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Preliminary Investigation of the Coulomb Stress Transfer of the 1939 6.2Mw Accra Earthquake, Ghana

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Abstract

The June 22nd, 1939 Accra earthquake (Mw = 6.2) of Ghana is one of the most devastating intra-plate earthquakes in the sub-Sahara West African region. The waveform inversion earlier carried out suggested that the earthquake was composed of two events. The smaller event (6.1 Mw) occurred 9.5 s before the onset of the larger event (6.4 Mw). The smaller event has a focal mechanism that suggests it occurred immediately north of the intersection of the Akwapim and Coastal Boundary fault. This study resolved the static Coulomb Failure Stress (CFS) change onto the finite fault models of the 6.4 Mw and 6.1 Mw earthquakes by USGS and its effect on associated receiver faults. Aftershocks were poorly spatially correlated with the enhanced CFS condition after the 6.4 Mw main shock and were explained to correlate with release of seismic energy from the associated secondarily stressed prominent strike-slip (Akwapim) fault and strike-slip (coastal boundary fault). Abrupt termination of the northeastward propagation of 6.1 Mw rupture surface was due to interaction with the strike-slip coastal boundary faults. The existing intersection between the Akwapim and Coastal boundary faults favored the enhanced CFS to generate the next major event of 6.4 Mw due to the deflection of motion transmitted from the seismically active fractured zones in the mid-Atlantic ridge (the boundary between the African plate and the South-American plate).

Keywords

Coulomb Stress, 1939 Accra Earthquake, Ghana, Gulf of Guinea

1. Introduction

In sub-Sahara West African countries, Ghana is one of the most prominent countries to have been impacted by destructive earthquakes: Ambraseys & Adams (1986); Claridge (1915); Quaah (1980); Junner (1941) reported the historical earthquake of Ghana in the following years: 1615 Ms = 5.7; 18 December 1636, (Ms) 5.7; 1862 (ML) 6.5, 1871 (M) 4.6; 1872 (M) 4.9; In 1883, there was another minor event, which was reported to have been felt in Accra Junner (1941); 20th of November 1906, (ML) 6.2 and 22nd of June 1939 (Mw) 6.2. Among the above-mentioned historically devastating earthquakes in Ghana, the 22nd June 1939 is considered to be near recent events, why? The waveform data of the event is available and was analyzed by the International Seismological Centre (ISC) which gave the Mw 6.2 and the hypo-central parameters as follows: Longitude −0.6276; Latitude 5.5519; depth 15 Km and 6.2 Mw, Yarwood & Doser (1990) carried out the waveform inversion of the 1939 Accra earthquake of Ghana to determine the fault plane solution of the event. Blundell (1976); Bacon & Quaah (1981); Junner (1941); Burke (1969); Eluyemi & Baruah (2016); Eluyemi et al. (2019a); Eluyemi et al. (2019b); Eluyemi et al. (2022a; 2022b) have utilized the data obtained from this event in some research studies which include but not limited to the followings: empirical relationships of earthquake magnitude studies, seismic hazard investigation and tectonic stress tensor inversion analysis work.

So far, Ghana is remote from the major earthquake zones of the world, it is moderately active in terms of seismicity but with a history of damaging earthquakes, most especially, in the capital city of Ghana, Accra. Amponsah (2002) states that the location of Ghana is on the southeastern margin of the West Africa craton which is far away from the major earthquake zones that characterized the present-day lithospheric plate boundaries. Damaging earthquakes have been recorded as far as 1636. The first earthquake event to be recorded occurred on 18th December 1636 in the Axim district in southwestern Ghana, having an intensity of IX destroying the buildings and underground gold mine. Kutu et al. (2013) propose the importance of re-interpretation of the 1939 Accra earthquake, which would explain the nature and cause of the recent seismicity in Ghana. The study revealed that the 1939 Accra earthquake event occurred at a shallow depth. Which emanated from high-angle submarine strike-slip faults in conjunction with the swarms of fractured lines emanating from the mid-Atlantic ridge in the Gulf of Guinea.

An interpretation of the offshore seismic surveys south of Accra, in Ghana, was carried out by Blundell (1976) which shows that Accra is located around the intersection of the northeast-trending Akwapim fault zone and the east-trending coastal boundary fault line. Bacon & Banson (1979) made a suggestion contrary to the general theory of the intraplate seismicity of the Accra-Ghana, due to an explanation that the recent seismic recording of the local earthquakes in southeastern Ghana, which revealed that almost all the seismicity occurred along the Akwapim fault zone, with little seismic events offshore. Thereby casting doubt on earlier theories and suggestions that the causative stress is a result of the transmission of movement or motion along the Romanche fracture zone near the continental margin.

Eluyemi et al. (2019a) carried out the seismicity and stress tensor inversion investigation of the Gulf of Guinea. The investigation revealed that the seismicity pattern indicates that most of the countries along the Gulf of Guinea are devoid of seismicity. However, the stress tensor inversion result and interpretation imply the sea floor spreading activities in and around the mid-oceanic ridges with the overall direction of the extensional stress regime found along the countries located on the shoreline of the Gulf of Guinea or towards the continents, along the line of migration/progression of earthquakes from the mid-Atlantic ridge. Fail et al. (1970) apply the use of magnetic and seismic reflection geophysical surveys to investigate the equatorial fracture zone of the Atlantic Ocean which extends into the Gulf of Guinea. The study revealed that the Romanche fracture zone can be located under the sediments of the Guinea abyssal plan and, towards the eastern side along the southern flank of a morphological feature of the Ivory Coast Rise. The study reveals the importance of studying the relationship between the oceanic transform faults and the continents, for a better interpretation of the geological structure of continental margins.

Eluyemi et al. (2020a) conducted preliminary investigations of a suitable site for nuclear power plants and industrial constructions free of land tremor and seismic shock in Nigeria using the probabilistic method. Eluyemi et al. (2019b) emphasized that the strength of an earthquake depends on its magnitude, thereby carrying out the empirical relationships of the earthquake magnitude scales for the Gulf of Guinea region. Eluyemi et al. (2020b) further proposed that equatorial fault lines beneath the subsurface from previously seismic active areas of the Gulf of Guinea are in a reactivation process which was projected by the use of GIS and was also used to create a detailed tectonic map of Nigeria. Considering the numerous scientific work carried out in this region, the coulomb stress studies of this important earthquake have not been done.

The function of the Coulomb stress study is based upon the hypothesis that faults interact by transfer of stress, through these conditions: i) the time scales of the earthquake sequences; ii) after-shocks of the earthquake events; iii) on broader time interval coupled with inter-event time of the largest shocks occurring in a specific region. The interaction between faults, magmatic bodies, and eruption of volcanoes as a result of static Stress change with or without earthquake events are also considered (Toda et al., 2005; Lin & Stein 2004). There exists a direct relationship between stress and a geologic process: stress makes geologic processes happen and geologic processes make stress: plate tectonics, earthquakes, volcanic eruptions, glacial rebound, landslides, tidal deformation, phase changes in fluid flow, rock folding are the geological processes that generate, and consume stress within the earth. Stress is directly related to force, therefore, mechanical processes in the solid or fluid part of the earth must involve stress (Ruff, 2002).

In this study, we have observed that no research has been done on the coulomb stress transfer of the 1939 earthquake event in Ghana. An attempt to construct the beach ball of the 1939 Accra earthquake in Ghana shows interesting features in **Figure 1**, hence, we aim to investigate the stress transfer of this event and the possible region where the impact of a return of this event will be severely affected. The coulomb stress transfer study of the 1939 6.2 Mw Accra earthquake of Ghana would brought about an insight to the direction of the return of the next big magnitude earthquake in Ghana and serve as a precursory study to the devastating earthquake in the sub-Sahara West African region. To achieve the aforementioned, we intend to carry out the coulomb stress transfer of the 1939 Accra earthquake 6.2 Mw Ghana, determining the epicentral location of the 1939 Accra earthquake in Ghana and identifying the source and the receiver faults.

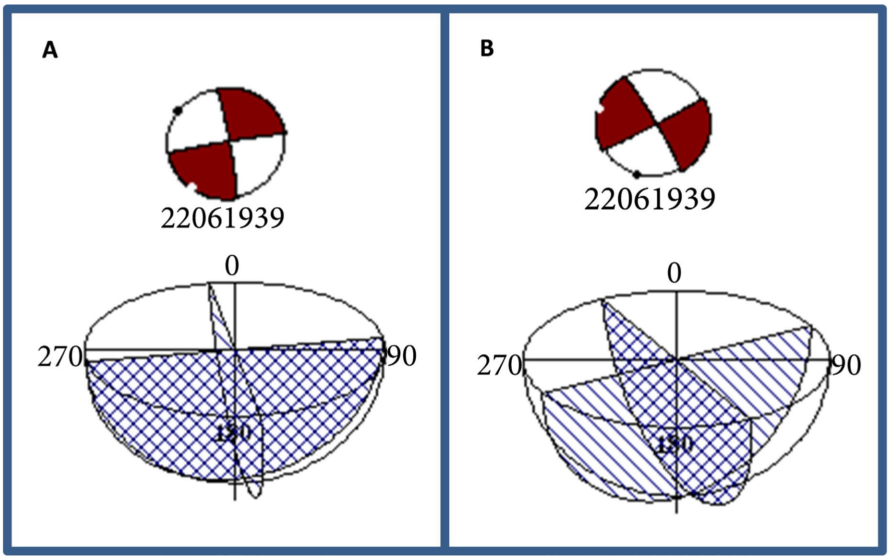

Figure 1. Illustrates the beach ball representation and the quadrant of occurrence of the 1939 Accra earthquake in Ghana.

2. Methodology

To obtain the historical and recent earthquake events that were instrumentally recorded, pertaining to Ghana, we attempt to query the International Seismological Centre (ISC) event catalog within the quadrangle of 11.1733N; 4.738751N; −3.255419W and 1.19177E, a total of sixty-seven (67) numbers of earthquakes were found pertaining to Ghana seismicity (**Table 1**). These events comprised of historical and recent seismicity including the 1939 6.2 Mw event. These events were then

Table 1. The sixty-seven (67) numbers of earthquake events that occurred in Ghana for the period of 1939 up to the year 2020. Downloaded from the International Seismological Data Center (ISC).

Longitude	Latitude	Depth	Mag	Year	Month	Day
−0.6276	5.5519	15.0	6.2	1939	06	22
1.0000	6.000	00.0	0.0	1939	08	18
−0.1534	5.5943	11.3	4.9	1969	02	09
−0.5	5.53	00.0	3.1	1978	03	03
−0.35	5.63	00.0	3.9	1978	09	05
−0.32	5.58	00.0	3.6	1979	01	09
−0.314	5.566	10.0	2.6	1987	11	05
−0.26	5.513	33.0	0.0	1987	12	03
−0.407	5.529	00.0	3.1	1988	12	03
−0.386	5.522	10.0	3.4	1988	02	27
−0.272	5.626	10.0	0.0	1988	03	06
−0.281	5.595	10.0	0.0	1988	03	25
−0.109	5.597	10.0	3.5	1988	03	29
−0.32	5.603	10.0	0.0	1988	05	06
−0.368	5.415	10.0	0.0	1988	05	31
−0.372	5.52	10.0	2.0	1989	03	23
−0.5	5.56	02.0	2.2	1989	06	27
−0.58	5.29	50.0	3.0	1990	02	12
−0.26	5.22	02.0	3.0	1990	04	14
−0.55	5.4	01.0	3.5	1990	09	15
−0.49	5.49	08.0	3.7	1991	08	23
−0.85	4.87	02.0	0.0	1992	07	10
−0.33	5.22	27.0	3.4	1993	06	27
−0.34	5.38	00.0	2.6	1994	01	15
−0.55	5.47	00.0	2.4	1994	01	17
−0.27	5.6	00.0	2.5	1994	01	27
−0.27	5.47	00.0	2.1	1994	08	26
−0.31	5.36	00.0	2.0	1994	08	28
−0.37	5.52	00.0	2.4	1994	09	06
−0.42	5.53	00.0	2.1	1994	09	06

Continued

−0.4	5.6	00.0	2.0	1994	10	22
−0.92	5.72	13.0	2.4	1994	11	10
−0.38	5.48	00.0	1.6	1994	11	15
−0.23	5.57	00.0	1.8	1994	12	02
−0.24	5.52	00.0	2.1	1994	12	07
−0.5	5.44	00.0	1.7	1994	12	16
−0.28	5.45	00.0	1.7	1995	01	03
−0.3	5.45	00.0	2.3	1995	01	27
−0.28	5.5	00.0	2.4	1995	01	28
−0.36	5.5	00.0	2.4	1995	01	28
−0.56	4.29	34.0	3.3	1995	01	28
−0.52	5.25	02.0	3.4	1995	01	28
−0.4	5.53	00.0	1.5	1995	02	01
−0.57	5.63	00.0	2.6	1995	02	01
−0.45	5.63	00.0	3.8	1995	02	01
−0.17	5.47	34.0	2.7	1995	02	01
0.35	5.37	27.0	4.0	1995	02	01
−0.47	5.53	00.0	1.5	1995	02	02
−0.52	5.68	02.0	3.5	1995	03	09
−0.51	5.81	00.0	4.2	1995	10	20
−1.42	5.28	25.0	2.9	1996	02	23
0.15	5.83	00.0	2.0	1997	01	08
−0.7517	6.9802	10.0	3.8	1997	02	14
−0.2744	5.6123	17.3	0.0	1997	03	06
−2.017	5.597	02.0	0.0	2003	02	23
−1.8802	6.6997	02.0	0.0	2003	06	22
−2.6235	5.3113	02.0	0.0	2004	04	17
−1.5214	9.1958	30.0	0.0	2008	08	16
−2.3589	9.3871	30.0	0.0	2009	10	23
−1.8711	7.02	02.0	0.0	2009	12	12
−0.5973	5.8781	10.0	3.6	2014	07	24
−1.9072	7.3027	30.0	0.0	2016	01	11
−2.8692	7.3605	00.0	0.0	2016	07	21
−0.4578	5.6849	00.0	4.3	2018	12	09
−1.6102	7.1715	00.0	2.2	2019	08	28
−0.4048	5.9495	00.0	3.4	2020	06	24
−0.3155	5.7544	10.0	4.0	2020	06	24

plotted on the image map, derived from Mirone software. This is to access an in-depth seismogenic sources in Ghana. However, the epicentral plots of the obtained earthquake events show a cluster of earthquake patterns confined to a narrow zone. This zone was then indicated with a red rectangular box labeled A, B, C, and D (Figure 2). The coordinates of this box were then traced on Google map to have first-hand prior information on the seismic risk/hazard

Susceptibility of the earthquake epicentral zone of Ghana. However, since the last destructive earthquake in Ghana, which took place in 1939 was instrumentally recorded, the global centroid moment tensor catalog was searched to obtain the fault plane solution of the event. This was further processed using rake software to derive the beach ball of the event. To study the stress transfer caused as a result of the 6.2 Mw earthquake event of the 1936, we employ the Coulomb software, which enables one to calculate the static displacements, strains, and stresses at any depth caused by earthquake fault slip. Using the fault plane solution derived from the global centroid moment tensor catalog and constraining our study with the available literature, we can calculate the following parameters: shear stress change, vertical displacement (net slip), and dilatation.

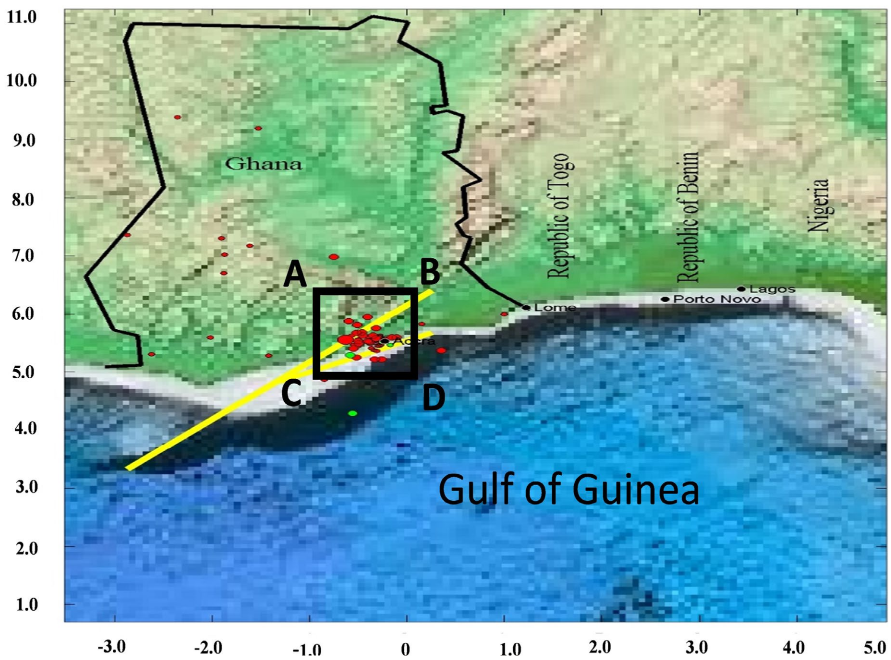

Figure 2. The map of Ghana and the epicentral plot of the earthquake events in Ghana and the adjoining sub-Saharan West African countries located along the Gulf of Guinea.

3. Result

The epicentral plots of the recent and the instrumentally recorded historical earthquake in Ghana show earthquakes clustered and confined in one locality, which could be described as the main seismogenic earthquakes sources in Ghana. Though there are also scattered epicentral plots of smaller magnitude of earthquake events. The 1939 6.2 Mw earthquake in Ghana also found to be located within this clustered epicentral location, which is located at the intersection of the Akwaipim fault and the costal boundary fault indicated with the rectangular box A, B, C, D (Figure 2). The coulomb stress analysis for the shear stress change and the vertical displacement is indicated in Figure 3 (A) and (B). In Figure 3 (A), the red coloration indicates zones of stress transferred and the direction where the return of this earthquake event is possible to be triggered. Figure 3 (B) indicates the direction of the vertical displacement of the return of this event, which is oriented along the Northeast and Southwest directions, with the maximum displacement of 1m to be expected. Both the shear stress change bar and the vertical displacement are indicated on the image map of Ghana in Figure 4.

The statistical analysis of the earthquake events in Ghana is indicated in Figure 5, A shows the plot of depth in Km against time in year, nearly 70% of the earthquake events in Ghana comes from shallow sources within the range of 20Km depth. Most of the event were recorded between the year 1990 and 2020. B shows the plot of earthquake magnitude against the year of occurrence, the plot indicates that after the 1939 6.2 Mw earthquake, the next big magnitude earthquake was a 5.0 Mw earthquake which occurred around late 1970. C shows the plot of the frequency of occurrence against time, out of the 67 earthquake events recorded in Ghana, nearly 27 numbers of earthquake events were recorded in the late 1990s. D Shows the cumulative number against the magnitude, which indicates the highest magnitude to ever occur as 6.2 Mw. The geographical location of the coordinate of the quadrangle A, B, C, D in Figure 2, when inserted into a google map revealed some recent settlements closely located to the epicenter location of the 1939 6.2 Mw Accra earthquake in Ghana (Figure 6). Images of scattered settlements located closely to the epicentral point of the 1939 6.2Mw Accra earthquake Ghana, were derived from on the Google map Figure 6.

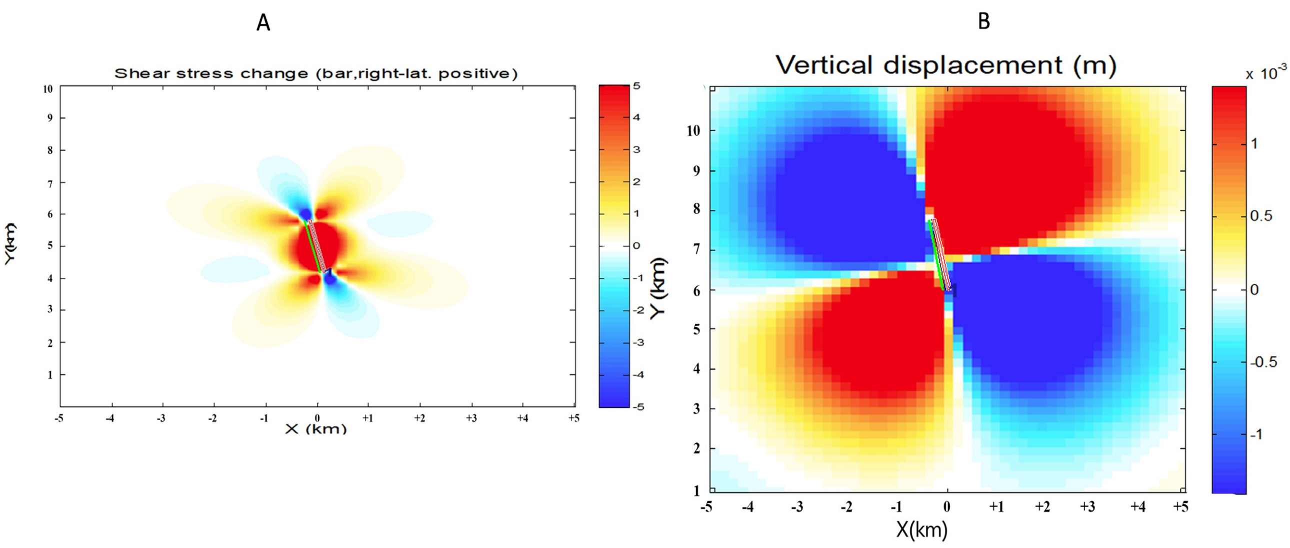

Figure 3. (A) illustrates the shear stress change bar and (B) shows the vertical displacement of the 1939 Accra earthquake in Ghana.

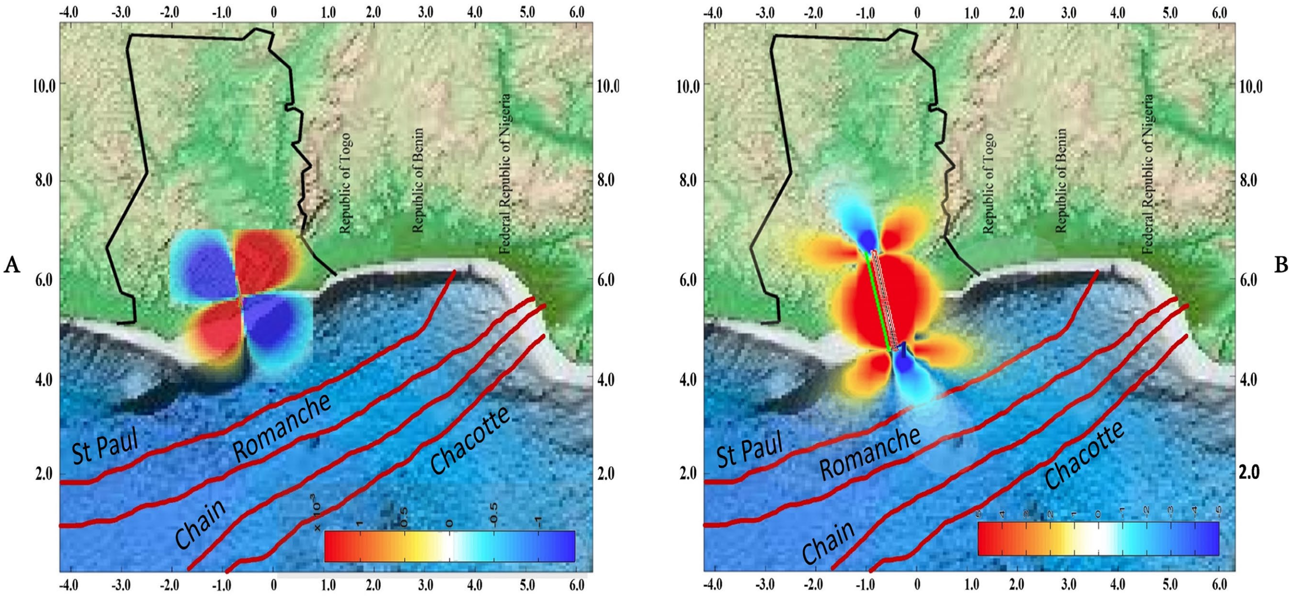

Figure 4. A shows the Focal Mechanism Solutions of the 1939 earthquake event as well as the epicenters of the earthquakes in Ghana while B illustrates the vertical displacement of the event.

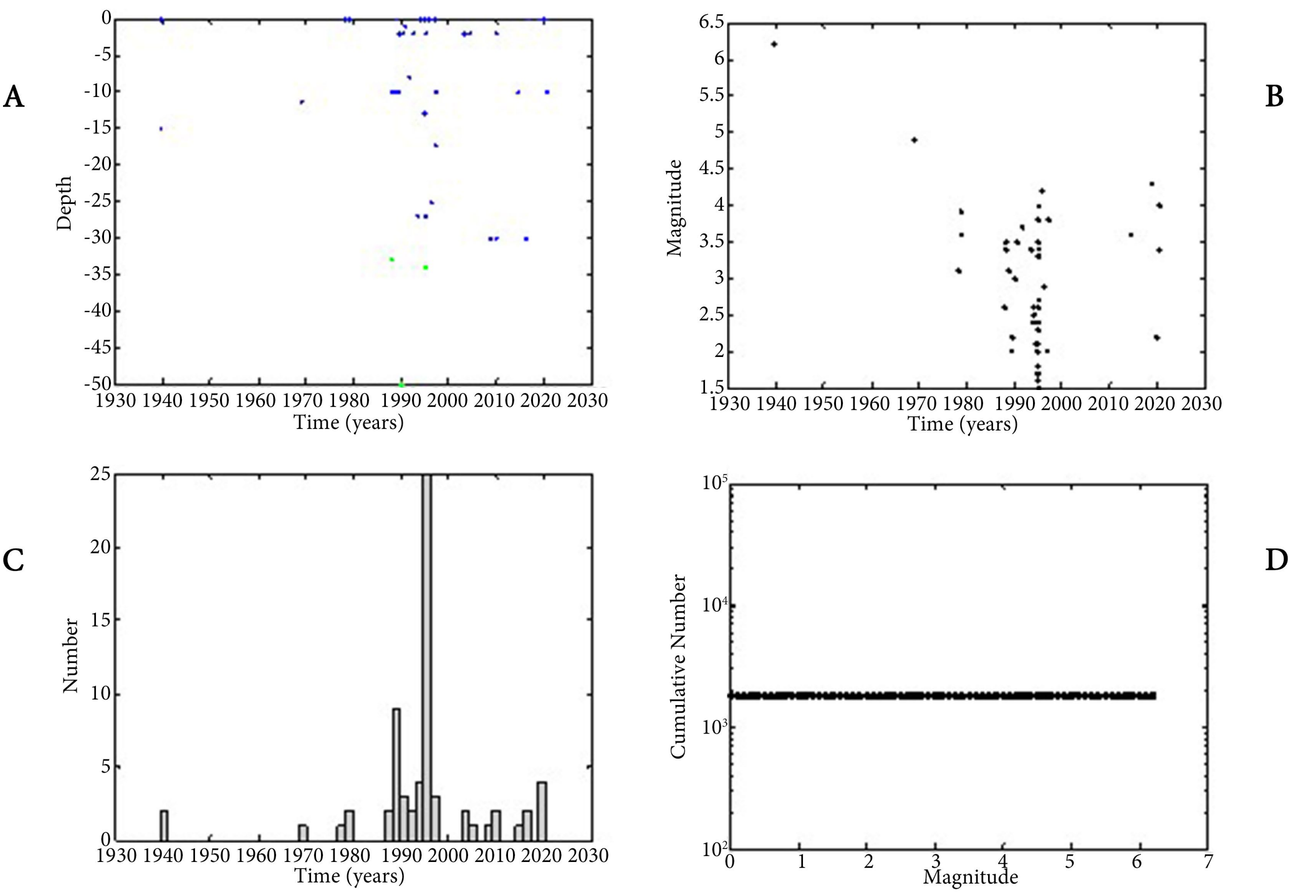

Figure 5. The statistical representation of the earthquake events in Ghana, majority of the events are clustered around Accra in Ghana (A) illustrates the plot of the earthquake Depth vs. magnitude; (B) shows Magnitude vs time (years); (C) shows the bar chart presentation of the earthquake events in Ghana while (D) represents the plot of Cumulative earthquake number vs Magnitude.

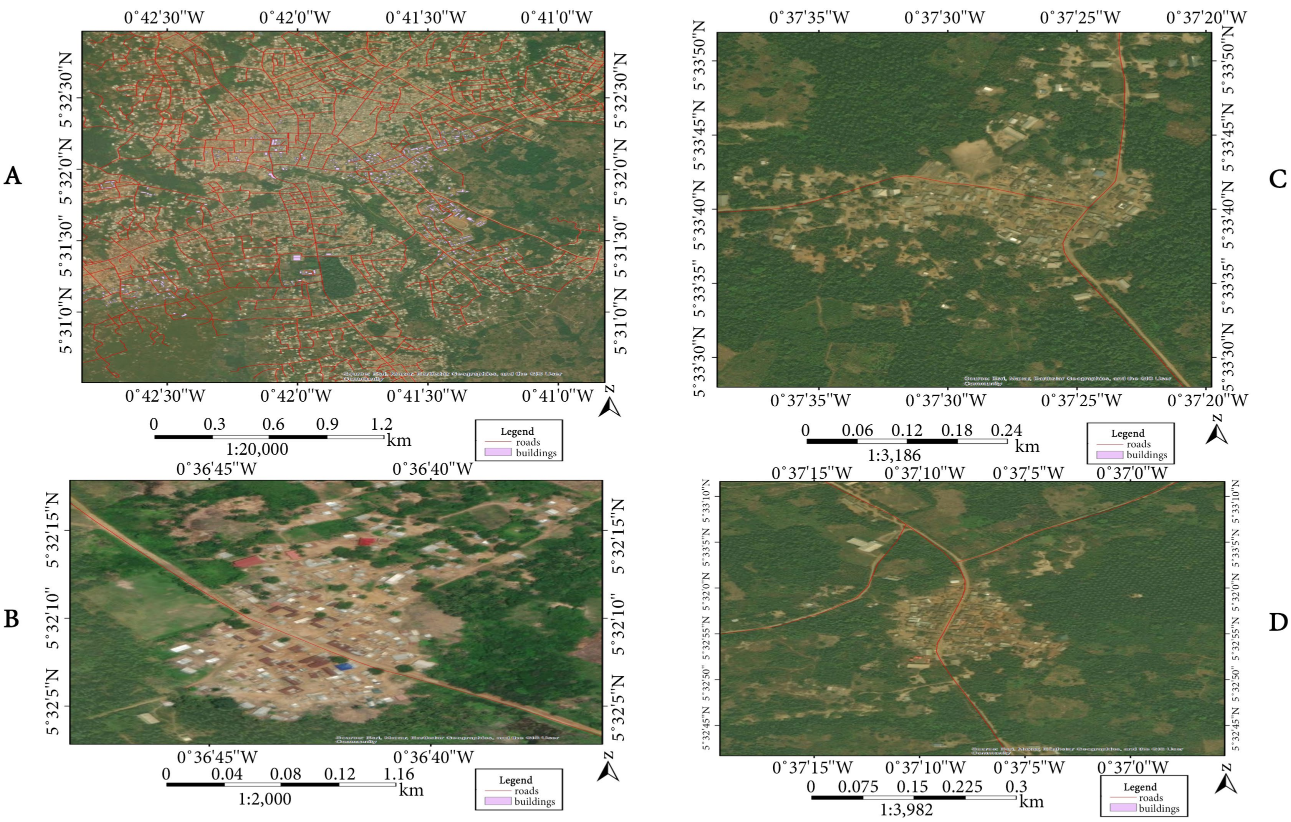

Figure 6. The Google map of various recent settlements located closely to the epicentral point of the 1939 6.2 Mw, Accra earthquake in Ghana. A is named Sweduru, B is called Odumasi, C, and D have no names.

4. Discussion

The geology of Accra city in Ghana is underlain by Dahomeyan Basin: A geological formation with rocks from the Precambrian era, which is characterized by Granite and Gneiss rock types and some notable volcanic and sedimentary rocks. The geology of Accra city is mainly influenced by the presence of the coastal boundary faults and the Akwapim fault which are part of a larger fault system that are connected to the trans-current fault structures of the gulf of Guinea in the seismically active zones of the south-Atlantic Ocean. However, the Akwapim and the coastal boundary faults could be reactivated to trigger to trigger a next big earthquake magnitude.

The Google map revealed the development of various settlements around the epicentral location of the 1939 Accra earthquake in Ghana. Those settlements are recent and are regarded as the satellite towns of the capital city of Ghana, Accra. A detailed geophysical investigation should be carried out around the zones of the epicentral location of the 1939 6.2 Mw earthquake, to investigate for the presence of the surface and subsurface faulted/fractured lines or zones. If present, those fractured zones could propagate the recurrence of the next big magnitude earthquake in that region. The Ghana government should evacuate the settlements close to the vicinity of the epicentral location of the 1939 6.2 Mw Accra earthquake in Ghana. A broadband seismometer should be deployed in the vicinity of the epicentral location of the 1939 6.2 Mw earthquake in Ghana, for earthquake precursory study and preparedness.

5. Conclusion

The 1939 Accra-Ghana earthquake was one of the most important earthquakes in the sub-Sahara West African region. The Coulomb stress bar indicates that stress is transferred in the direction of the North West and South East (NW/SE). This direction is towards the two (2) of the recent settlements (town) one of them by name is called Odumasi and the other has no name. These settlements are being developed around the epicentral location of the 1939 6.2 Mw Accra earthquake in Ghana, indicated by the red coloration. However, the vertical displacement of the fault slip is oriented along the northeast and southwest (NE/SW) Orientation.

The statistical analysis for the plot of the Depth against Time; Magnitude vs. time; Guttenberg vs. Richter and Number of earthquakes against Time. Revealed that the depth of occurrences of earthquakes in Ghana is shallow majorly at the depth of 30 Km and on the average at the depth of 15 Km, including the 1939 6.2 Mw devastating earthquake Accra Ghana but the deepest earthquake event ever recorded occurred at the depth of 50 Km, this event took place in the year 1990. The plots of the Magnitude against Time revealed that since the occurrence of the 1939 6.2 Mw Accra earthquake event in Ghana, the next big magnitude earthquake to have occurred is 4.9 Mw which took place on the 9^{th} of February, 1969. A five (5) years period of quietness was observed between 1998, 1999, 2000, 2001, and 2002. There is no record of earthquake events from those years. The plots of the Number of earthquake events against Time show that the highest frequency of occurrence of the earthquake magnitude occurred between the years 1990 and 1997.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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