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Present-day Crustal Deformation in West Sumatra After Series of Sumatran Great Earthquakes from 2004-2010

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Abstract
Present-day crustal deformation was an attempt to estimate earthquake potential, yet the presence of postseismic deformation should be carefully identified. Studying crustal deformation in West Sumatra has been important for this purpose since the series of Sumatran Great Earthquakes from 2004-2010. This study utilized present-day GNSS data (2017-2021) and pre-2004 GNSS velocities to understand the present-day crustal deformation. Bernese 5.2 was used to process the GNSS data and linear regression was used to calculate present-day velocities. These velocities were transformed into an ITRF2000-based Sundaland plate reference frame and then the velocities were compared to pre-2004 velocities in the same reference frame. The present-day velocities were ranging from 28.4 mm/yr to 58.3 mm/yr in ITRF2014 and from 8.8 to 44.8 mm/yr in the Sundaland plate reference frame. This suggests West Sumatra was located on the Sumatra block of the Sundaland plate. The low-velocity difference (< 11.7 mm/yr) with the random vector direction between present-day velocities and pre-2004 velocities shows that there is no postseismic deformation affecting West Sumatra. This proposes the utilization of present-day velocities for earthquake potential estimation in West Sumatra.

1. Introduction

Understanding crustal deformation is the initial attempt to estimate earthquake potential in a region. The study of present-day crustal deformation and past earthquakes, due to the effect of postseismic deformation, is necessary to obtain a precise estimation [1]. West Sumatra is such a location that experienced numerous earthquakes with magnitudes ofmore than 7 in the last 20 years. It is located in the center of Sumatra Island in Indonesia and close to the subduction zone or Sunda Trench which generates those earthquakes (Figure 1). The subduction zone is formed due to the subduction of the Indo-Australia plate beneath the Sundaland plate [2] at a rate of around 46 mm/year [3]. There was also the Sumatran Fault Zone in West Sumatra, including Mentawai islands, that accommodates the trench-parallel component of the oblique subduction [4].

Those series of Sumatra great earthquakes that affecting West Sumatra occurred in all regions of Sumatra Island. The earthquakes that occurred in northern Sumatra, which are more in number and larger in magnitude, were the 2004 M9.2 Sumatra Andaman earthquake, the 2005 M8.6 Nias earthquake, and the 2010 M7.8 Simeulue earthquake. The 2007 M8.5 Bengkulu earthquake was the only earthquake that occurred in southern Sumatra. This earthquake and the 2012 M8.6 earthquake, which occurred west of Sunda Trench, caused the postseismic deformation to the whole of Sumatra based on Global Navigation Satellite System (GNSS) velocities up to 2014 [5]. The initial attempt to test whether the postseismic deformation still presents is by understanding GNSS velocities direction. The postseismic deformation still presents when the direction of GNSS velocities, referring to the respective plate (Sundaland plate in the case of West Sumatra), should be toward the epicenter.

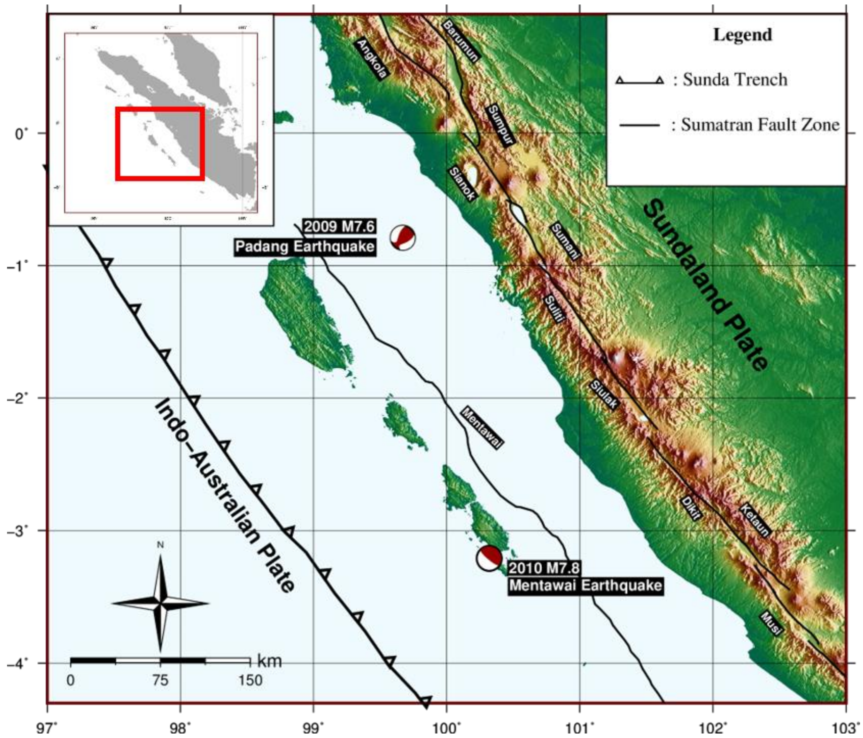

Figure 1. Tectonic settings of West Sumatra. Red beach balls show earthquakes with magnitude more than 7 from 2004 to 2010.

There are two earthquakes in West Sumatra that probably still cause the postseismic deformation up to the present day. Those earthquakes, the 2009 M7.6 Padang earthquake, and the 2010 M7.8 Mentawai earthquake are highly suspected since the epicenter is located inside the region of West Sumatra. The 2009 earthquake occurred at 0.720° S, 99.867° E, with a depth of 81.0 km at 10:16:09 UTC on 30 September 2009 and the 2010 earthquake occurred at 3.487° S, 100.082° E, with a depth of 20.1 km at 14:42:22 UTC on 25 October 2010 according to the United States Geological Survey (USGS). The 2010 earthquake is a rare tsunami earthquake [6] while the 2009 earthquake has uncommon characteristics which are intraslab earthquakes [7] the hypocenter is inside the slab indicated by the depth of the earthquake [8]. Nevertheless, both the intraslab earthquake and tsunami earthquake could also generate postseismic deformation [9, 10].

The GNSS velocities are commonly used to study present-day crustal deformation in a region. However, no study on GNSS velocities in West Sumatra from 2017 in general and earthquake potential estimation in specific. Understanding the direction of GNSS velocities in West Sumatra would determine whether considering postseismic deformation in earthquake potential estimation is necessary. The study has been conducted in southern Sumatra related to the 2007 M8.5 Bengkulu earthquake [11] which clarify no postseismic deformation needs to be considered. Therefore, in this study, GNSS velocities are used to obtain the present-day crustal deformation in West Sumatra after a series of Sumatran Great Earthquakes from 2004-2010.

2. Methodology

GNSS data were used to understand crustal deformation patterns in the area located spread in West Sumatra from 2007 to 2021, west of the Sumatran fault. Most of these continuous GNSS data were Sumatran GPS Array (SuGAr) provided by the Earth Observatory of Singapore (EOS), named as Sumatran GPS Array (SuGAr) [12] (Table 1). 19 of them were located on the Mentawai islands while 4 of them were located on the main island of Sumatra. 9 InaCORS sites, the continuous GNSS sites provided by the Geospatial Agency of Indonesia (BIG) for mapping purposes, were also used to obtain the pattern in the main island of Sumatra (Figure 2). All GNSS data had a sampling interval of 30 seconds. These sites have been used as an indispensable tool for crustal deformation study, especially to monitor the deformation due to a series of Sumatra great earthquakes (e.g. Tsang et al., 2016).

Table 1. GNSS Sites used in this research

No	Site Name	Longitude (◦)	Latitude (◦)	Location	Data Period	Reference
1.	CAIR	99.3945	0.2079	Sungai Beremas	2017.0-2021.5	BIG
2.	CBKT	100.3711	-0.3089	Bukit Tinggi	2017.0-2021.5	BIG
3.	CPAR	100.1320	-0.6251	Pariaman Tengah	2017.0-2021.5	BIG
4.	CPDG	100.3631	-0.9539	Padang Selatan	2017.0-2021.5	BIG
5.	CPET	99.1967	-1.5635	Siberut Selatan	2020.0-2020.9	BIG
6.	CPSM	100.1738	0.1201	Tanjung Beringin	2018.8-2021.4	BIG
7.	CSEL	100.8392	-1.7981	Ranah Pesisir	2017.0-2021.4	BIG
8.	CTEK	99.1186	0.3649	Pasar Baru	2020.0-2021.4	BIG
9.	PANJ	100.3795	-0.4662	Padang Panjang	2018.1-2021.4	BIG
10.	ABGS	99.3875	0.2208	Air Bangis	2017.0-2021.5	SuGAr
11.	BALA	98.4958	-0.5333	Siberut	2017.2-2021.4	SuGAr
12.	BTET	98.6439	-1.2815	Betaet	2017.2-2021.4	SuGAr
13.	BUKT	100.3181	-0.2018	Bukit Tinggi	2017.0-2021.2	SuGAr
14.	KLEA	98.8385	-1.5832	Kalea	2019.1-2019.6	SuGAr
15.	KM20	98.7576	-1.0808	Kilometer 20	2017.1-2018.6	SuGAr
16.	LBHU	98.6918	0.0771	Lahewa	2017.0-2021.4	SuGAr
17.	MSAI	99.0894	-1.3264	Muara Saibi	2017.0-2021.0	SuGAr
18.	NGNG	99.2683	-1.7996	Nyang Nyang	2017.3-2021.4	SuGAr
19.	PARY	100.3186	-0.7525	Paryaman	2017.0-2021.3	SuGAr
20.	PBJO	98.5157	-0.6365	Pulau Bajo	2019.3-2021.1	SuGAr
21.	PPNJ	99.6036	-1.9939	Pulau Panjang	2017.0-2021.4	SuGAr
22.	PTLO	98.2800	-0.0545	Pulau Telo	2017.0-2021.3	SuGAr
23.	SLGM	99.1201	-1.4533	Siberut	2017.0-2019.0	SuGAr
24.	SOBY	98.9399	-1.2015	Sot Boya	2017.0-2021.4	SuGAr
25.	SRSU	99.2179	-1.6464	Siberut Selatan	2017.0-2017.4	SuGAr
26.	TAMR	98.9695	-1.1243	Tamariang	2017.0-2019.6	SuGAr
27.	TIKU	99.9441	-0.3991	Tiku	2017.0-2021.4	SuGAr
28.	TLBD	98.3221	-0.5144	Pulau Batu	2017.0-2019.7	SuGAr
29.	TLLU	99.1341	-1.8003	Taileleu	2017.2-2021.4	SuGAr
30.	TNTI	98.7315	-0.9666	Tiniti	2017.2-2021.4	SuGAr
31.	TRTK	100.6242	-1.5207	Taratak	2017.0-2021.4	SuGAr

The present-day crustal deformation was obtained through the processing of GNSS data and GNSS velocity calculation. The GNSS data processing was conducted by using the scientific software: Bernese 5.2 [13]. This software, which utilized a double-difference positioning strategy, was commonly used for crustal deformation studies in Indonesia [14]. The International GNSS Service (IGS) sites [15] in International Terrestrial Reference Frame (ITRF) 2014 [16] (IISC, KARR, PIMO, YAR2, ALIC, DARW, DGAR) was used as constrained sites to obtain the daily coordinates of GNSS sites. The processing also involved The IGS final ephemeris, the Earth rotation parameters, The IERS Conventions 2010, and the DRY-GMF model as the supporting data.

The velocity was calculated by using linear regression with the least square approach on the daily coordinates. This linear regression was modified with the step function [17] to anticipate the coordinate jumps due to unknown causes. The epoch where the coordinate jumps were identified manually to obtain precise fitting. Prior to linear regression, the outliers which are larger than 95% confidence level of coordinates were removed. This linear regression was conducted well since there is not only any exponential or logarithmic trend found but also no sinusoidal pattern due to earth tides being found on the coordinate time series since earth tides were also considered in the GNSS data processing.

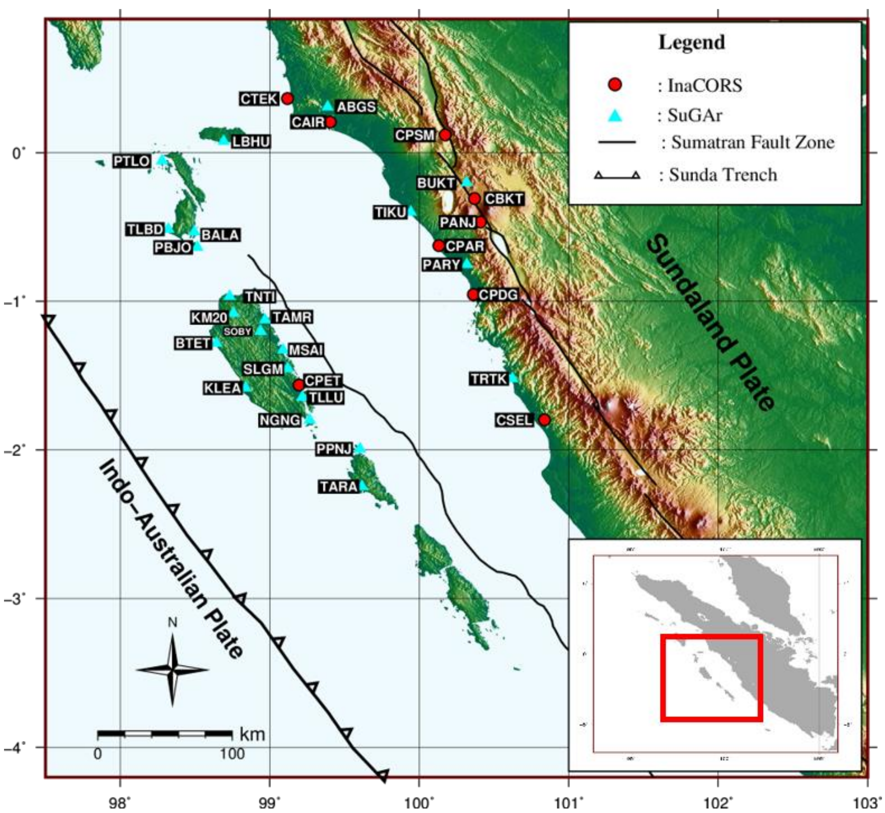

Figure 2. Distribution of GNSS sites used in this research.

A comparison between present-day velocities and pre-2004 velocities was conducted to obtain whether the deformation due to Sumatran Great Earthquake from 2004-2010 still affected West Sumatra. Pre-2004 velocities were obtained from [18] that utilized 34 GNSS sites in Sumatra. Prior to comparison, the reference frame for present-day velocities and pre-2004 velocities were transformed into one single consistent reference frame, which is the ITRF2000-based Sundaland plate reference frame. Transformation of present-day velocities into ITRF2000 used the parameter from Altamimi [16] and transformation into Sundaland plate reference frame used parameter from Simons [19] and Euler pole formula [20]. The published pre-2004 velocities were already in the ITRF2000-based Sundaland plate reference frame. The subtraction of velocities on those time periods was conducted on the common grid points with the grid spacing of 0.25° made by interpolating the velocities following inverse-distance weighing.

3. Results and discussions

Present-day velocities showing northeast direction for all GNSS sites in ITRF2014. This is consistent with the subduction direction of the Indo-Australia plate beneath the Sundaland plate [21]. These velocities are almost homogenous in the value and the direction resulting from the linear regression calculation. There is no coordinate jump found in the coordinate time series (Figure 3). The only notable pattern is the direction of velocities on the main island is a bit southward compared to the velocities on the Mentawai islands (Figure 4). This homogenous pattern shows that West Sumatra is dominated by one phenomenon, either interseismic deformation or postseismic deformation. The velocities are ranging from 28.4 mm/yr to 58.3 mm/yr (Table 2). Although these GNSS sites are located on the Sundaland plate, these velocities values are higher than other published velocities of the Sundaland plate (e.g. Hanifa [22] which is around 15.3 - 31.4 mm/yr). This is possibly due to the higher contribution of plate-boundary distribution or this region is part of the Sumatra block [23].

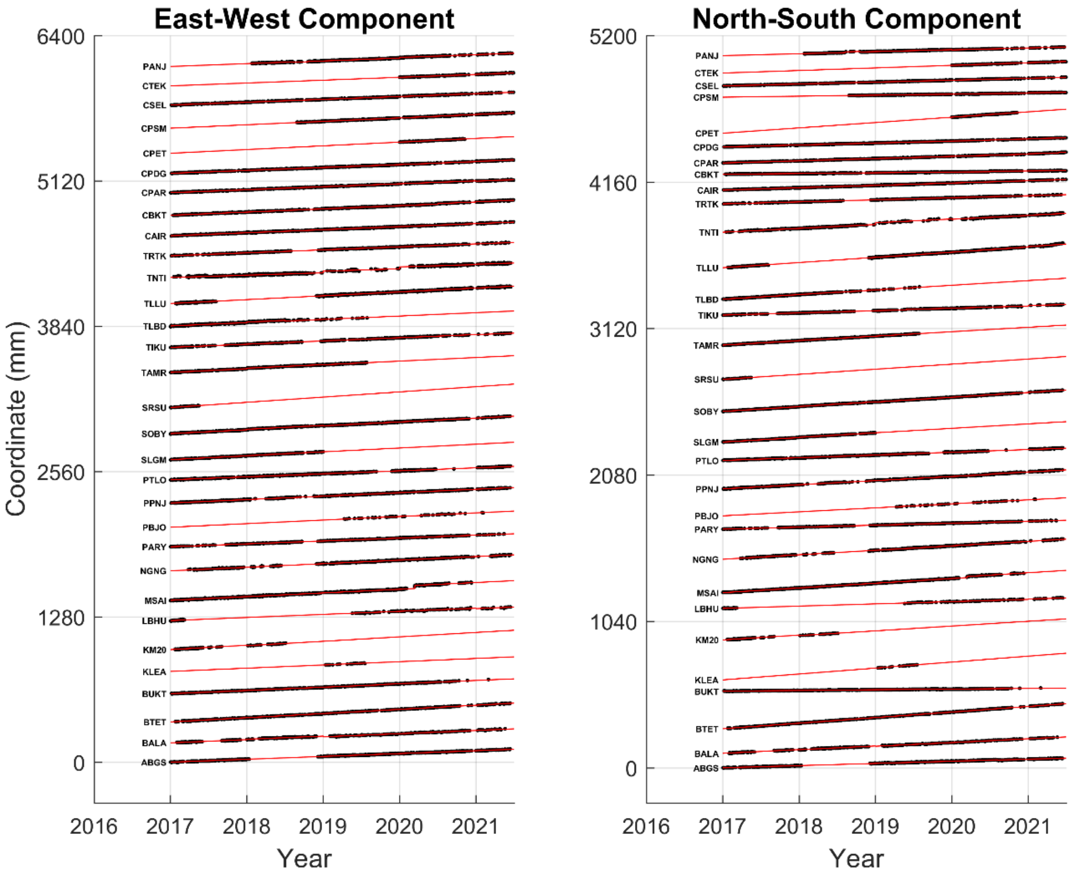

Figure 3. Coordinate time series calculated in this research.

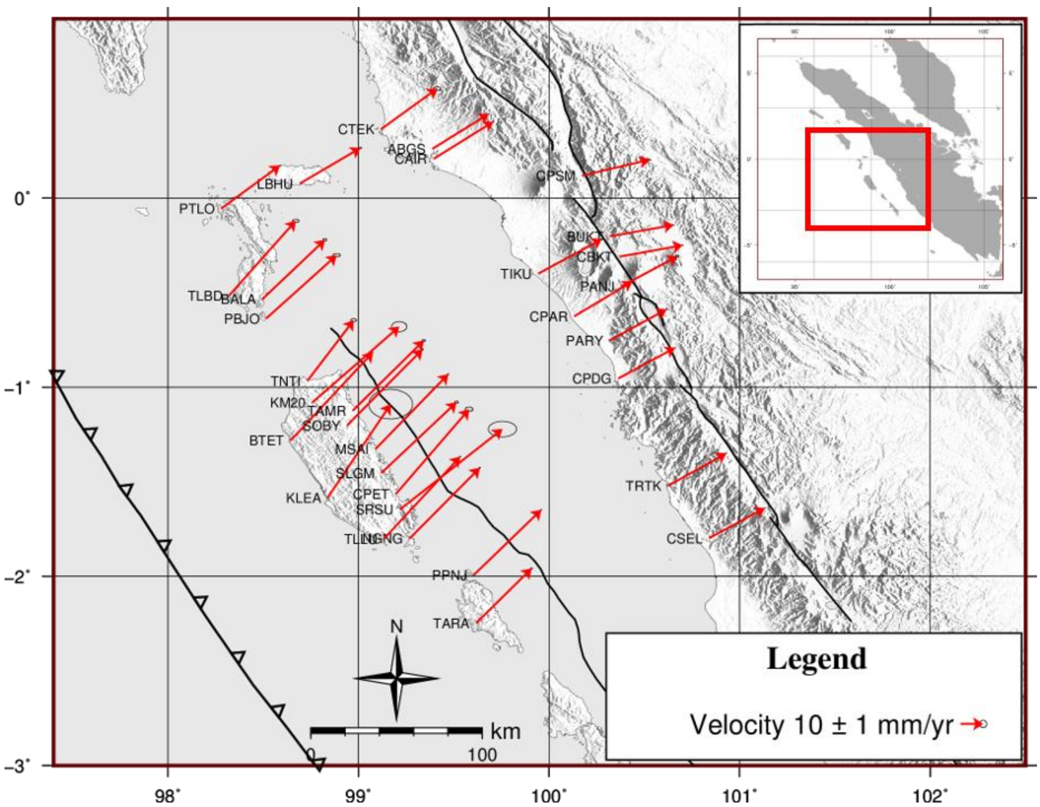

Figure 4. Present-day velocities refer to ITRF2014.

Table 2. The velocities of the GNSS sites refer to ITRF 2014 and Sundaland plate.

Site	ITRF2014 (mm/yr)				Sundaland plate (mm/yr)			
	V_E	V_N	σ_{VE}	σ_{VN}	V_E	V_N	σ_{VE}	σ_{VN}
CAIR	26.74	16.66	0.11	0.05	-0.34	19.86	0.11	0.05
CBKT	28.16	5.08	0.12	0.06	1.32	8.75	0.12	0.06
CPAR	26.08	15.64	0.12	0.06	-0.60	19.19	0.12	0.06
CPDG	25.48	13.81	0.11	0.06	-1.03	17.48	0.11	0.06
CPET	32.72	37.92	1.04	0.59	6.49	41.03	1.04	0.59
CPSM	30.12	7.07	0.25	0.13	3.07	10.65	0.25	0.13
CSEL	24.99	13.51	0.10	0.05	-1.11	17.40	0.10	0.05
CTEK	25.12	18.27	0.97	0.50	-2.04	21.34	0.97	0.50
PANJ	25.02	13.44	0.45	0.25	-1.73	17.12	0.45	0.25
ABGS	25.23	15.64	0.10	0.07	-6.7	18.84	0.10	0.07
BALA	27.94	26.53	0.51	0.31	-1.86	29.30	0.51	0.31
BTET	36.81	39.54	0.11	0.05	1.21	42.37	0.11	0.05
BUKT	28.61	5.10	0.15	0.07	10.44	8.75	0.15	0.07
KLEA	28.19	41.86	5.98	4.03	1.72	44.79	5.98	4.03
KM20	38.90	34.01	2.08	1.37	1.98	36.91	2.08	1.37
LBHU	27.21	16.01	0.28	0.15	12.44	18.88	0.28	0.15
MSAI	32.52	33.49	0.16	0.08	0.19	36.54	0.16	0.08
NGNG	31.40	31.68	0.17	0.11	6.18	34.82	0.17	0.11
PARY	25.49	13.98	0.12	0.06	5.29	17.63	0.12	0.06
PBJO	31.56	28.37	0.99	0.44	-1.12	31.15	0.99	0.44
PPNJ	30.33	29.31	0.11	0.09	4.88	32.60	0.11	0.09
PTLO	26.32	19.34	0.11	0.07	4.32	22.00	0.11	0.07
SLGM	33.64	31.71	0.50	0.27	-0.63	34.78	0.50	0.27
SOBY	33.77	34.06	0.26	0.13	7.36	37.04	0.26	0.13
SRSU	45.85	36.06	3.84	2.12	7.36	39.17	3.84	2.12
TAMR	31.81	31.43	0.47	0.23	19.66	34.43	0.47	0.23
TARA	24.77	24.45	0.24	0.13	5.37	18.86	0.21	0.13
TIKU	28.36	15.39	0.21	0.13	1.56	36.10	0.89	0.41
TLBD	29.72	33.42	0.89	0.41	2.99	39.81	0.14	0.09
TLLU	34.08	36.73	0.14	0.09	7.97	30.10	0.77	0.40
TNTI	20.76	27.22	0.77	0.40	-5.75	18.32	0.11	0.06
TRTK	26.10	14.53	0.11	0.06	-0.13	18.84	0.10	0.07

The transformed velocities into the Sundaland plate reference frame strengthen the idea of the Sumatra block of the Sundaland plate. This is due to the velocities referring to the Sundaland plate are still high enough (8.8 - 44.8 mm/yr), and the velocities should be close to zero when the reference is transformed into the plate where the sites locate (Sundaland plate in the case of West Sumatra), The direction of those velocities is more westward compared to those present-day velocities in ITRF2014 (Figure 5 left). These velocities are interpolated into the grid points to understand general velocities in West Sumatra. These grid velocities are ranging from 9.4 mm/yr to 40.0 mm/yr. These values resemble the pre-2004 velocities on grid points which are ranging from 15.1 mm/yr to 39.6 mm/yr. The direction of those pre-2004 velocities is also a bit similar to present-day velocities where these velocities are a bit eastward compared to the present-day velocities (Figure 5 right). This is probably due to the distribution of GNSS sites for present-day velocities being concentrated on the western area on the Mentawai island, and those velocities on the western area are more westward than those on the main island of Sumatra so that grid point velocities interpolation is biased.

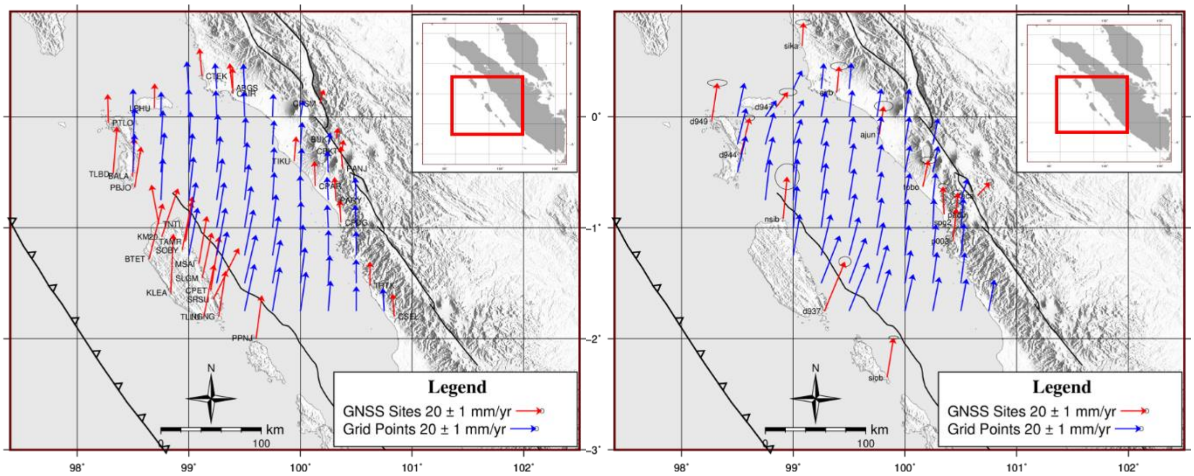

Figure 5. Present-day velocities refer to the Sundaland plate reference frame (left). Pre-2004 velocities refer to the Sundaland plate reference (right)

The difference between present-day velocities and pre-2004 velocities shows that there is no single dominant phenomenon affecting West Sumatra. The velocity differences are ranging from 1.1 mm/yr to 11.7 mm/yr with the random direction (Figure 6). This difference could be the bias or error resulting from the interpolation into the grid points either for present-day velocities or for pre-2004 velocities. Therefore, the postseismic deformation of Sumatran Great Earthquakes was not indicated in West Sumatra for recent periods (2017-2021). The long-time gaps between the last earthquake (2010) and recent periods could be the main cause of the postseismic deformation is ended.

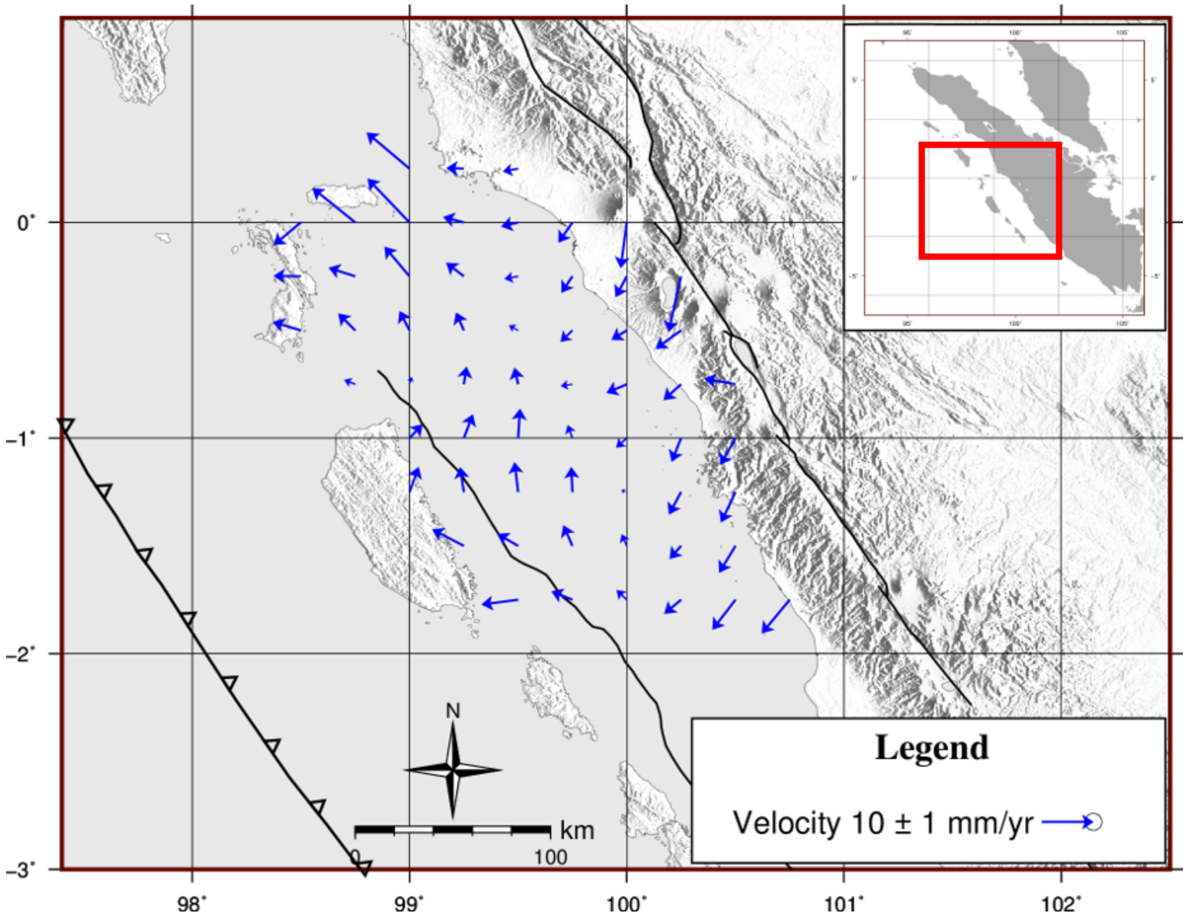

Figure 6. Velocities difference on grid points between two periods

The highly possible non-existence of postseismic deformation means the recent velocities are interseismic deformation and could be used for earthquake potential estimation. Prior to earthquake potential estimation, the slip deficit rate is calculated first from geodetic data. Such slip deficit rate has been estimated before by Yong [24] and shows that this region is the region with a higher value of slip deficit rate up to 2016, thus the higher potential to the higher magnitude of the earthquake. They utilized the GNSS velocities and block modeling to obtain the slip deficit rate, yet it is not clear whether either the postseismic deformation is still present in that period or the GNSS velocity is corrected by the postseismic deformation. The velocity baseline inversion model is the other method to obtain the slip deficit rate and both methods utilized the GNSS velocities [25]. Therefore, these methods could be used to estimate earthquake potential for future research without worrying about the effect of postseismic deformation. This earthquake potential is very important since earthquakes could cause other disasters like tsunamis and landslides [26].

4. Conclusion

Crustal deformation from GNSS velocities in West Sumatra from 2017 to 2021 shows no indication of postseismic deformation from the Sumatran Great Earthquakes. This result is obtained by comparing present-day velocities with pre-2004 velocities or velocities before the series of Sumatran Great Earthquakes started in 2004. The low-velocity differences with random vector direction indicate present-day velocities condition resembles pre-2004 velocities. The long-time gaps from the 2010 earthquake could be the main cause of the end of postseismic deformation. These present-day velocities could be used for further research about earthquake potential in West Sumatra.

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