Seismicity and influence of coulomb stress on the risk of earthquakes in South Sulawesi

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Seismicity and influence of coulomb stress on the risk of earthquakes in South Sulawesi

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Abstract. This study aims to analyze the distribution of earthquake events, analyze seismicity based on the parameters of b value, analyze changes in Coulomb stress and analyze the risk of earthquake events in South Sulawesi based on seismicity levels and changes in Coulomb stress in the range of 1991-2021. The data used in this study is data on earthquake events in 1991-2021 obtained from the IRIS and ISC catalogues. Data from the IRIS catalogue is mapped using ArcGIS software to see the distribution of the next earthquake spread processed by using MATLAB-based ZMapp 7 software to obtain the value of seismicity parameter (b value). Data from the ISC catalogue is mapped using Google Earth software to see the spread of earthquakes and then processed using MATLAB-based Coulomb 3.1 software to obtain analysis of stress Coulomb changes. Based on the results of the analysis obtained a value of b between 0.9-1.5 shows the value of b obtained is relatively low which correlates with a high level of stress. Based on the results of the analysis of changes in Coulomb stress obtained the movement of increased stress towards the red lobe with a value of 0.1 to 1 bar and decreased stress towards the blue lobe with a value of -0.1 to -1 bar. In general, earthquake-prone areas are located in the northern to central parts of South Sulawesi.

1. Introduction

Sulawesi is one of the islands in Indonesia with a fairly high level of earthquake. Sulawesi is geographically located at the confluence of three plates, namely Indo-Australia, Eurasia, and the Philippines. The Indo-Australian Ocean Plate moves north at a speed of about 50–70 mm / year and plunges under the deep-sea trough of Sumatra – Java to the west of Timor Island in NTT [1]. Meanwhile, the Pacific Plate hit the north side of Irian Island and the islands north of Maluku at a speed of 120 mm / year, twice as fast as the plate sharpening speed on the western and southern sides of Indonesia. Based on tectonic conditions, the eastern part of Indonesia has a potential for earthquake disasters twice as high when compared to the western part of Indonesia. [2].

Generally, earthquakes are considered a series of natural events that occur randomly. However, studies have shown that the spatial distribution of earthquakes can be well explained one way by analyzing the b value and changes in Coulomb stress. b Value is the tectonic parameter of an area that depends on the characteristics or rock properties of a region. Coulomb stress changes are geological processes due to changes in voltage in the material due to local discrete deformation. b Value and the coulomb stress change are precursors to earthquakes. Basically, the term precursor refers to a form of change in physical phenomena that can be observed shortly before the occurrence of a large earthquake

[3]. Change in b value describes local stress activity [4]. Significant spatial variation of the b value indicates strong heterogeneity in the distribution of voltage or crustal material in the plate boundary area [5]. Value b is a seismic parameter that reflects the relative frequency of the number of large earthquake and small earthquake events in a region [6].

Earthquakes that occur due to the release of stress cause stress to be transferred to the fault field or the surrounding area. One of the parameters used to study the relationship of stress with a fault is the coulomb change in stress. Coulomb stress from a major earthquake is a parameter that is able to explain the spread of aftershocks triggered [7]. This coulomb stress change is believed to control the location of the next earthquake in a region. Areas experiencing increased Coulomb stress, there was an increase in aftershock activity after the Palu Mw 7.5 earthquake in 2018 [8]. Earthquake distribution cannot be explained simply by using coulomb stress change analysis [9][10] however, conducting research on coulomb stress changes can still provide an idea of the sequence of earthquake events [11]. Generally earthquakes occur in areas with positive coulomb stress changes, although there are conditions in which, earthquakes occur in neglected areas[12].

2. Data and Methods

2.1. Research Location

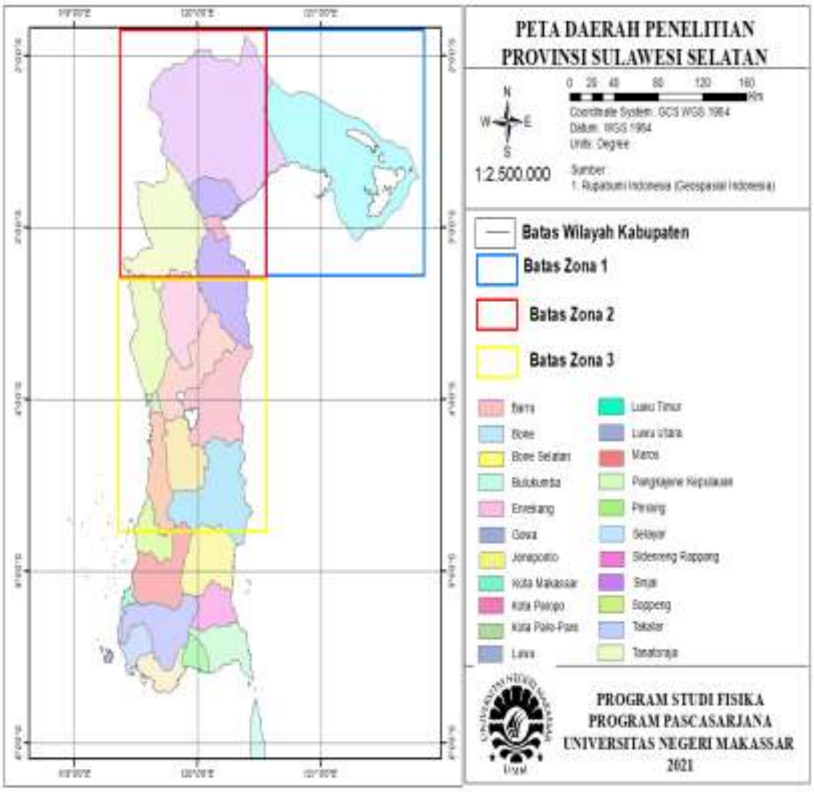

Figure 1. Research Sites in South Sulawesi

Figure 1 is a map of the research area on a scale of 1:2,500,000 based on Rupabumi Indonesia (Geospatial Indonesia) sources. Zone 1 is bounded by the blue line, zone 2 is bounded by the red line and zone 3 is bounded by the yellow line. The distribution of earthquakes in the three zones was further analyzed at the Laboratory of Earth Physics department of Physics, State University of Makassar.

2.2. Research Data
Data in this research form of earthquake data in January 1991-January 2021 includes; longitude, latitude, year, month, day, magnitude, depth, hour, minute of earthquake occurrence and earthquake fault parameters namely strike, dip and rake. The earthquake event data used is obtained from two catalogues.

2.2.1. IRIS catalogue (Incorporated Research Institutions for Seismology) [13]

2.2.2. ISC catalogue (International Seismological Centre) [14]

2.3. Data Analysis

2.3.1. b Value
Earthquake data downloaded from ArcGIS software in excel files is then compiled in ASCII (American Standard Code for Information Interchange) format i.e. Lon, Lat, Year, Month, Day, Mag, Depth, Hour and Min stored in .txt file format. The data inputted in the ZMAP software [15] is stored in file form. Mat, then the value b is analysed using the relationship between the magnitude of the earthquake and the frequency of the earthquake [16].

2.3.2. Coulomb stress
Analysis of coulomb stress changes was conducted using data obtained from the ISC catalogue. Earthquake data is plotted into google earth software to make it easier to choose earthquakes that occur in South Sulawesi. The amount of data relevant to South Sulawesi is 3 earthquake events. The required data is Lat, Lon, Strike, Dip and Rake inputted into Coulomb Software 3.3 [17] [18].

3. Results and Discussion
South Sulawesi is one of the areas on the island of Sulawesi that is affected by the existence of several faults including the Palu Koro Fault, Matano Fault and Walanae Fault [19]. Earthquakes that occur in the South Sulawesi region are shallow earthquakes that occur below a depth of 60 Km. The shallower the hypocentre the earthquake the more likely the resulting tremor will cause damage despite the magnitude of the earthquake is small. South Sulawesi is composed of 5 units, namely Camba Volcano Formation Unit, Walanae Formation, Basalt Intrusion Unit, Lompobattang Volcano Rock Unit and Alluvial Deposits, Swamps and Beaches. The rock formations that make up South Sulawesi cause the high nature of rock heterogeneity. The heterogeneity of rocks causes differences in the receiving pressure at the time of plate movement, so the accumulation of energy stored in the rock is different.

3.1. b Value
b Value is analysed using the relationship between the frequency of earthquake events and the magnitude of earthquakes occurring (FMD). The amount of data analysed was 114 earthquake events from the IRIS catalogue. The magnitude of the earthquake ranged from 3.0 to 6.1 with a depth of less than 60km.

3.1.1. Zone 1
Zone 1 is located in the northern part of South Sulawesi bordering Central Sulawesi and Southeast Sulawesi. This section is influenced by the presence of the Matano Fault. The distribution of earthquakes indicates earthquakes in Zone 1 are dominated by moderate earthquakes with magnitudes of 4.0-4.9.

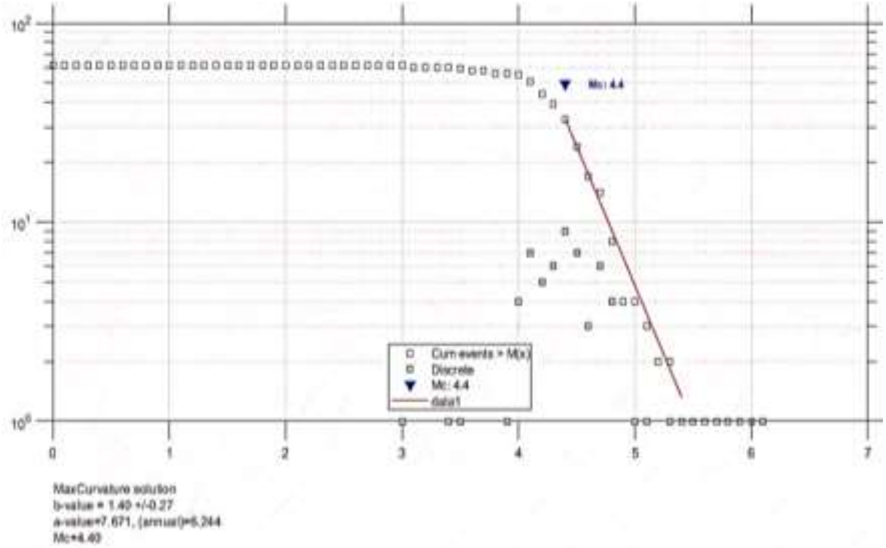

Figure 2. Zone 1 value analysis using ZMAP Software

Analysis of the b value in Zone 1 for earthquake events of 63 is shown by Figure 2. This zone is located around the Eastern Luwu region. The result of the analysis of the b value for Zone 1 is 1.40 ± 0.27 with Mc 4.4. The earthquake magnitude recorded in this zone is 3.5-6.1. A major earthquake in Zone 1 occurred in 2012 with a magnitude of 6.1. A high b value correlates with low stress levels. This is appropriate resulting in frequent earthquakes with a magnitude of less than 5.0. The geological map for Zone 1 represented by the Malili Geological Sheet shows Zone 1 composed by the Somata Formation consisting of sandstone, conglomerates, napal inserts and lignite, alluvial. Walange Wasuponda formation consisting of ultramafic rocks, limestone and red clay base mass, Bone-Bone Formation consisting of sandstone, conglomerate, napal and tupan clay. Ultrabasa Complex Formation consisting of superpentinite, danit, gabro and diabas.

3.1.2. Zone 2

Zone 2 is located in the northern part of South Sulawesi bordering Central Sulawesi and West Sulawesi. Earthquakes that occur are shallow earthquakes with a depth of less than 100Km and dominated by earthquakes with magnitudes of 4.0-4.9. Earthquakes in this zone occur most often in Tanatoraja.

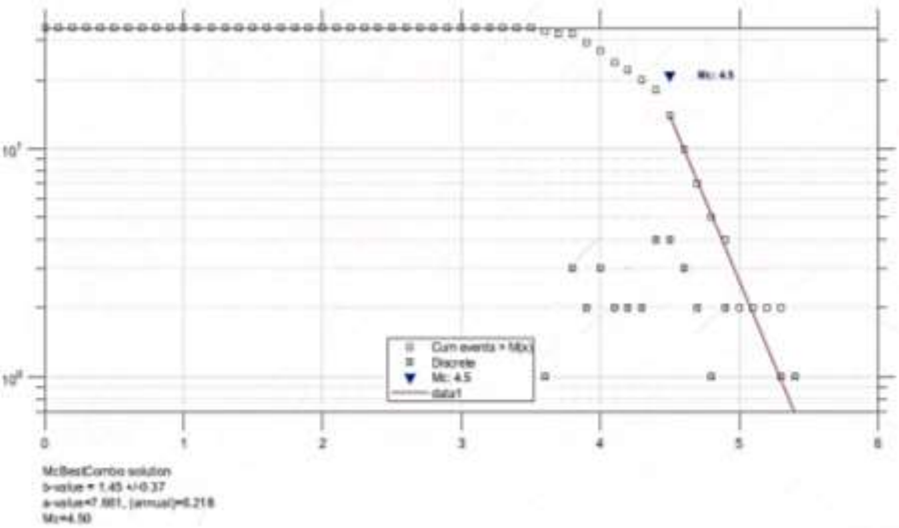

Figure 3. Zone 2 value analysis using ZMAP Software

Zone 2 is located in the area of North Luwu, Luwu, Palopo and Tanatoraja. Analysis of the b value was conducted on 38 earthquake events recorded to occur in the span of 30 years. The b value in zone 2 is 1.45 ± 0.37 with a magnitude of Mc4.50. The magnitude recorded in this zone is located between 3.0-5.5. The earthquake event in this region is most likely influenced by the Palu-Koro Fault located in the Northwest to Southeast Sulawesi. The value of b for Zone 2 is quite high when compared to the b value of South Sulawesi in general. The b value in zone 2 which is higher than zone 1 should cause more earthquakes. However, the geological condition of Zone 2 is more stable compared to the geological conditions of Zone 1. Based on the Geological Map of Zone 2 represented by the Majene and Palopo Sheets compiled by many different rock formations, the existence of alluvium, sandstone, quartz among conglomerate rocks, andesite rocks, limestone and igneous rocks, making this Zone has an area with low stress levels.

3.1.3. Zone 3

Zone 3 is located in the middle of South Sulawesi. This section is affected by the Walanae Fault. The distribution of the earthquake indicates that the earthquake was a shallow earthquake with a depth of less than 60km and occurred around the Walanae Fault.

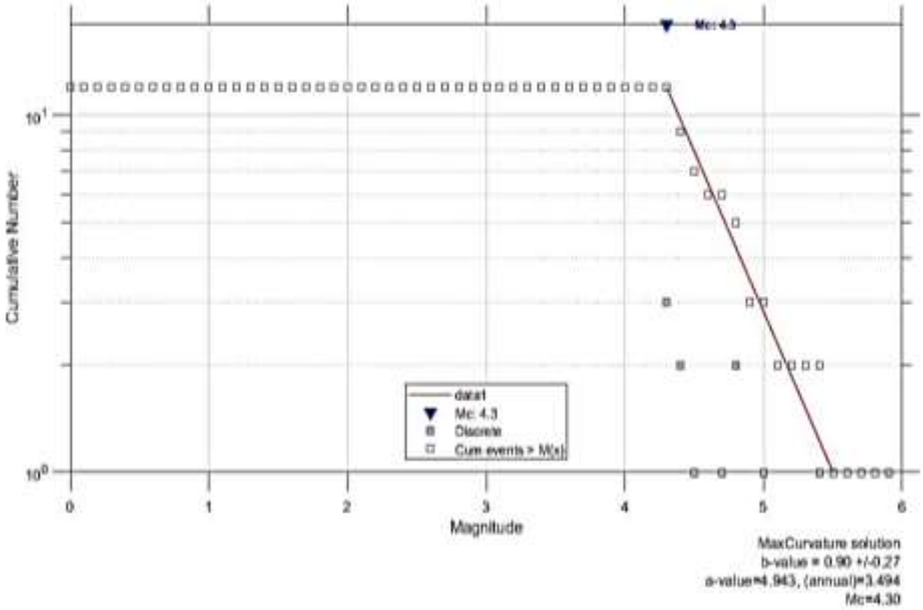

Figure 4. Zone 3 analysis b value using ZMAP Software

Zone 3 is located in the central part of South Sulawesi, which is around the area of Enrekang, Pinrang, Sidrap, Pare-Pare City, Wajo, Soppeng, Barru and Bone. The analysis of the b value for this zone is about 0.90 ± 0.27 with a large Mc 4.3. The magnitude recorded in this zone is 4.0-6.0. Generally, b value smaller than 1 represents a high level of stress [20]. High stress levels provide a very high chance of earthquakes with large magnitudes. [21] A relatively low b value indicates that the region is likely to have a major earthquake in the future due to the accumulation of energy causing high levels of stress in the region. Based on geological conditions, Zone 3 is dominated by conglomerate rocks, limestone and sedimentary rocks. The type of rock that dominates is a rock that has solid and rigid properties. Rocks that are strong in withstanding pressure will be able to store the accumulation of energy for a long time. As a result, compared to Zone 1 and Zone 2, Zone 3 has a considerable chance of producing destructive earthquakes in the future.

3.2. Coulomb Stress Changes in Earthquake-Prone Areas in South Sulawesi

Analysis of Coulomb stress changes in earthquake-prone areas was conducted using Coulomb software 3.1 based on earthquake data from the ISC catalogue. This analysis is done to find out the direction of stress movement after an earthquake. Coulomb analysis of stress in the southern Sulawesi region based on earthquake events that have occurred. There are 3 earthquake events, namely the June 17, 2017 earthquake in East Luwu, the December 7, 1994 earthquake in Tanatoraja, and the September 28, 1997 earthquake in Pinrang. The red colour indicates the direction of increased stress while the blue colour indicates the direction of the decrease in stress after an earthquake occurs. To facilitate the analysis of coulomb stress changes, earthquake-prone areas are divided into 3 zones based on the distribution of earthquake events that have occurred.

3.2.1. Zone 1

Coulomb analysis of stress in zone 1 for the Eastern Luwu region is affected by the presence of the Matano Fault. Coulomb stress analysis conducted on the earthquake event of June 17, 2017.

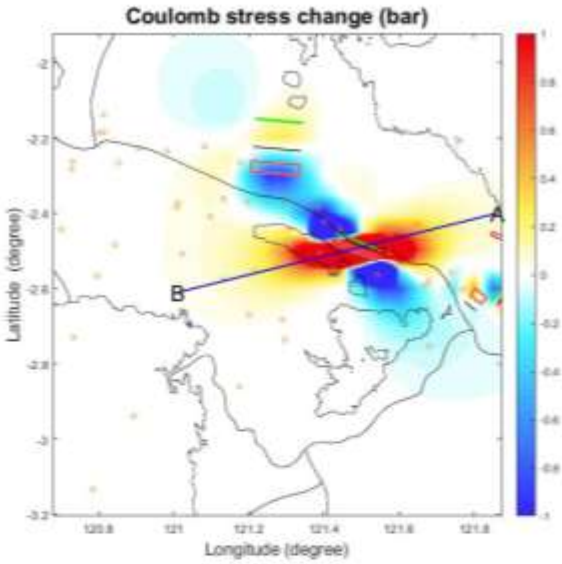

Figure 5. Distribution of Coulomb Stress Changes Earthquake 17 June 2017 Horizontally

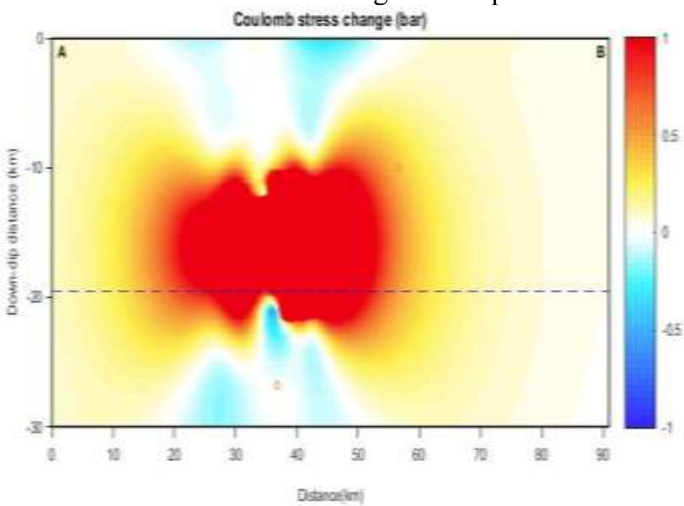

Figure 6. Distribution of Changes in Coulomb Stress earthquake 17 June 2017 Vertically Results of Transverse Slices

Figure 5 shows an increase in voltage after an earthquake occurs by 0.1 to 1 bar indicated by the red lobe and a voltage decrease of -0.1 to -1 bar indicated by the blue lobe. When viewed vertically (Figure 6), coulomb stress changes spread to depths of more than 30 km. The increase in stress spread horizontally for more than 80 Km. The direction of the increase in stress extended East Luwu from northeast to southwest. Most of the earthquakes that occur in Zone 1 are located in areas that experience increased stress. Analysis of earthquake fractures [22] on the 15 February 2011 earthquake showed the longest fracture length of 1,722 km with earthquake energy of 1.6737 x 1015 J and a fracture speed of 79,629 m/s was affected by the hardness and flabby of the ground as well as the degree of rock hardness present at the earthquake site and the paths traversed by the earthquake waves.

3.2.2. Zone 2

Coulomb analysis of stress for Zone 2 is located in the area around North Luwu, Luwu, Palopo and Tanatoraja. Analysis of coulomb stress changes due to the December 7, 1994 earthquake in Tanatoraja. Zone 2 is affected by the Palu-Koro Fault from the northwest to the southeast of Sulawesi.

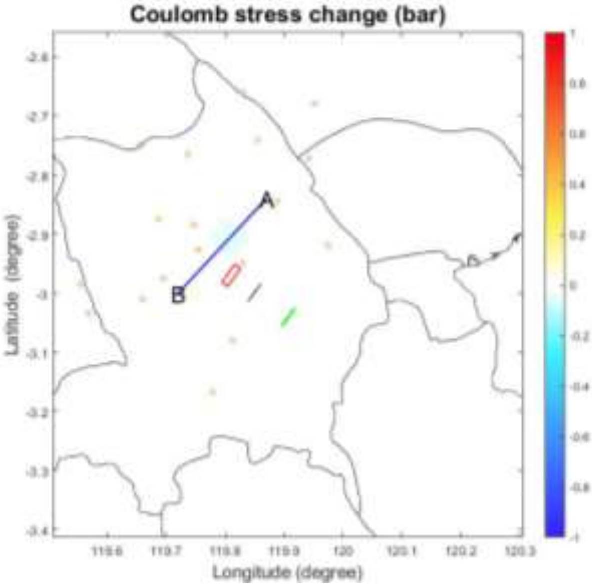

Figure 7. Distribution of Coulomb Stress Changes in Earthquakes in Zone 2 Due to the December 7, 1994 Earthquake Horizontally

Figure 7 shows coulomb stress analysis does not show an increase in stress after an earthquake, but there is a decrease in voltage of about -0.5 bar. The direction of the movement of the voltage below the surface is analyzed by doing transverse slices as in Figure 8.

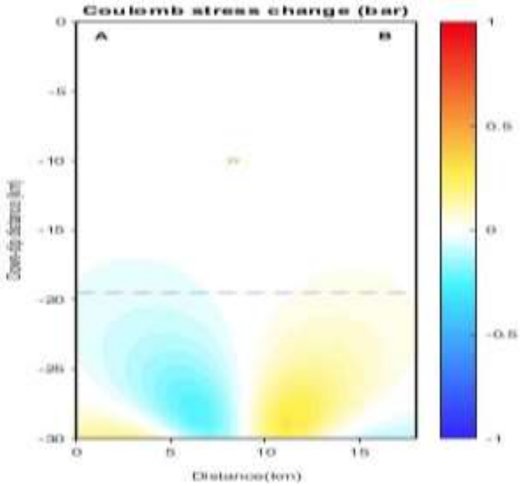

Figure 8. Distribution of Coulomb Stress Changes in the December 7, 1994 Earthquake in Zone 2 Vertically

The increase in stress in the December 7, 1994 earthquake occurred at depths of more than 30km as far as 5 to 10km. The stress reduction occurs at depths of more than 17km as far as 10 to 15km. Based on Figure 4.13 there is no movement of stress at a depth of 0 to 15km. The blue lobe that experienced decreased stress indicated seismic activity at a depth of 10Km. [23] Coulomb's pattern of stress change by the Wenchuan earthquake with Ms = 8.0 and its effect on aftershock events. The results showed that the incidence of aftershocks was located in the area of increased Coulomb stress, even with a consistency value of up to 90%. This suggests that the likelihood of areas experiencing decreased stress experiencing seismic activity cannot be ignored. Voltage changes due to Toraja earthquakes do not cause an increase in stress that can trigger seismic increases. This is one of the causes of no earthquakes in the next 5 years. However, 10 years later there was an increase in seismic activity that was likely triggered by earthquakes that occurred around the zone 2 area.

3.2.3. Zone 3

Zone 3 is located in the central part of South Sulawesi, which is around the area of Enrekang, Pinrang, Sidrap, Pare-Pare City, Wajo, Soppeng, Barru and Bone. Coulomb's analysis of stress was conducted for the September 28, 1997 earthquake.

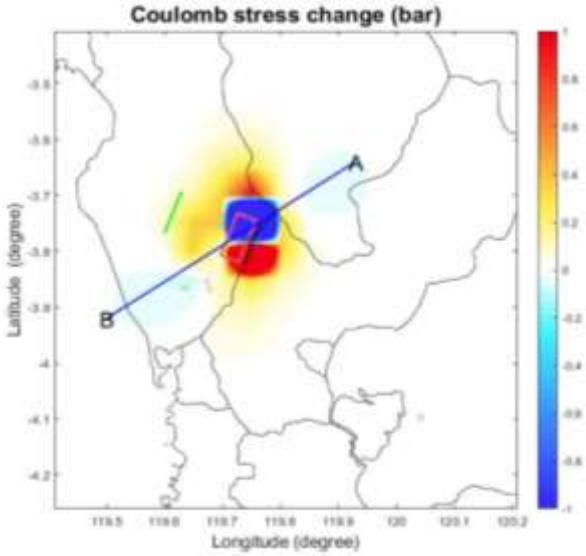

Figure 9. Distribution of Coulomb Stress Changes in the September 28, 1997 Earthquake horizontally

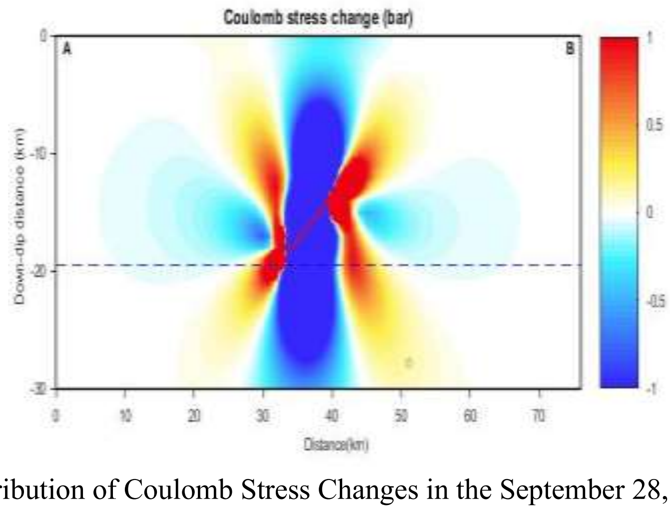

Figure 10. Distribution of Coulomb Stress Changes in the September 28, 1997 Earthquake Vertically

From the analysis of coulomb stress changes in zone 3 obtained an increased value of Coulomb stress that ranges from 0.1 to 1 bar indicated by red and coulomb stress decrease ranges between -0.1 to -1 bar indicated by blue. Zone 3 with normal fault type N6E/32 South-North [24]. Analysis of coulomb stress change distribution showed increased stress and decreased stress by perpendicular to each other. The distribution of coulomb stress changes vertically indicates an increase in stress occurring at depths of less than 30 km. There is seismic activity at a depth of about 28 km in areas that experience increased stress. The increase in stress is indicated by the four red lobes. The increased stress moved towards Pinrang, Enrekang, Sidrap and Pare-Pare City.

4. Conclusions

b value of South Sulawesi region is in the range of 0.9 to 1.5. b value varies in each zone in South Sulawesi indicating a difference in stress. Zones 1 and 2 have a b value that is more than 1 means the stress condition is quite low while Zone 3 has a value of b less than 1 means a high enough stress condition. Changes in the stress coulomb that occurred in 3 zones indicated that the direction of the spreading increased stress that occurred when the earthquake went to the red lobe with a value of 0.1 to 1 bar and the alignment of decreased stress when the earthquake headed to the blue lobe with a value of -0.1 to -1 bar. Areas that have a high risk of seismicity are the areas around East Luwu, Palopo, North Luwu, Tanatoraja, Pinrang, Enrekang, Sidrap and Pare-Pare.

References

[1] Bock, Y., Prawirodirdjo, L., Genrich, J. F., Stevens, C. W., McCaffrey, R., Subarya, C., Puntodewo, S. S. O., and Calais, E. 2003., Crustal motion in Indonesia from Global Positioning System measurements, J. *Geophys. Res., 108, 2367, doi:10.1029/2001JB000324, B8Another reference*

[2] Natawidjaja, D.H. Wahyu Triyoso.2007. Sumatera Fault Zone-From Source to Hazard. Journal of Earthquake and Tsunami. Vol. 01, No. 01, pp. 21-47

[3] Nuannin, P., Kulhanek, O., Persson, L., 2005. Spatial and temporal b value anomalies preceding the devastating off coast of NW Sumatra earthquake of December 26, 2004, Geophysical Research Letters. 32, L11307, doi:10.1029/2005GL022679

[4] Khulhanek, O. 2005. *Seminar on b-value*. Prague: Dept. of Geophysics: Charles University.

[5] Meng, X., Yang, H., & Peng, Z. 2018. Foreshocks, b value map, and aftershock triggering for the 2011 M_w 5.7 Virginia earthquake. Journal of Geophysical Research *: Solid Earth* ,123,5082–5098 .https://doi.org/10.1029/2017JB015136

[6] Ghassabian, N. N., Khatib, M. M., Nazari, H., dan Heyhat, M. R. 2016. Fractal dimension and earthquake frequency-magnitude distribution in the North of Central-East Iran Blocks (NCEIB). Geopersia, 243-264

[7] Geoffrey C. P. King, Ross S. Stein, Jian Lin.1994. Static stress changes and the triggering of earthquakes. Bulletin of the Seismological Society of America 1994;; 84 (3): 935–953.

[8] Ning lei, dong, Wu, J., & Yang, G. 2019. Coseismic Coulomb stress changes imparted by the 1996 Minahasa Mw7.9 earthquake on the 2018 Palu Mw7.5 earthquake and expected seismicity rate changes. Terra Nova. doi:10.1111/ter.12434

[9] Navas-Portella, V., Jiménez, A. & Corral, Á. 2020. No Significant Effect of Coulomb Stress on the Gutenberg-Richter Law after the Landers Earthquake. *Sci Rep 10, 2901 (2020). https://doi.org/10.1038/s41598-020-59416-2*

[10] Gunawan, E., Widiyantoro, S., Supendi, P., & Nishimura, T. 2020. Identifying the most explainable fault ruptured of the 2018 Palu-Donggala earthquake in Indonesia using Coulomb failure stress and geological field report. Geodesy and Geodynamics. doi:10.1016/j.geog.2020.04.004

[11] Mohammadi, H., Quigley, M., Steacy, S., & Duffy, B. 2019. Effects of source model variations on Coulomb stress analyses of a multi-fault intraplate earthquake sequence. Tectonophysics. doi:10.1016/j.tecto.2019.06.007

[12] Mildon, Z.K., Roberts, G.P., Faure Walker, J.P. et al. 2019. Coulomb pre-stress and fault bends are ignored yet vital factors for earthquake triggering and hazard. Nat Commun 10, 2744 (2019). https://doi.org/10.1038/s41467-019-10520-6
[13] http://ds.iris.edu/ieb/
[14] http://www.isc.ac.uk/iscbulletin/search/catalogue/.
[15] Wiemer, S, Wyss M, and Zúñiga, R, 2002, ZMAP A Tool For Analyses Of Seismicity Patterns, Typical Applications And Uses: A Cookbook.
[16] Geutenberg, B., and Richter, C.F., *Seismicity of Earth and Associated Phenomenon,* Princeton Univ. Press
[17] USGS. Inside the Earth. Retrieved from USGS: *https://pubs.usgs.gov/gip/dynamic/inside.html*
[18] Toda, Shinji, Stein, R.S., Sevilgen, Volkan, and Lin, Jian, 2011, Coulomb 3.3 Graphic-rich deformation and stress-change software for earthquake, tectonic, and volcano research and teaching—user guide: U.S. Geological Survey Open-File Report 2011-1060, 63 p., available at http://pubs.usgs.gov/of/2011/1060/.
[19] Maulana, A. 2019. Geological constraints for disaster mitigation model in South Sulawesi. Journal of Physics: Conference Series 1341 (2019) 052004 IOP Publishing doi:10.1088/1742-6596/1341/5/052004
[20] Nuannin, P., Kulhanek, O., Persson, L., 2005. Spatial and temporal b value anomalies preceding the devastating off coast of NW Sumatra earthquake of December 26, 2004, *Geophysical Research Letters. 32, L11307, doi:10.1029/2005GL022679*
[21] Ngadmanto, D, 2012. Penentuan Potensi Gempabumi Merusak Berdasarkan Parameter Kegempaan Di Wilayah Busur Banda. *Jurnal Meteorologi dan Geofisika. Vol. 8 No.1 Juli 2012 : 16 – 22*
[22] Sari R, Andi Wirma, Jasruddin D. Malago, Nasrul Ihsan.2012. Analisis Rekahan Gempa Bumi dan Gempa Bumi Susulan dengan Menggunakan Metode Omori. *Jurnal Pendidikan dan Fisika. vol. 8, no. 3, 2012, doi;10.35580/jspf.v8i3.922.*
[23] Xie, C., Zhu, Y., Lei, X., Yu, H. dan Hu, X. 2010, Pattern of Stress Change and Its Effect on Seismicity Rate Caused by Ms8.0 Wenchuan Earthquake, *Science China Earth Sciences, Vol.53, No.9, hal. 1260–1270. http://doi.org/10.1007/s11430- 010-4025-9.*
[24] Lorna, Rahmaniah, Ayusari Wahyuni, 2019. Identifikasi jenis dan arah sesar aktif di wilayah sulawesi selatan menggunakan metode hipocenter dan centroid (*H-C). JFT. No.1, Vol. 6, Juni 2019*