents an asperity that facilitates high-stress accumulation and rupture initiation. Postseismic slip persists for several months along the onshore creeping segment. We derived a slip rate of 2.8 to 4.3 cm/year from long-term and short-term slip measurements. Furthermore, we calculated a recurrence interval of 16 to 41 years for earthquakes similar to the 2020 Masbate earthquake. Our study highlights how heterogeneity in fault properties, including geometry and coupling state, influences the distribution of slip and magnitude of earthquakes. The 2020 Masbate earthquake provides valuable insights into the rupture dynamics and fault behavior of the Philippine Fault in the Masbate region.
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Key Points:

- The 2020 Masbate earthquake nucleated offshore along the Philippine Fault, rupturing 23 km onshore accompanied by postseismic slip.

- The Masbate segment of the Philippine Fault is characterized by both aseismic and seismic slip which account for the total slip budget.

- The earthquake demonstrated how fault properties, such as geometry and coupling, control the deformation and seismic behavior of faults.
Abstract

The magnitude ($M_W$) 6.6 earthquake that struck Masbate Island on 18 August 2020 offers a unique opportunity to investigate the slip and seismic behavior of the Philippine Fault in the Masbate region. In this study, we employ InSAR, seismicity analysis, and field investigations to comprehensively characterize the coseismic and postseismic slip associated with the event. Our findings reveal a 50-km-long fault rupture along the Masbate segment of the Philippine Fault, with ~23 km surface rupture mapped onshore, despite the occurrence of interseismic creep. The slip distribution demonstrates decreasing displacements northwestward towards the creeping section, with a maximum left-lateral displacement of 0.97 m near the epicenter. Toward the southeast offshore, the rupture terminates at a fault left stepover. While the surface rupture appears relatively straight and narrowly concentrated, the secondary ruptures and mapped offshore faults reveal a more complex transtensional fault structure in the vicinity of Cataingan Bay. This fault complexity represents an asperity that facilitates high-stress accumulation and rupture initiation. Postseismic slip persists for several months along the onshore creeping segment. We derived a slip rate of 2.8 to 4.3 cm/year from long-term and short-term slip measurements. Furthermore, we calculated a recurrence interval of 16 to 41 years for earthquakes similar to the 2020 Masbate earthquake. Our study highlights how heterogeneity in fault properties, including geometry and coupling state, influences the distribution of slip and magnitude of earthquakes. The 2020 Masbate earthquake provides valuable insights into the rupture dynamics and fault behavior of the Philippine Fault in the Masbate region.

Plain Language Summary

The 2020 earthquake on Masbate Island, Philippines, provided an opportunity to study how faults behave during earthquakes. We used different methods to understand the movement of the ground during and after the earthquake. We found that the fault ruptured for about 23 kilometers on land, despite it moving slowly before the earthquake. The rest of the rupture extends along the offshore extension of the fault. The fault is more complex near Cataingan Bay. After the earthquake, the ground continued to move for several months along the fault. Our research helps us understand how different factors affect earthquakes, which is important for predicting and preparing for future earthquakes in the region.

1 Introduction

The Philippine Fault has been responsible for several significant earthquakes throughout its history. Over the past five decades, multiple surface-rupturing earthquakes have been recorded along the fault (Figure 1a). These include the 1973 $M_L$ 7.0 Ragay Gulf (Morante, 1974; Tsutsumi et al., 2015), the 1990 $M_S$ 7.8 Luzon (Nakata et al., 1996), the 2003 $M_S$ 6.2 Masbate (Besana and others, 2004; Besana & Ando, 2005; Papiona & Kinugasa, 2008), the 2017 $M_W$ 6.7 Surigao del Norte (PHIVOLCS Quick Response Team, 2017; Marfito et al., 2022), and the 2017 $M_W$ 6.5 Leyte (Llamas et al., 2017; Dianala et al., 2020).

On 18 August 2020, a magnitude ($M_W$) 6.6 earthquake struck off the southeastern coast of Masbate Island (Figure 1b). The hypocenter was located southeast of Cataingan, Masbate (11.98° N, 124.01° E) with a depth of 13 km (PHIVOLCS, 2021a). Ground shaking was felt in the entire Bicol Region and many parts of the Visayas. The highest felt intensity, corresponding to PHIVOLCS Earthquake Intensity Scale (PEIS) VII (Destructive; equivalent to Modified Mercalli Intensity Scale or MMI VII), occurred in areas along the eastern portion of Masbate Island, while
the rest of the island experienced intensities ranging from PEIS III (Weak; MMI III) to PEIS VI (Very Strong; MMI VI). This earthquake caused casualties and severe damage to houses and infrastructures. It also resulted in several environmental effects, such as liquefaction, sinkhole collapses, earthquake-induced landslides, and a localized tsunami. Earthquake data from the Philippine Institute of Volcanology and Seismology (PHIVOLCS) (2021a, 2021b), including distributions of aftershocks and focal mechanism solution, combinedly indicate a northwest-striking left-lateral strike-slip fault was responsible for the earthquake. The focal mechanism denotes a strike of 142°, a dip of 85° and a rake of 26° (PHIVOLCS, 2021b). This is consistent with the strike and kinematics of the Philippine Fault (Figure 1). This was confirmed by the presence of a surface rupture along the Philippine Fault: Masbate Segment (PFMS) initially observed by the PHIVOLCS Quick Response Team (QRT) a few days after the earthquake (PHIVOLCS, 2020).
Figure 1. The seismotectonic setting of the 2020 $M_w$ 6.6 Masbate Earthquake. (a) The Philippine Fault is a major left-lateral strike-slip fault that has generated large-magnitude earthquakes. PF – Philippine Fault, MT – Manila Trench, ELT – East Luzon Trough, PT – Philippine Trench, NT – Negrost Trench, ST – Sulu Trench, CT – Cotabato Trench. (b) Masbate Island is located in the
central portion of the Philippines and is traversed by PF along the southeastern portion of the island. (c) The $M_w$ 6.6 earthquake’s focal mechanism and aftershock distribution are consistent with the left-lateral Philippine Fault. The active fault traces (red lines) are from PHIVOLCS (2021c) and Tsutsumi and Perez (2013). The earthquake epicentral locations and the focal mechanism are also from PHIVOLCS (2021a, 2021b).

The 2020 Masbate earthquake marked the second occurrence of a significant earthquake with a magnitude greater than 6 that struck the island in a span of 17 years, following the 2003 MS 6.2 Masbate earthquake. This relatively short time interval between the two seismic events is particularly striking when considering that Papiona and Kinugasa (2008) had previously suggested a recurrence interval of 130 - 170 years for surface rupturing events along this fault segment. With very close proximity in both space and time, the occurrence of two strong earthquakes generated by the same fault segment offers a unique opportunity to gain insights into the seismic and slip behavior of the PFMS. Previous studies have provided valuable information regarding the 2003 earthquake, including its surface rupture characteristics, slip distribution, and observation of foreshocks and postseismic slip (Besana et al., 2004; Besana and Ando, 2005). While the 2003 earthquake originated in Naro Bay in the northern portion of the fault, the 2020 earthquake nucleated in Cataingan Bay in the southern portion (approximately 35 km southeast of the 2003 epicenter), and also produced surface rupture onshore. This unusual recurrence pattern challenges the established seismic recurrence models and underscores the need for further investigation into the seismic behavior of this fault segment.

In this study, we aim to comprehensively characterize the coseismic and postseismic slip of the 2020 Masbate earthquake through the integration of Interferometric Synthetic Aperture Radar (InSAR), field, and seismicity data. Moreover, we analyzed marine geophysical datasets to investigate the southeastern offshore trace of the Masbate fault segment and its subsurface geometry, and possibly constrain the extent and location of the fault rupture associated with the earthquake. Detailed information on the deformation characteristics associated with the 2020 earthquake, including extent, distribution, displacements, and sense of slip, is essentially important to explore how it compares with the previous events and how the PFMS accommodated the slip derived from the relative plate motion.

2 Seismotectonic Setting

Masbate Island is located in the central part of the Philippines. The Philippine archipelago is situated along a complex boundary between the northwestward drifting Philippine Sea Plate and the Sunda Plate (Figure 1a). The oblique convergence between these two tectonic plates produced two oppositely-dipping subduction systems bounding the archipelago. The Philippine Trench marks the west-dipping subduction zone, which is believed to be propagating along the east Luzon margin, while the east-dipping subduction zones comprise the Manila Trench, Negros Trench, Sulu Trench, and Cotabato Trench (Hamilton, 1979; Acharya & Aggarwal, 1980; Hamburger et al., 1983; Lewis & Hayes, 1983; Hayes & Lewis, 1985; Bautista et al., 2001). These trenches are major sites of seismicity and define the regions where the Cenozoic oceanic lithosphere surrounding the Philippines is being consumed (Cardwell et al., 1980; Aurelio, 2000). Aside from these subduction zones, numerous active faults straddle the Philippine archipelago that play a crucial role in accommodating the residual strain arising from the oblique convergence. These faults primarily operate as strike-slip faults to accommodate the lateral component of this oblique
convergence. A prominent fault within this context is the Philippine Fault, which effectively accommodates the trench parallel component of the slip resulting from the oblique convergence, thereby exemplifying the shear partitioning mechanism. (Fitch, 1972; Rangin, 1991; M. Aurelio, 2000). However, the occurrence of other faulting mechanisms, such as the reverse faulting observed during the 2012 Negros and 2013 Bohol earthquakes in the Central Philippines, challenges the simplicity of shear partitioning and advocates for a more complex model (Rimando et al., 2019; Rimando et al., 2020).

The ~1500-km-long NE-striking left-lateral Philippine Fault (Figure 3) spans the entire archipelago from northern Luzon to the east of Mindanao (Allen, 1962; Aurelio et al., 1997; Nakata et al., 1996; Quebral et al., 1996; Tsutsumi & Perez, 2013). An average slip rate of 2-4 cm/yr for the Philippine Fault was derived from various methods including calculations from earthquake slip vectors and regional kinematic data (Barrier et al., 1991), and geodetic measurements (Bacolcol et al., 2005; Galgana et al., 2007; Yu et al., 2013; Hsu et al., 2016).

The Philippine Fault runs along the southeastern portion of Masbate Island and is also known as the Philippine Fault: Masbate Segment (PFMS). This segment stretches for approximately 30 km onshore along the island’s eastern edge, between Naro Bay in the north and Cataingan Bay in the south. Striking N40W, the fault trace on Masbate Island (Figure 5) is nearly straight except for the curved portion to the south where it continues to traverse a linear peninsula that borders Cataingan Bay to the east (Tsutsumi & Perez, 2013). The PFMS is hypothesized to be a transition between the mostly creeping Leyte segment to the south and the mostly locked Guinayangan (Ragay Gulf) segment to the north (Figure 1b). It accommodates slip partly creeping (aseismic) and partly by generating moderate to strong earthquakes (Bacolcol, 2003; Besana & Ando, 2005). Alinement array surveys conducted by Tsutsumi and others (2016) attest to the creeping behavior of the PFMS, with a measured creep rate of 7-17 mm/yr over a 3-year period. The PFMS has experienced several moderate to strong earthquakes (magnitudes 5 to 6) that are clustered both spatially and temporally, including the 2003 $M_S$ 6.2 earthquake, which exhibited an "unusually" long surface rupture and postseismic slip (Besana and Ando, 2005).

Several maps indicate the presence of a western fault, referred to as the Uson Fault, which runs parallel to the PFMS (Besana & Ando, 2005; PHIVOLCS, 2021c). PHIVOLCS (2021c) has recognized this fault as potentially active (Figure 1c).

3 Geodetic Observation Using InSAR

3.1 Coseismic Deformation

InSAR analysis was carried out to investigate the coseismic deformation of the 2020 Masbate earthquake. We generated three sets of interferograms, which were derived from the Sentinel-1 ascending and descending track and the ALOS-2 descending track. SAR images acquired in 2020/08/15 and 2020/08/21 were used to generate the Sentinel-1 ascending track interferograms, image pair 2020/08/14 and 2020/08/20 for the Sentinel-1 descending track, and image pair 2020/07/11 and 2020/08/22 for ALOS-2 descending track (Table S1 in the Supplementary Information).

The resulting coseismic interferograms are shown in Figure 2. The wrapped interferograms derived from Sentinel-1 data show distinct fringes that are convex towards the west at the center portion of the island in both ascending and descending tracks (Figures 2a and 2c). A much denser set of fringes can also be observed immediately west of the epicentral area. One complete cycle is
equivalent to ~2.8 cm of ground displacement along the radar line-of-sight (LOS). Coherence is low closer to the epicenter, as well as along the suspected rupture zone along the PFMS. The low coherence is probably due to dense vegetation, high displacement values near the epicenter, or extensive damage due to ground shaking or a combination of them – which limits the further interpretation of surface deformation. Also, ground deformation signals are only observable on land, so observations to the east of the PFMS are limited.

The Sentinel-1 ascending track unwrapped interferogram suggests that the block west of the epicenter moved away from the satellite (Figure 2b). On the other hand, the Sentinel-1 descending unwrapped interferogram indicates that the same area moved toward the satellite (Figure 2d). This implies dominant horizontal movement and that the western block shifted towards the southeast, which is consistent with the left-lateral nodal plane of the mainshock focal mechanism solution. The peak LOS displacements in ascending and descending unwrapped deformation maps were ~35 cm and ~37 cm, respectively.

The ALOS-2 interferograms (Figures 2e and 2f) obtained high coherence for the whole source region, hence it can be used to augment the deformation observation, especially along the suspected rupture zone. The ALOS-2 fringe patterns are much less dense as compared to those in Sentinel-1 interferograms because of the longer wavelength of L-band radar (each color cycle represents ~12 cm of LOS displacements). A clear displacement discontinuity (black arrows in Figure 2f) on the known trace of the Philippine Fault is recognized both in the wrapped and unwrapped interferograms from ALOS-2 data. Hence, the displacement discontinuity corresponds to a clear slip along the PFMS and probably indicates a surface rupture associated with the 2020 Masbate earthquake. Consistently, the maximum displacement of ~37 cm toward the satellite was measured from the ALOS-2 data. Interferometric fringes to the northwest that correspond to a positive LOS displacement (dashed circle in Figures 2e and 2f) are most likely atmospheric noise and are not associated with any earthquake deformation (Zebker et al., 1997; Ding et al., 2008).

From the satellite data, it is clear a large amount of deformation was concentrated around the epicenter, hence there was a local concentration of strain release. The slip managed to propagate towards the northwest along the PFMS; the displacement seems to be decreasing northwestward but still generated a clear displacement discontinuity in the ALOS-2 interferograms.

Additionally, in the Sentinel-1 interferograms (indicated by black arrows in Figures 2a and 2c), a distinct displacement discontinuity becomes evident west of the PFMS. This intriguing observation could suggest a secondary slip occurring along a distinct structure situated to the west of the PFMS. Notably, this displacement occurred at a considerable distance from the epicenter of the significant aftershocks. As such, attributing this secondary slip to an aftershock seems implausible, pointing instead towards a more likely coseismic origin. The secondary slip seems to be coinciding with an existing structure situated west of the Uson Fault, as depicted by the black arrows in Figure 1c. Nonetheless, the precise nature of this secondary slip, whether it represents a distributed or triggered slip, remains an open question. It is pertinent to note that this paper exclusively centers its investigation on the principal rupture along the PFMS.
Figure 2. Coseismic deformation observed using InSAR. (a) Wrapped and (b) unwrapped interferograms derived from Sentinel-1 ascending track (image pair: 2020/08/15 and 2020/08/21). (c) Wrapped and (d) unwrapped interferograms derived from Sentinel-1 descending track (image pair: 2020/08/14 and 2020/08/20). (e) Wrapped and (f) unwrapped interferograms derived from Sentinel-1 descending track (image pair: 2020/07/11 and 2020/08/22).

3.2 Postseismic Deformation

To detect and analyze the postseismic deformation, SAR images acquired after the earthquake from August 2020 to December 2020 were obtained from Sentinel-1 ascending track (Table S2). We conducted the stacking of Sentinel-1 interferograms using ISCE2 and proceeded to InSAR time-series analysis using the Miami InSAR time-series software in Python (MintPy) (Yunjun et al., 2019) based on Small-Baseline Subset (SBAS) method (Berardino et al., 2002; Schmidt & Bürgmann, 2003). The network of InSAR pairs is shown in Figure S1 in the Supplementary Information.

Figure 3 shows the LOS velocity by combining 4 months of Sentinel-1 data acquired after the mainshock, with the earliest SAR data on 2020/08/21, 3 days after the mainshock. The color contrast clearly identifies the surface trace of the PFMS (Figure 3a). The contrast in the velocity between the opposite fault blocks is a clear indication of the occurrence of postseismic deformation along the Masbate fault segment associated with the 2020 Masbate earthquake. A reference point (a point assumed to be stable or has zero displacements) was set several kilometers from the deformation field of the earthquake (black square in Figure 3c). The velocity map (Figure 3) shows that the eastern block had a slower LOS velocity (~5 cm/yr), thus behaving in a more relatively stable manner. On the other hand, the western block was shifting at a faster LOS velocity (~20 cm/yr) away from the satellite. Assuming a dominant horizontal movement, the postseismic slip was consistent with the left-lateral motion and it continued until the last image acquisition.
Figure 3. Postseismic deformation from InSAR Timeseries. (a) LOS velocity from 4 months of InSAR data along the Masbate fault segment, with the dashed line indicating the across-fault displacement profile in (b). (b) A transect shows a sharp contrast of velocities that coincided with the trace of the fault. (c) The velocities are referenced to a point located at the western part of Masbate Island.

There are usually three proposed mechanisms of postseismic transient deformation. These include afterslip, which occurs in or beyond the coseismic ruptured fault (Johanson, 2006; Barbot et al., 2009; Scholz, 2019); poroelastic rebound, which occurs in the upper crust but usually with kinematics opposite to that of coseismic (Peltzer et al., 1996; Wang et al., 2022); and viscoelastic relaxation between the lower crust and upper mantle due to stress change, which has a substantial effect in the far-field deformation. Afterslip alone can explain the near-field velocity field as the kinematics is consistent with that of the coseismic. The combination of poroelastic rebound (which is usually in small magnitude) and afterslip can also explain the near-field velocity field. However, poroelastic rebound is usually observed localized in fault geometric irregularities, such as bends and jogs; this is not the case for the Masbate fault segment. On the other hand, far-field deformation (>60 km) is not observed in the velocity field and the magnitude of the earthquake is not that large to generate significant stress, hence the viscoelastic relaxation is ruled out as a possible mechanism. All of these suggest that afterslip is the dominant mechanism contributing to the observed near-field postseismic deformation in the four months after the 2020 Masbate earthquake. Moreover, the higher velocity observed in proximity to the fault trace (Figure 3c) suggests that postseismic deformation represents a mechanism for the gradual resolution of stress that was not fully released during the earthquake. For simplicity, postseismic deformation is referred to here as postseismic slip.

4 Fault Rupture Mapping and Offsets

4.1 Distribution of Surface Ruptures

Field mapping of the surface rupture associated with the 2020 $M_w$ 6.6 Masbate earthquake was conducted in March and June 2021. Field investigation, complemented by remote sensing analysis, revealed an approximately 23-km long, NW trending (N30-45W) surface rupture onshore. The surface rupture generally coincides with the previously mapped trace of the Philippine Fault in Masbate, except in the Cataingan basin to the southeast (Figure 4). Surface rupture varies from continuous surface breaks to en echelon shear faults or tensional cracks, and mole tracks, which developed within a deformation zone of a few meters (generally < 5 m). Evident from its morphological and structural characteristics, and offset features, the surface rupture indicates dominant left-lateral strike-slip movement with minor normal displacements. The peak horizontal displacement reaches ~97 cm (Figure 4b) near the southwest terminus of the onshore rupture and displacements appear to decrease to the northeast. Field measurements (Table S3 in the Supplementary Information) yield an average displacement of 44.5 cm. It is important to take note that since the field mapping was done 7 months after the mainshock, and given the evidence of near-field postseismic slip from remote sensing, the observed surface rupture extent and displacements are likely a combination of both coseismic and postseismic signals. The details of surface ruptures in order of proximity to the epicenter, from south to north, are described below.
Figure 4. Surface ruptures associated with the 2020 $M_w$ 6.6 Masbate earthquake. (a) The surface rupture extends for 23-km along the PFMS. The traces of the surface ruptures are based on the combination of field investigation and remote sensing analysis. (b) Slip distribution of the left-lateral component of the surface ruptures along the Masbate fault segment. The displacements were measured both in the field (red dots) and in drone orthophotos (yellow dots). Black boxes indicate the locations of the following figures.
Figure 5. (a) Distribution of surface ruptures and locations of ground (red dots) and drone (black boxes) photos. (b) A displaced fishpond dike marks the southern terminus of the onshore surface rupture. (c, d, e, f, g) The surface rupture traverses dried fishponds and discernable offsets were observed on the fishpond dikes. (h) The surface rupture aligns with a subtle pre-existing fault scarp, where the northeast block is upthrown.

4.1.1 Surface ruptures in Cataingan

From Cataingan Bay, the rupture extends northwestward into the mainland, traversing the Cataingan basin (Figures 5, 6, and 7). Striking N30-35W, the fault rupture cut through the western
part of the Cataingan basin. While the existing map depicts a fault trace running along the eastern part of the Cataingan basin that curves to the left, the 2020 fault rupture deviated from this path (Figure 4a). The surface rupture in the Cataingan basin occurred mostly as a continuous sharp cut on the surface with minor right steps. Several cultural features, including rice paddies, fishpond dikes, and roads, were left-laterally displaced and the amount of left-lateral offset ranges from ~21 cm to ~97 cm (Figures 5 and 6). The maximum offset was measured on a displaced fishpond dike nearest to the coast, close to the epicenter (Figure 5a). The measured maximum offset is consistent with its magnitude based on the empirical relation (Wells & Coppersmith, 1994). UAV survey over the flat terrain facilitated the continuous tracing of the surface rupture and also augmented the measurement of displacements.
Figure 6. (a) Distribution of surface ruptures and locations of ground (red dots) and drone (black boxes) photos. (b) The surface rupture displaced the roots of a coconut tree with approximately 34 cm amount offset. (c) The surface rupture was observed along which the alignment of coconut trees was systematically displaced (by previous events). A cumulative displacement up to 1.65 m was measured at the site. (d, e, f) Several rice paddies were displaced by the surface rupture, from which the offsets were measured.
Figure 7. (a) Distribution of surface ruptures and locations of ground (red dots) photos. (b) A road in Cataingan was transected by the surface rupture marked by a displaced centerline. (c, d) The surface rupture is defined by a series of right-stepping en echelon faults, each exhibiting
approximately 11 to 12 cm of vertical displacement, with mole tracks interspersed in between.
(e) A concrete river dike was damaged due to the rupture displacement.

4.1.2 Surface ruptures around the Cataingan-Palanas boundary

The surface rupture continues northwest of the Cataingan basin towards the rolling hills topography of Cataingan and Palanas (Figures 8 and 9). The dense vegetation and the rugged terrain restricted the continuous mapping of the surface rupture, although it generally follows the previously mapped trace. The surface rupture in this area is mostly characterized by typical Riedel structures, and these structures are generally concentrated in a narrow zone of <5 m in width. Along the rupture zone, en echelon shear faults (R-shear) and tensional cracks (T-cracks) are right-stepping, and the mole track structures are usually located in between. The lack of discernible piercing points restricted the assessment of left-lateral displacement. Nonetheless, recorded displacements vary between 4 and 42 cm. In Matugnao, Palanas, a coconut tree was split in half by the fault rupture during the 2020 $M_W$ 6.6 earthquake (Figure 9c), with a horizontal offset of 27 cm. The same tree was also displaced during the 2003 $M_S$ 6.2 earthquake. This phenomenon indicates a significant overlap between the successive ruptures of these two earthquakes and underscores the precision of the rupture propagation.
Figure 8. (a) Distribution of surface ruptures and locations of ground (red dots) photos. (b) The systematic offset of aligned coconut trees shows cumulative displacement up to 1.42 m from past earthquake events. (c) Approximately 38 cm of left-lateral displacement was observed in the hollow block wall of an unfinished house construction. (d) Typical Riedel shear structures such as T-cracks and mole tracks were observed along the rupture zone.
Figure 9. (a) Distribution of surface ruptures and locations of ground (red dots) photos. (b) A road in Palanas, Masbate was displaced by the surface rupture. (c) The surface rupture cut a coconut tree in half in Palanas, Masbate. (d) The surface rupture is marked by typical Riedel shear structures.
Another road in Dimasalang, Masbate was displaced by 16 cm, which was the last observation point of the surface rupture during the fieldwork. (c) The surface rupture transected the front portion of a house.

4.1.3 Surface ruptures around the Palanas-Dimasalang boundary

The surface rupture becomes less recognizable towards the northwestern terminus as fault displacements decrease. Near the boundary of Palanas and Dimasalang, discernable displacements were observed on concrete flooring, pathway, and road (Figure 10). Horizontal offsets measure up to 16 cm. Figure 10b shows the last observation site of the surface rupture, however, the trace probably extends farther by 2 km to the north, which was inferred using InSAR observation. Field evidence for postseismic slip was documented near the boundary of Palanas and Dimasalang (Figure 10c). At this site, the surface rupture transected a concrete flooring in front of a house. The homeowner stated that 4 months after the earthquake (December 2020), they repaired the damages brought by the rupture. During the field visit in March 2021, the repaired concrete floor showed evidence of renewed movement causing damage and a gap between the floor and the concrete front steps. The gap was measured at ~6 mm along the strike of the inferred rupture trace (Figure 10c). The site was revisited in June 2021 and the concrete floor displayed progressive damage. The gap was remeasured, and the amount of offset was increased by ~4 mm. The gap represents the lateral...
offset caused by the postseismic slip along the fault rupture. Due to the observation gap, we did not observe the typical logarithmic behavior of slip decay associated with the postseismic slip. However, an average postseismic slip rate of ~20 mm/yr was calculated from this site for the particular time interval.

4.1.4 Secondary (off main Philippine Fault trace) ruptures

In the local area of Madamba in the northwest part of the Cataingan peninsula, discontinuous surface ruptures were observed (Figure 11). Several houses and other cultural features were transected and were left-laterally displaced by ~6 cm to ~7 cm. It was initially inferred to be the continuation of the main trace of the surface rupture across the bay, however, the sudden decrease in the amount of displacement (Figure 4b) and the lack of continuity despite the proximity to the epicenter raised uncertainty on the nature of these surface ruptures. These surface ruptures are characterized by right-stepping traces oriented N45W, which is slightly oblique to the general trend of the main surface rupture. Hence, these are interpreted to be secondary ruptures (which can be associated with Riedel structures closely related to the main fault) and the main rupture is hypothesized to be located offshore. Determining the probable location of the fault rupture in Cataingan Bay is discussed in section 5.
Figure 11. (a) Distribution of surface ruptures and locations of ground (red dots) photos. Slightly oblique to the general orientation of the main rupture, secondary ruptures were observed in a local area beside Cataingan Bay. (b, c, d, e, f) The rupture exhibits 6-7 cm of offset and transected several cultural features. (g) They coincided with pre-existing fault scarps.
On the crest of the Cataingan peninsula, another set of secondary ruptures, which are subparallel to the main rupture, were also mapped (Figure 12). These secondary ruptures show dominant normal movement with vertical throws ranging from ~5 cm and ~23 cm. Based on morphotectonic interpretation, the secondary ruptures are closely associated with pre-existing scarps, which may suggest cumulative deformation along these rupture zones. Most of the fresh ruptures and the identified pre-existing scarps are east-dipping (Figure 12). These observations suggest that these ruptures are guided by local geologic structures that may or may not connect at the main fault at depth and it indicates a typical slip-partitioning case (Toda et al., 2016; Choi et al., 2018). Given that the primary fault rupture appears to be situated offshore, it could be challenging to support the concept of slip partitioning solely based on onshore slip distribution data.
4.2 Typical Surface Rupture Structures

The 2020 Masbate surface rupture includes different types of remarkable fractures that can be expected in a strike-slip mechanism. Different analog experiments have shown the formation of Riedel structures along shear zones (Tchalenko, 1970; Naylor et al., 1986), which generally consist of Riedel (R) shears, antithetic (R’) shears, P shears, tensional (T) cracks and Y- shear faults (Figure 13a and b). R-shears, which form an acute angle (10-20°) anticlockwise to the principal deformation zone (PDZ), are usually the first fracture to occur in an en echelon array and are prominent. P-shears are contractional synthetic faults that accommodate the fault parallel shortening and are much less common than R’-shears. They often connect two R-shears. T-cracks are inclined at an angle >40° to the PDZ and accommodate the extension. These may require more displacement to form. Y-shears are parallel to the PDZ and are less important. These structures were observed in several strike-slip faulting earthquakes (Rao et al., 2011; Ren et al., 2021).

Figure 12. (a) Distribution of surface ruptures and locations of ground (red dots) photos. (b, c, d, e) Secondary ruptures were observed on the crest of the Cataingan Peninsula. These ruptures coincided with pre-existing morphotectonic features suggesting previous movements.

Figure 13. (a) Diagram of typical Riedel shear structures B) Geometrical complexities of fractures in a strain ellipse. (c, d) Configuration of structures in different sites along the surface rupture as observed in the field. PDZ – Principal deformation zone.
For the 2020 Masbate surface rupture, both R-shears and T-cracks were arranged in *en echelon* arrays. R-shears are oriented approximately N60W, which is oblique to the general trend of the fault and consistent with the left-lateral mechanism. P-shears which correspond to mole tracks were usually located in between R-shears. The surface rupture in Figures 9c and 9d exhibited *en echelon* arrays of R-shears with P-shears in between as illustrated in Figure 13c. Another expression observed was in Figure 8d in which T-cracks appeared. This is illustrated in Figure 13d.

The observed features are consistent with the Riedel shear zone model and the left-lateral mechanism of the Philippine Fault. Similar expressions have been observed from the surface rupture of the 2003 *Ms* 6.2 Masbate (Besana & Ando, 2005) and other previous earthquakes along the Philippine Fault, such as the 2017 *Mw* 6.5 Leyte (Llamas et al., 2017) earthquakes. Different expressions may imply different stages of formation and may provide insights into the amount of slip relative to other sites along the surface rupture.

### 4.3 Pre-existing Fault Features and Cumulative Displacements

The mapping of the surface rupture motivated a more comprehensive examination of the tectonic geomorphology using archived aerial photographs and high-resolution elevation data (i.e., Light Detection and Ranging Digital Terrain Model or LiDAR DTM). The LiDAR data (with 1m x 1m spatial resolution) were acquired between 2014 to 2017 (before the earthquake) by the University of the Philippines – Training Center for Applied Geodesy and Photogrammetry (UP-TCAGP) under the Phil-LiDAR program.

The surface rupture generally follows pre-existing morphotectonic features that characterize the PFMS. Some of these morphotectonic features that are related to faulting include fault scarps, sag ponds, linear valleys, fault saddles, faceted spurs, and deflected streams.

Near the northern terminus, the surface rupture was observed to coincide with a fault saddle (Figure 10a). To the south, the fault traverses the rolling hills of Palanas and forms linear valleys bounded by faceted spurs to the east (Figures 9a and b). The fault cuts through the ragged topography forming high fault scarps and deflected stress, and minor left-stepover forms a sag pond (Figure 8a).

In the Cataingan basin, the surface rupture deviates from the previously mapped fault trace (Tsutsumi & Perez, 2013). However, morphotectonic analysis reveals there are pre-existing fault scarps on the western part of the Cataingan basin, that seemed to be aligned or coincident with the surface rupture. These pre-existing fault scarps on the alluvial plain are evidence of recent cumulative displacement along the PFMS which traverses the Cataingan basin. At the central part of the Cataingan basin, a fault scarp was identified on the alluvial plain. The fault scarp is recognizable both in aerial photographs (Figure S2) and LiDAR DTM (Figure 14b and c). The scarp’s height ranges between 1 and 1.5 m with the east side up (Figure 14e).
Figure 14. (a) The map shows the location of the surface rupture relative to the known traces of the Philippine Fault based on existing maps. (b, c) LiDAR data and (c) drone orthophotos revealed
Evidence for cumulative displacement is not only demonstrated by the pre-existing morphotectonic features but also by displaced cultural features. Several rice paddies show cumulative displacements which are recognizable in LiDAR-DTM (Figure 14b and c) and orthophotos (Figure 14d) derived from the UAV survey. The systematic offset of aligned coconut trees (Figures 6c and 8a) also indicates cumulative displacement along the fault. The amount of cumulative displacement ranges from >1 m to ~10 m. However, the maximum horizontal displacements generated by the 2003 and 2020 earthquakes were only less than 1 m. Hence, the cumulative displacement of cultural features suggests the occurrence of frequent strong earthquakes, including the 2003 and 2020 earthquakes, over the past hundred years (cultural years), which may be accompanied by creep movement during the interseismic period. This supports the earlier interpretation of the behavior of the PFMS. The systematic offset of aligned coconut trees in Figure 8b shows a cumulative displacement of 1.42 meters. These coconut trees were erected in the 1970s based on interviews with the locals. Hence, we calculated a slip rate of 2.8 - 3.4 cm/year. This is slightly higher than previous estimates of 2.2 cm/yr from the GPS calculation (Bacolcol et al., 2005).

5 Offshore Fault Extension and Subsurface Structure

To investigate the possible offshore trace of the PFMS, sub-bottom profiles were acquired through two single-channel acoustic marine surveys conducted in Cataingan Bay in March and June 2021. This study used industry unmigrated seismic reflection profiles to further investigate the subsurface structure of the fault. These seismic reflection profiles were acquired from the Department of Energy (DOE) of the Philippine government. Figure 15 shows the transects of the sub-bottom profiles gathered from Cataingan Bay and its vicinity and the acquired deep seismic profiles.

5.1 Interpretation of Acoustic Sub-bottom Profiles

Generally, the profiles manifest wide U-shaped seafloor morphology (Figure S3). Despite the lack of well-defined acoustic sub-bottom layers in the profiles, which may be due to the degraded performance of the instrument, the seafloor acoustic reflectors reveal evidence of fault-related deformation. Features observed from the sub-bottom profiles include submarine mounds, ridges, linear depressions, tilting, fault drags, and scarps. The lateral continuity of these features across several profiles became the basis for identifying fault-related deformation. Representative sub-bottom profiles are shown here.

From the terminus of the onshore surface rupture, the fault continues offshore in Cataingan Bay (Figures 15 and 16). The sub-bottom profile DCSL1, the nearest profile to the onshore surface rupture, displays an offset seafloor reflector forming a depression (Figure 16a). The seafloor is generally downthrown to the west, which is consistent with the fault scarps observed onshore in the Cataingan basin. The depression is likely bounded by faults that connect to a slightly SW-dipping fault on the subsurface.
Figure 15. Offshore extension of the Philippine Fault to the southeast. Marine geophysical data revealed several active fault traces, which show dominant transtensional deformation. White lines indicate deep seismic profiles transect (acquired from DOE). Yellow lines indicate transects of acoustic sub-bottom profiles (from our field survey) in Cataingan Bay and its vicinity.
Figure 16. Acoustic Sub-bottom and deep seismic profiles. (a) DSCL1 sub-bottom profile shows seafloor offset near the onshore surface rupture. (b) CSL12 sub-bottom profile shows presence of fault scarp coinciding with acoustic masking at the eastern side of the bay. (c) CSL8 sub-bottom shows fault scarps and displaced acoustic reflectors. (d) ESL2 sub-bottom profile located outside the bay shows presence of fault scarps and fault drag. (e) L-102 seismic profile shows negative flower structure with main fault dipping to the west. (f) L-106 seismic profile shows also a negative flower structure with main fault dipping to the east. (g) 9730-94 seismic profile shows also a negative flower structure at the east side of the profile.
The offshore fault extension continues along the eastern side of Cataingan Bay for ~6 km (Figure 15). It is expressed either by single or multiple fault strands (Figures 16b and 16c and S4). Some fault strands appear along the center of the bay (Figure S5). Sub-bottom profile CSL12 (Figure 16b) displays disturbed seafloor at the eastern side. In this portion, acoustic masking is observed to be disrupting the acoustic profile up to the top layer, which makes it also difficult to identify its detailed structure. The presence of acoustic masking, however, probably indicates sound scattering due to the gas in the sediments (Acosta, 1984; Yasuda et al., 2015). Hence, this further substantiates the presence of the fault structure, as it probably served as a conduit for the gas or increased the permeability of the sediments.

In sub-bottom profile CSL8 (Figure 16c), the submarine seamount appeared to be cut by two oppositely dipping fault strands. Seafloor and sub-bottom acoustic layers are offset, with progressively increasing displacement on deeper and older layers (Figure 16c). Seafloor morphology from the derived bathymetry (Figure S3) suggests that the seamounts are dissected pieces from the peninsula. Fault saddles and probable lateral offsets can be observed in these seamounts at the eastern part of Cataingan Bay.

As it exits Cataingan Bay, the main fault trace continues southeast for ~8.3 km towards Bugtong Island (Figure 15). It is associated with prominent fault scarps and bounds a submarine linear ridge (Figure 16d, S6 and S7). The fault trace slightly curved forming a minor restraining bend, causing a portion of the submarine ridge to be more uplifted. The main fault is also marked by normal fault drags, as shown in sub-bottom profiles ESL2 (Figure 16d) and ELS1 (Figure S7). Closely associated with the main fault, a subsidiary fault can be delineated from these sub-bottom profiles. The subsidiary fault is marked by a more subtle fault scarp facing oppositely the main trace. Together with the main fault, it forms a ~250-wide linear depression (Figure 16d and S7). Further to the west and closer to the mainland, other parallel fault strands can be observed. These are marked by smaller fault scarp, tilted seafloor, and linear depressions, as also shown in sub-bottom profiles ESL2, CSL3 and ESL1 (Figure 16d, S6 and S7).

South of Bugtong Island, the offshore faults were approximately traced using the interpreted deep seismic reflection profiles and available GEBCO basemap. It is characterized by left-stepping NW-striking traces connecting the PFMS to the Leyte segment of the Philippine Fault (Figure 37a). These left-stepovers serve as relay zone and are a mechanism to accommodate the gradual change in the strike of the Philippine Fault. The interpretation of the seismic profiles is discussed in the succeeding subsection.

From the acoustic records, a ~17.2 km-long N33W-trending offshore active fault zone was identified (Figure 15). It is composed of a nearly continuous main trace and shorter subsidiary traces that extend from the sub-bottom profile DCSL 1, near the shoreline of the Cataingan basin, to the northern tip of Bugtong Island, which is cut by the fault. The main trace runs along the eastern side of the Cataingan Bay with minor steps and bends. Subsidiary traces are parallel with the main trace. Some subsidiary traces are closely associated with the main trace, while some are found along the eastern side of the bay up to ~1.6 km from the main trace. Seafloor deformation is more prominent south of Cataingan Bay (Figures 15 and 16c). The inferred dip-slip movement of the offshore traces is dominantly normal. Collectively, these fault traces mostly form linear depressions or grabens. Derived morphology from acoustic seafloor depths is shown in Figure S3 in the Supplementary Information.
5.2 Interpretation of Deep Seismic Profiles

The seismic reflection profiles further constrained not only the location of the offshore extension of the Philippine Fault southeast of Masbate Island but also its subsurface structure. Deformation analysis revealed that the fault is dominated by negative flower structures, in which the deformation zone reaches up to ~2.5 km in width. Consistently, the major fault zones are marked by depression on the basement rocks and thicker overlying strata, with increasing displacement at depth.

In seismic reflection profile L-102, prominent disturbance of the seafloor and subsurface strata can be observed on the western portion (Figure 16e). The strata appear to be folded but cut by several fault strands with a significant amount of normal displacement. Multiple events west-facing scarp can be observed on the seafloor reflector, which marks the main fault. A subsidiary strand can be delineated west of the main fault that seems to connect at depth (2.0 s TWT). These two closely associated strands are consistent with those delineated in sub-bottom profiles ESL1 and ESL2, which form a 250 m wide linear depression (Figure 16d and S7). Two other strands cut through the strata and probably connect to the main fault at depth. An older reverse fault was interpreted to be attributed to the folding of the strata.

Likewise, fault strands showing normal displacements occur in rather folded strata as observed in seismic profile L-106 (Figure 16f). These fault strands connect at depth (~1.5 s TWT) to a main fault that appears to be gently dipping probably due to the oblique orientation of the transect. However, in this profile, it can be observed that the main fault has already shifted its dip direction to the east. The older reverse fault observed in L-102 can also be discerned from this profile.

At the eastern portion of seismic profile 9730-84 (Figure 16g), the offshore extension of the Philippine Fault appears as 3 fault strands that eventually connect to the main fault at ~2.0 s TWT depth. Consistent with the previous interpretations, the fault manifests a significant amount of normal slip. In the western section of the profile, there is another fault that is noticeable. However, the type of movement observed is reverse slip, characterized by an increasing displacement at greater depths.

The subsurface structure reveals the fault complexity and its dominant nature of deformation. The structure corresponds to a wide shear zone rooted into the basement and affecting the overlying sedimentary sequence. The significant normal displacement and persistent negative flower structure suggest that the fault is dominantly transtensional, which resulted in the formation of linear depressions and valleys, including the Cataingan Bay itself.

6 Seismicity Pattern Analysis

6.1 Background Seismicity and Foreshock Activity

We analyze the earthquake sequence of the 2020 Masbate earthquake using the earthquake catalog of PHIVOLCS (2021a). We further attempt to unveil the physical properties of the source fault and constrain its geometry using the pattern of seismicity. Background seismicity along the PFMS from 2011 to 2019 (Figure 17a) shows minor to moderate earthquakes – five are sufficiently large to have focal mechanism solutions ($M_{LF}$ 4.5 - 5.5). These earthquakes are predominantly strike-slip in mechanism, consistent with the known mechanism of the Philippine Fault. Temporal and spatial clustering of earthquakes can be observed in the Masbate Pass and offshore...
southeastern Masbate Island, and a lesser number of earthquakes are plotted along the onshore portion of the PFMS (Figure 17a). The clustering of seismicity is closely tied to interseismic coupling, especially along faults with mixed mechanical behavior (Kanamori, 1981; Barbot et al., 2012; Liu et al., 2022). Hence, these clusters may imply the existence and extent of “asperities” or locked portions along the PFMS that persist over multiple earthquake cycles. Coinciding with these inferred asperities are the nucleation sites of the recent M>6 earthquakes, both of which propagated onshore as observed in the field. The relatively low background seismicity along the onshore portion of the PFMS suggests lower coupling and supports the idea of its creeping behavior (Bacolcol et al., 2005; Besana & Ando, 2005; Tsutsumi et al., 2016).

A short period of relative quiescence was noted from the pattern of background seismicity in 2020, which was followed by accelerated clustering of earthquakes two months prior to the mainshock. These earthquakes are located within ~10 km of the 2020 $M_W$ 6.6 mainshock epicenter, hence they are classified as foreshocks (Figure 17b). The foreshocks include the 11 August 2020 $M_W$ 4.9 and the 17 August 2020 $M_W$ 4.6 events, both of which have strike-slip focal mechanisms. Since the foreshocks are concentrated near the mainshock epicenter, the mechanism for the foreshock occurrence is interpreted to be a local concentration of stress within the asperity, in which sub-faults were broken and therefore related to the earthquake nucleation process (McLaskey, 2019; Scholz, 2019).
Figure 17. (a) Background seismicity (2011-2019) along the PFMS, colored by year and scaled by magnitude. Red dashed circles show observed clustered seismicity (b) Foreshock activity of the 2020 Masbate earthquake two months prior to the mainshock. (c) Mainschok and plotted aftershocks within the first 24 h. (d) Seismicity distribution within one year after the mainshock, colored by date. Focal mechanisms are from the SWIFT-CMT catalog of PHIVOLCS (2021b).
6.2 Mainshock and Aftershock Distribution

A day after the second largest foreshock, the $M_w$ 6.6 mainshock occurred in Cataingan Bay on 18 August 2020. The focal mechanism derived from the Source parameter determination based on Waveform Inversion of Fourier Transformed seismograms (SWIFT) Centroid Moment Tensor (CMT) solution and aftershock distribution suggest that the faulting occurred on an NW-striking left-lateral fault with a strike of 142°, a dip of 85° and a rake of 26°) (Bonita et al., 2015; Punongbayan et al., 2015; PHIVOLCS, 2021b). The mainshock rupture nucleated in the foreshock area and propagated along the trace of the Philippine Fault. The distribution of the early aftershocks (first 24 or 48 h) is usually assumed to represent the extent and structure of the mainshock rupture plane. These aftershocks mostly occur on the same rupture area of the mainshock due to the re-rupture of unbroken fault surfaces (Kisslinger, 1996; Das & Henry, 2003). Thus, several studies estimated the extent of faulting using the distribution of early aftershocks (e.g. Besana and Ando. 2005). Since there is a limited observation of the surface rupture towards the offshore area, the 1-day aftershock distribution is used to estimate the rupture length of the $M_w$ 6.6 earthquake (Figure 17c). The aftershock plots indicate a ~50 km rupture length. The extent of the 1-day aftershock distribution correlates well with the northwestern termination of the mapped surface rupture onshore. To the southeast, the aftershock plots terminate ~24 km from the mainshock epicenter, which coincides with the shift in fault dip direction and probably a fault stepover (Figure 17c).

Another notable observation is that the aftershock distribution is wider and denser on the offshore Masbate island to the southeast as compared to the onshore area where the surface rupture was mapped (Figures 17c and d). The large aftershocks (shown by the focal mechanisms in Figures 17c and d) are also concentrated in the offshore area to the southeast. This is probably due to the higher coupling consistent with the location of the inferred asperity and lower coupling onshore due to its partially creeping behavior. The wider distribution of aftershocks can also be attributed to the wider and distributed deformation near the epicenter, as revealed by mapping the offshore secondary ruptures and the offshore traces in Cataingan Bay.

An interesting part of the aftershock sequence is that the largest aftershock ($M_w$ 5.1), which occurred ~22 h after the mainshock, displays a reverse faulting mechanism with a minor strike-slip component on either a NNW- or NNE-striking nodal plane. There were no previously known reverse faults in the area. Although, evidence of reverse faulting in the region can be rather seen in seismic profile 9730-84, as discussed previously. This means that the shear displacement is also accommodated by an almost E-W shortening, supporting the hypothesis of volume compensation along arcuate strike-slip faults (Aurelio et al., 1997).

7 Discussion

7.1 Rupture Dynamics

Our investigation unveiled the mechanisms behind the rupture dynamics of the 2020 $M_w$ 6.6 Masbate earthquake. The earthquake originated from an inferred asperity or locked portion of the fault located along an unmapped offshore extension of the PFMS in Cataingan Bay. This rupture initiation spot fits perfectly with the foreshocks’ location, which probably indicates a nucleation process (McLaskey, 2019; Scholz, 2019). To the southeast, the rupture reaches 24 km from the epicenter before being arrested at a releasing fault stepover. The dense aftershock
distribution and concentration of the large aftershocks in the offshore area suggest the high-stress accumulation in the area, consistent with the interpretation of asperity in the area.

To the northeast, the rupture continued along the offshore fault until it reached the coast, where the maximum left-lateral displacement was measured onshore. Although believed to be creeping during the interseismic period, the onshore portion of the fault hosted the fault rupture where we mapped approximately 23 km of the rupture on the surface, with a decreasing slip to the northeast. The surface rupture generally occurred along pre-existing fault features and followed an almost straight path. The penetration of slip into supposed creeping areas, which also hosted the postseismic slip, is also consistent with the relatively lower activity of nearby aftershocks along the onshore segment (Barbot et al., 2009; Jiang et al., 2021). The 2020 Masbate earthquake's calculated rupture length of approximately 50 km surpasses the expected length, whereas the measured maximum displacement of 0.97 m aligns with its magnitude according to the empirical relation (Wells and Coppersmith, 1994). The calculated rupture length corresponds to magnitude ($M_w$) 6.8 based on empirical relation.

The rupture extent and slip distribution of the recent earthquake demonstrate how the physical properties of the fault influence the rupture propagation and size of earthquakes. Physical properties, such as fault geometry, frictional properties, materials surrounding the fault, and stress state, are believed to control the rupture dynamics of an earthquake. For the 2020 Masbate earthquake, the creeping behavior of the fault to the northwest and the left stepover to the southeast appeared to act as barriers that limited the earthquake rupture. Rupture can propagate for a significant distance into the creeping zone, but it may also act as a barrier as it slows down the rupture propagation (Harris, 2017; Scholz, 2019). This will depend on the interseismic coupling state or creep rate along the creeping zone (Kaneko et al., 2010; Thomas et al., 2014). Although, postseismic slip or afterslip may be observed in large portions of the creeping zones, beyond the area affected by coseismic slip (Harris, 2017; Scholz, 2019). These factors could potentially contribute to an extended calculated rupture length. On the other hand, geometric irregularities along a fault such as fault steps, bends and jogs may initiate, slow down, and stop the rupture propagation (Harris et al., 1991; Klinger et al., 2006; Wesnousky, 2006). Hence, the existence of the left stepover could have stopped the rupture propagation of the Mw 6.6 earthquake to the southeast. The initial stress state of the fault may also influence the propagation of earthquake rupture. Stress shadows or areas with stress decrease in the prior earthquakes can also act as a barrier (Sykes, 1971; Scholz & Lawler, 2004). Hence, it is also important to explore the interaction of the 2020 M6.6 earthquake with the 2003 $M_s$ 6.2 earthquake.

7.2 Seismic and Aseismic slip along PFMS

The Philippine Fault accommodates the relative plate motion through seismic and aseismic slips. The PFMS, based on both geologic and seismological evidence presented here, displays a mixed mechanical behavior such that both creeping and locked portions exist along the fault. The existence of asperity or a locked portion, surrounded by creeping zones, suggests a localized area of high-stress concentration. This concentration of stress around the asperity is demonstrated by the clustered background seismicity and the foreshock concentration (Kanamori, 1981; Barbot et al., 2012; Liu et al., 2022). Moreover, aftershock distribution shows a contrast in the density and size of the earthquakes which reflects the variation of fault coupling along the fault. Postseismic slip is common in transition zones or faults with mixed mechanical behavior (Scholz, 2019) as observed in Parkfield earthquakes along the San Andreas Fault (Lienkaemper & Prescott, 1989;
Barbot et al., 2009, 2012) or in 2003 $M_W$ 6.8 Chengkung earthquake (Thomas et al., 2014). Hence, the occurrence of postseismic slip further substantiates the PFMS having a mixed mechanical behavior. The asperity, which is a source of moderate to strong earthquakes, may persist over multiple earthquake cycles. It is important to determine the distribution, quantify, and develop kinematic models of these locked and creeping portions possibly through joint inversion of InSAR and GNSS, if data resolution permits. Hypocentral relocation of earthquakes is recommended for more accurate seismicity pattern analysis to determine their relationship with the physical properties of the fault.

In considering a mechanical model for the build-up and release of stress in this type of fault behavior, both slips that occur seismically and aseismically must be accounted for. The interseismic creep, coseismic and postseismic slip are important components of the overall slip budget of the fault. Alinement arrays along the fault revealed a 7-17 mm/yr creep rate during the interseismic period (Tsutsumi et al., 2016). A 17-year cumulative aseismic slip would reach $\sim$12-29 cm. The average displacement from field measurement of the coseismic and postseismic slip associated with the 2020 earthquake is $\sim$44.5 cm. Although the postseismic effects may persist for several more years, the calculated postseismic slip rate during the fieldwork almost approaches the interseismic creep rate. The total slip from the interseismic creep, coseismic, and postseismic slip suggest a slip rate of $\sim$3.3 – 4.3 cm/yr, closely consistent with the calculated long-term slip rate calculated from the cumulative offsets from the field (i.e. cumulative offset of aligned coconut trees near Palanas-Cataingan boundary shown in Figure 8b). The accumulated slip deficit along the fault before the earthquake was effectively balanced by the combined coseismic and postseismic slip associated with this earthquake event. Furthermore, by factoring out the influence of interseismic creep from the accumulated displacement from the field, we deduce a recurrence interval of 16 to 41 years for earthquakes resembling the 2020 Masbate earthquake. Intriguingly, the actual interval between the 2003 and the 2020 Masbate earthquake events is approximately 17 years, aligning with the calculated range. This consistency suggest that PMFS exhibits a tendency for recurrent strong earthquakes with short recurrence intervals.

Our analysis demonstrated the slip character of the PFMS, a behavior that arises from the coupling heterogeneity along the fault as much as we can expect from a transition zone, consistent with the interpretation of previous work. This is analogous to the Parkfield segment of the San Andreas Fault. The observed slip characteristics from previous Parkfield earthquake events have led many investigators to establish the Parkfield segment as a transition zone (Scholz et al., 1969; Harris & Segall, 1987; Johanson, 2006). In the Parkfield segment, the fault experiences frequent moderate to strong earthquakes, making it an ideal location for studying earthquake behavior and earthquake prediction. However, it is important to note that there may be differences in the controls and mechanisms of how the seismic and aseismic slips are distributed, given the difference in geologic and tectonic settings.

7.3 Transtensional deformation along the Central Philippine Fault

The structural and morphotectonic analysis shows that the 2020 earthquake occurred along the PFMS which consists of transtensional zones. While the surface rupture onshore followed an almost straight path and concentrated on a narrow zone, the secondary ruptures, and mapped offshore traces revealed a more complex fault structure in the vicinity of Cataingan Bay that denotes transtensional deformation. The dip-slip component of the primary left-lateral faults and
the associated normal faults, where the secondary rupture occurred, accommodate the extensional deformation. These normal faults are previously unidentified but play an important role in the distribution of slip during earthquakes. The complex fault structure in the vicinity of Cataingan Bay suggests that the origin of the asperity is geometrical in nature. The geometric irregularities can create roughness along the fault where high-stress accumulation can occur, and thus, might lead to rupture nucleation (Sagy & Brodsky, 2009).

Several transtensional zones were identified along the Central Philippine Fault. Marfito and others (2022) identified a large pull-apart basin linking the Surigao and Leyte segments of the Philippine Fault. Llamas and Marfito (2022) and this study also revealed other transtensional zones which include the Naro and Cataingan Bays and the left-stepovers linking Masbate and Leyte segments. These transtensional zones are possible locations of rupture initiation or termination and the formation of these zones can be attributed to the overall geometry of the Central Philippine Fault. The trace of the Central Philippine Fault gently changes strike (from N20W in southern Leyte to N50W in Quezon) resulting in its arcuate shape (convex to the northeast) that follows the shape of the Philippine Trench (Figure 1b). The left-stepovers and transtensional basins serve as relay zone and are a mechanism to accommodate the gradual change in the strike of the Philippine Fault. Thus, the gentle curvature controls the deformation style, stress state, and seismic behavior along the Philippine Fault. This highlights the role of fault geometry in the behavior of faults.

8 Conclusions

In conclusion, our investigation of the 2020 Masbate earthquake along the Philippine Fault has provided valuable insights into the rupture dynamics, fault behavior, and the role of geometric irregularities in seismic activity. The findings support the interpretation that the Masbate segment of the Philippine Fault acts similarly like a transition zone, characterized by a combination of creeping and locked portions, as well as the presence of an asperity. This transitional behavior is consistent with previous studies, further strengthening our understanding of fault mechanics in this region. This explains the occurrence of moderate to strong earthquakes accompanied by long rupture lengths and postseismic slips. Also, the Masbate segment has exhibited a notable pattern of seismic activity characterized by strong earthquakes with relatively short recurrence intervals.

The Masbate earthquake demonstrates how the physical properties of the fault influence the extent and distribution of slip during seismic events. Moreover, it emphasizes the role of transitional behavior in controlling the earthquake rupture, with the creeping zones and left-stepovers acting as barriers and influencing the propagation of seismic activity. By comprehending the complexities along faults and their slip behavior, we can enhance our ability to anticipate and mitigate the impact of future earthquakes. Further research is warranted to explore the interaction between the 2020 Masbate earthquake and previous seismic events. Such knowledge will enable us to better assess seismic hazards and develop effective strategies for earthquake risk reduction and resilience in the Philippines.

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Data Availability Statement

Data in this study were uploaded into the open-access Zenodo repository: Surface rupture data associated with the 2020 Mw 6.6 Masbate earthquake, Philippines [Data set]. Zenodo. https://doi.org/10.5281/zenodo.8213361 (Llamas et al., 2023); Offshore active faults associated with the 2020 Masbate earthquake investigation [Data set]. Zenodo. https://doi.org/10.5281/zenodo.8213387 (Llamas et al., 2023). All earthquake and existing active faults data used in this study are available at the PHIVOLCS website (https://www.phivolcs.dost.gov.ph/). Sentinel-1 SAR data are accessible through the Alaska Satellite Facility data search engine (https://search.asf.alaska.edu/#/)

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