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Causative Mechanism of the January 2018 m 6.0 Bago Yoma Earthquake and a New Insight into the Nature of Bago Yoma Mountain Building in Myanmar

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

The 2000 km long, and approximately 200 km wide elongated tectonic zone in Myanmar has been wedged between the northward moving India plate on the west and southeasterly extruding Indochina plate on the east. The tectonic setting between these moving rigid plates and the highly oblique subduction of the India oceanic plate beneath the Burma continental plate has caused extension to occur on the ductile crust. In turn, this has caused the brittle continental crust to be pulled apart laterally, forming a rift zone. The Central Myanmar Basin has a classic continental rift structures that are arranged in basin-and-uplift configuration in N-S direction. The Bago Yoma is a prominent feature in the Central Myanmar Basin, developed by the basin inversion tectonics due to a change from the extensional regime to compressional regime in Pleistocene to Recent. The Bago Yoma is driven mainly by crustal shortening and uplift, squeezed upward between the Sagaing fault on the east and the Bago fault, Taikkyi fault and Shwepantaw fault on the west. It was formed when linkages among faults have cut through the Bago basin forming Bago Yoma by transpressional push-up and basin inversion in late Tertiary. A strong earthquake of 11th January 2018 occurred at 39 km WSW of Phyu. The magnitude of this earthquake is 6.0, with focal mechanism solution of oblique reverse faulting at the depth of 10 km (USGS). The epicentral location is at latitude 18.363°N- longitude 96.080°E, 39 km WSW of Phyu in the Bago Yoma

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mountains, Central Myanmar. The main shock was followed by at least six aftershocks with M 5.3, M 5.2, 5.0, 4.8, M 4.6, M 4.3 in the vicinity of epicentral location. The distribution of aftershocks defines a 70-km-wide WNW-ESE-trending weak zone across the Bago-Yoma.

Keywords: Strong earthquake; aftershocks; conjugate fault; shaking; reverse fault; strike-slip component.

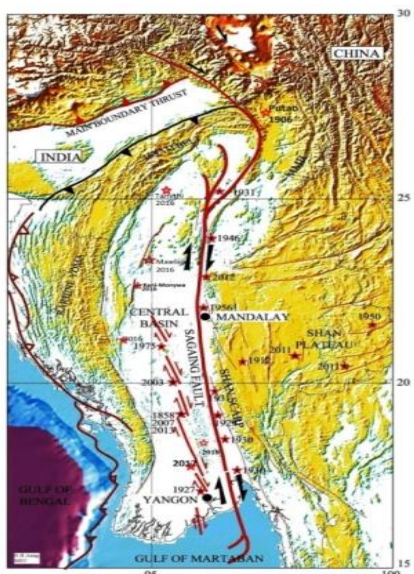
1. INTRODUCTION

1.1 Tectonic Settings

Myanmar is composed of two different evolving continents: The Burma plate and the Sunda plate. The Sagaing Fault is interpreted as an active dextral strike slip fault and a continental transform plate boundary that separates the Burma plate from the Sunda plate [1,2,3,4]. Within the neotectonic framework of Myanmar, the Sagaing Fault is from longitude is 96° 30'E (coastline in the south)- 96°E (from Pyinmana to Tagaung) -96°45E to the north. In other words, the fault is relatively more westerly (NNW-SSE) in the south than the N-S segment in the central part between Pyinmana and Thabeikyin, a distance estimated to be 300 km. The fault then swings to the east (NNE-SSW) again further north of Thabeikyin. The rate of motion of the Burma plate with respect to the Sunda plate has a rate of 18-25 mm/yr towards the north [5]. The average trend of the Sagaing fault is 351° (N9°W) west (Fig. 1a). When a fault trend differs from the plate motion, dip slip faulting occurs and the plate motion becomes complex [6]. The Bago Yoma ('Yoma' means a long linear range in Myanmar language) in southern Myanmar illustrates the characteristics of a large restraining bend in the Sagaing fault system. This range has been uplifted in response to a combination of dextral motion and compression across a portion of the fault that strikes more westerly than general strike of the fault system. Seismic section reveals a positive flower structure, push-up and transpression. Surface and subsurface data suggests that these basins experienced NNW-SSE extension in the Miocene, followed by ENE-WSW transpression in the Pliocene during a change of maximum horizontal stress direction, resulting in a variety of structural styles, such as thrust faults, reverse faults, positive flower and folds that are compartmentalized by normal faults [7]. Faults are trending in NE-SW, NW-SE, NNW-SSE, ENE-WSW, WNW-ESE, E-W direction and the folds in N-S, NNW-SSE direction are developed by the ductile extension started in the late Eocene mainly in the Miocene to Recent. A series of basins are formed in Central Myanmar Basin in which Bago basin is one of these basins. Each basin has two sets of margin (Fig. 1b). One set of basin bounding faults are parallel to the movement direction along the Sagaing fault which is a continental plate boundary between the Burma plate and Indochina plate and the other set parallel to rifting direction. Folds and faults trend oblique to the Sagaing fault and extensional faults are perpendicular to extensional direction. There are other different types of faults such as synthetic, antithetic, and' p'shear faults.

2. THE NATURE OF MOUNTAIN BUILDING OF THE BAGO YOMA

The Central Myanmar Basin is made up of Tertiary sedimentary rocks between the Rakhine Western Ranges in the west and Shan Plateau to the east. The basin consists of seven sub-basins: Hukawng, Chindwin, Salin, Pyay, Bago Yoma (Bago basin), Sittoung and Ayeyawady Delta basin. The satellite images interpretations and fault plane solutions data revealed that normal faults and six ENE-oriented rift system are the most prominent active tectonic features in Myanmar. The presence of a series of en echelon basins and intervening uplift areas and the dominance of high-angle normal faults on N60°E on average are suggestive of a NNW-SSE extensional stress direction [8]. The seismotectonic and geomorphic analyses of the 2018 M 6.0 Bago Yoma earthquake provides several new insight into the nature of mountain building of the Bago Yoma (Pegu Yoma) on the western side of Sagaing Fault. The Bago Yoma, a mountain range approximately 660 km (400 mile) long and 66 km (40 miles) wide is formed by NNW-SSE trending extensional deformation regime in Mio-Pliocene and ENE-WSW oriented compressional deformation in Pleistocene-Quaternary. Tectonic geomorphic interpretation was carried out using Landsat ETM images, geological map at scale 1:25 km, base map at scale 1:63,360 topographic map, 1:24,000 aerial photographs and collected available data. The result show that a series of NNW-SSE trending strike-slip faults and a group of cross faults in WNW-ESE direction are found within the Bago Yoma, making 60° between each other (conjugate faults) (Fig. 2a). The Bago Yoma, about 660 km long and 60 km wide is dominated by NNW-SSE striking strike-slip faults with 45-50° dipping to the east and a series of anticlines between them (Fig. 2b).

(a) 

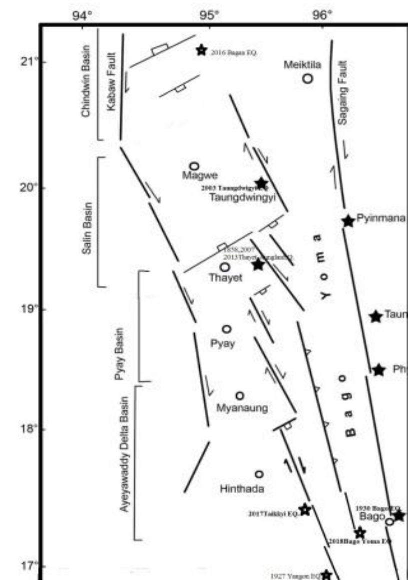
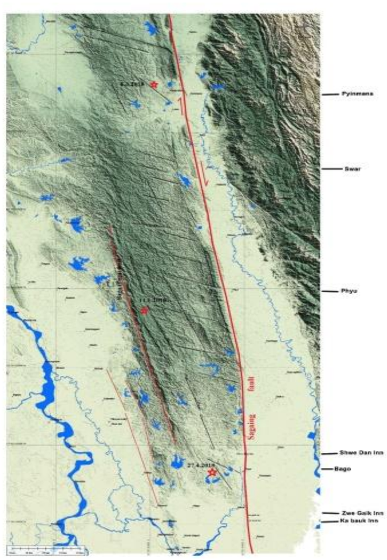
(b) 

Fig. 1(a). Map of satellite image showing all epicenters of earthquakes over Myanmar region. 1(b). Map showing epicentral locations of earthquake in Central Myanmar basin associated with basin bounding faults. Bago Yoma can easily be seen in the map

(a) 

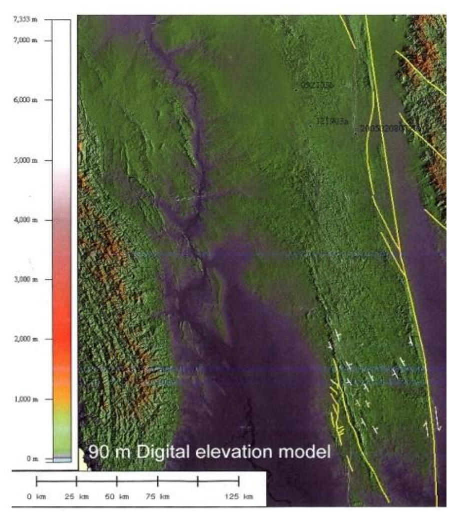
(b) 

Fig. 2(a). Shaded relief map of Bago Yoma showing conjugate faults of NNW-SSE and WNW-ESE direction. Stars in red color are shown on the map to indicate epicenter of Bago Yoma earthquake of 11thjanuary2018 and epicenter of aftershock on 8th march 2018, NW of Nay Pyi Taw. Each occurred on conjugate faults of NNW-SSE and WNW-ESE direction. (b) The synthetic and antithetic faults are identified along the NNW-SSE direction and along WNW-ESE direction which is at the angle of 60° (conjugate set) to each other and the folds and thrusts in NNW-SSE direction are developed by the extensional scheme

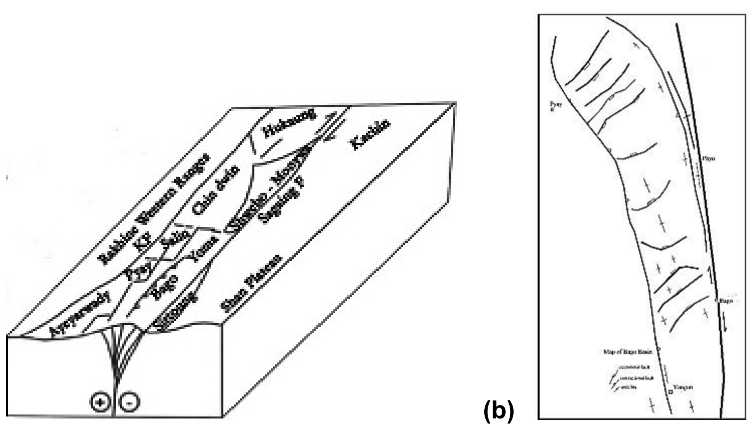
It plunges to the south beneath the sediments of Irrawaddy Group and also plunges to the north beneath the unconsolidated Quarternary sediments of the Shwebo basin [9]. To the west of the Bago Yoma is bounded with a fault escarpment of Taikkyi fault in Ayeyawady Delta basin, Shwepantaw fault in Pyay Basin and the Bago fault. In the east, the Bago Yoma is bounded with the Sagaing fault and the Sittoung basin (Fig. 3a).

The transfer of about 60 km of dextral strike-slip motion across this step-over during the late Tertiary has resulted in a series of oblique anticlines, reverse faults and surface uplifts that form a stepped, overlapping en echelon pattern. The Bago Yoma is the largest push-up in the Myanmar region and is a broad ridge composed mainly of Miocene rocks and Pliocene sedimentary rocks. Bago Yoma represents a group of anticlinal folds.

The axis of the western BagoYoma anticline approaches Yangon and eastern fold extends to Thanlyin-Kyauktan to the south. The Miocene and Pliocene deposits are contorted and Quarternary pebbles and terraces are uplifted. Two terraces are found near Yangon. The thick bed of alluvial clays situated 70 km north of Yangon near Taikkyi and Okkan are raised 20 m above sea level [10]. Studies of fluvial terraces suggests uplifting of the crust over tens of thousands years ago. Crustal uplift and reverse faulting have been resulted from crustal thickening associated with ENE-WSW shortening. The Bago Yoma was formed when linkages among faults have cut through the Bago basin forming Bago Yoma Range by transpressional push-up and basin inversion in late Tertiary. Reverse faulting occurred after the pull-apart had formed [11].

The Bago basin had been deformed into a Bago Yoma which is the longest of rift system in Central Myanmar Basin extends about 660 km from the Shwebo-Monywa basin in the north to the Mottama basin in the south. The rift is consist of at least three grabens or half-grabens (Fig. 3b). The Bago Yoma in Myanmar illustrates the characteristics of a large restraining bend or a branch of the Sagaing fault (Fig. 4a). The ranges have been uplifted in response to a combination of dextral motion and compression across a portion of the fault that strikes more westerly than the general strike of the Sagaing fault system.

Most faults in this Bago Yoma region exhibit component of right-lateral and reverse slip, with NE side up. The morphology of reverse fault scarp shows that hanging wall blocks override the foot wall blocks and may collapse onto or roll over the foot wall. Commonly such faults do not break the surface, instead having a surface expression of a broad warp. This situation generally gives rise to the development of flexural scarps at the front of fault propagated fold as reported location worldwide [3]. Such scarps may result from the warping of strata at the shallow tip of a blind fault or in a fault bend fold. Such near-surface deformation is commonly expressed by flexure-pressure ridges or flexural slip folding (Fig. 4b).



(a) (b)

Fig. 3(a). Block diagram shows distribution of basins in Central Myanmar basin between Rakhine Western Ranges and Shan Plateau. (b) Map of Bago basin showing extensional faults, contractional faults and anticlines. Bago Yoma was formed by transpressional push-up and basin inversion

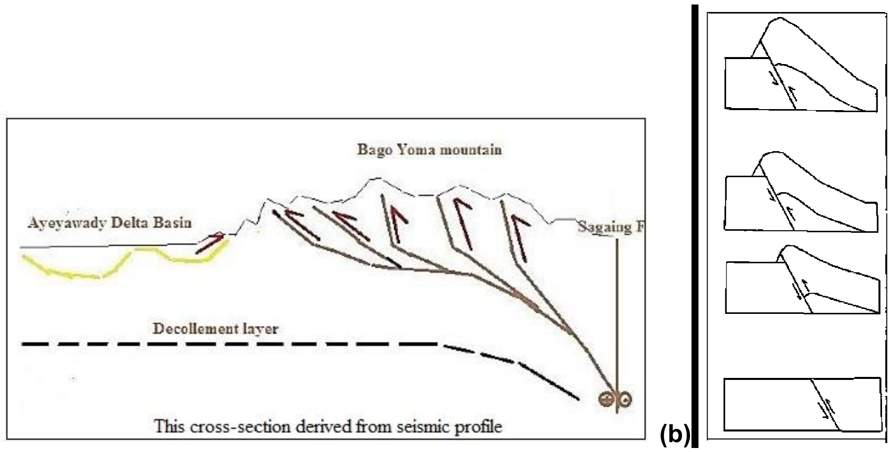
(a)


Fig. 4(a). A cross section along E-W showing the relation between Ayeyawady Delta basin and Bago Yoma mountain with active faults of strike-slip fault and reverse fault derived from line drawings of seismic profile of the sagaing fault across Nyaunglaypin latitude (approximately latitude 18°N) in lower part of Myanmar. (Source: MOGE) 4.b. Sequential illustration of development of mountain building resulted from extensive ENE-WSW shortening by reverse faulting and folding in Bago Yoma

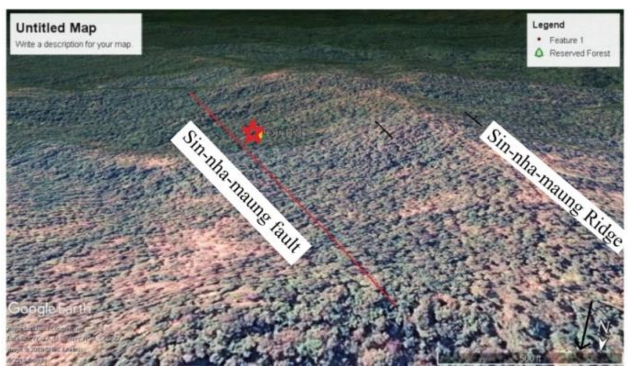


Fig. 5. Google Earth map showing the epicentral location of the 2018 Bago Yoma earthquake (red color star) associated with surface expression of reverse fault and fault propagation fold

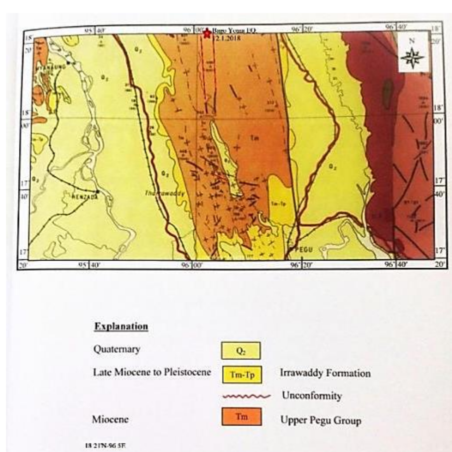
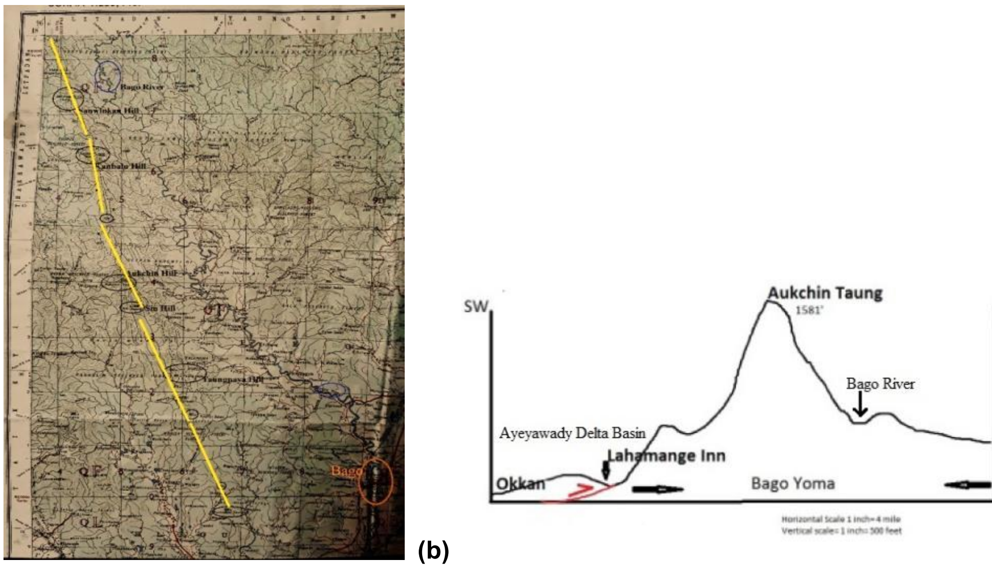


Fig. 6. Geological map of southern part of the Pago Yoma derived from geological map of Myanmar, showing structural features within the Bago Yoma

(a)


(b)

Fig. 7(a). Topographic map shows the trend of Sin-nha-maung ridge, Sanwingan ridge, Aukchin ridge in NNW-SSE direction with right step-over structures. (b) Topographic profile across the study area along the minhla- letpadan (17°55'N latitude) show the relation between the Ayeyawady Delta Basin in the west and the Bago Yoma in the east

3. GEOLOGIC SETTINGS

The Bago Yoma Range has elevated more than 850 m above the surrounding area. The Bago Yoma which lies in the west of the Sagaing fault is composed of Mio-Pliocene sediments of the Pegu and Irrawaddy Group (Fig. 6). The name of the ridge on the Bago (Pegu) Yoma Range where the 2018 M 6.0 Bago Yoma earthquake occurred is Mt. Sin-nar-maung ridge (2693'). The anticlinal ridges of Sin-nhar-maung ridge (2693'), Sanwinkan ridge(2257'), Kanbalu ridge (2633'), Aukchin ridge (1581'), Sin Taung ridge (1238'), Taung Bayar ridge (491'), and many hills in Bago Yoma Range are trending in NNW-SSE direction. These ridges are right-handed folds developed by the right-lateral movement of the Sagaing fault. The Bago (Pegu) River starts to flow from this ridge to south-south-east direction in the east of that ridge.

The epicenter of Bago Yoma earthquake is located on the west an unknown fault which runs in NNW-SSE direction for (80) km long. The name of the fault that ruptured the Bago Yoma earthquake is given as Sin-nhar-maung fault as epicenter locates on the western side of that mountain (Fig. 5). The rectangular drainage pattern in the region has been controlled by structure of sedimentary rocks in the area and the Bago River is running in NNW-SSE direction until it meets the Sagaing fault.

Topographic profile across the study area along the Min Hla- Letpadan (17°55'N latitude) show gradual gradient from 48m in the west and then risen abruptly to 875 m of Kanbalu Hill to the east and then to 53 m further in the east near Letpadan, passing several mountain peaks. Further to the north of Kanbalu Hill approximately along the NNW-SSE direction, several hills with the height of more than 750 m are found (Fig. 7b).

4. DISTRIBUTION OF AFTERSHOCKS

The seismic data used in this study consists of earthquake parameters and focal mechanism solutions, derived from United States Geological Survey (USGS) and Thai Meteorological Department (TMD). The aftershock activity which occurred during 11th January 2018 to 31st June 2018 was distributed in and around the Bago Yoma. Beginning at 12 January 2018, a sequence of 125 aftershocks is found by TMD in which there are 34 aftershocks of ≥ 4.0, 43 aftershocks of ≥ 3.0 and 48 aftershocks of ≥ 2.0. The area of aftershocks migrated to the north to Nay Pyi Taw area and to the south to Bago area. The aftershock distribution indicates that the seismogenic structure is N-S trending Bago Yoma.

The range is 400 mile long and 40 mile wide, as can be seen in the satellite image and topographic map. The interpretation of satellite image and topographic profile across the basin is typically a rift basin bounded by a NNW-SSE trending strike-slip fault in the west and N-S trending Sagaing fault in the east. The event was nucleated on the NNW-SSE trending steeply east dipping, oblique reverse fault in the rugged terrain of Bago Yoma. The earthquake occurred in hilly region and the seismic waves have been amplified on the ridge crest leading to the strong shaking over much of the area. This fault is the causative fault for the 2018 Bago Yoma earthquake. The two earthquakes followed on the date of 13th January 2018 M 4.8 and M 4.6 at latitude 18.344 °N-longitude 96.111°E and latitude 18.366°N longitude 96.233°E respectively at the depth of 10 km. There was another seismic occurrence at latitude 18.41°N-longitude 95.34°E in the west of the town, Nattalin in the Ayetawady Delta Basin, west of Bago Yoma. Most aftershocks occur in the vicinity of WNW-ESE trending faults in the Bago Yoma. That means that stress increase to the southeast and northwest of the main shock. These earthquakes propagated to the south-east and to the northwest of main shock along the WNW-ESE direction and display two isolated zones. Some observational phenomena show that there exits seismicity increase beyond the traditional aftershock area after some big earthquakes. It happens when there are local zones of weakness [12]. On the 7th March 2018 at 3:00 a.m., an earthquake with M=5.3 occurred at 10 km depth, 24km WNW of Nay Pyi Taw. The epicenter was latitude 19.835°N, longitude 95.915°E (USGS) near Lethargyi (Ledagyi) village. The causative fault is NW-SE trending conjugate fault of Bago Yoma fault system. The shock was powerful, shaking the city Nay Pyi Taw and surrounding area. The lateral shaking was preceded by vertical movement from beneath the surface with loud sound. Some pagodas near Nay Pyi Taw were damaged. On the 17th March 2018 at 2:30 a.m., an earthquake with M=5.1 occurred at 30 km depth, 25km WSW of Phyu.

The epicenter was latitude 18.313°N, longitude 96.153°E (USGS). On the date of 21st April,2018, an aftershocks with M=5.1 occurred at depth 18.9 km. The epicenter was 33 km. WSW of Phyu at latitude 18.344°N, longitude 96.152°E (USGS). These shocks took place very close to the main shock of M= 6.0 Bago Yoma earthquake at deeper depth than the main shock and easterly. It meant that the fault that triggered both earthquakes is believed to be a reverse fault with 50° dipping to the east. Aftershocks continue to occur until April, 2018. Two aftershocks occurred in Yangon area with M=4.7 and 4.0 at early morning of 5:00 am. Some areas of Yangon felt the strong shaking. On the date of 18th April 2018, an earthquake occurred 12 km WNW of Twante, a town west of Yangon with M=4.2 at depth 10 km. Epicentral location is latitude 16.750°N-95.821°E. The causative fault of this event is the Dedaye fault with right-lateral strike-slip mechanism. The city Yangon felt this shock widespread but no casualties.

5. CO-SEISMIC DEFORMATION

The NNW-SSE oriented, Bago Yoma Range which is located at the western side of the Sagaing fault was produced by contractional push up and basin inversion. It is a fault bounded ridge. The interpretation of remote sensing images reveals that the 2018 Bago Yoma earthquake ruptured NNW-SSE trending fault among multiple strands of Bago Yoma. Two main zones of surface rupture were identified in which the primary surface rupture zone occurs along the NNW-SSE direction and the second surface rupture zone occurs along WNW-ESE direction which is at the angle of 60° (conjugate set) to the primary rupture zone. Tectonic deformation and crustal shortening caused by oblique reverse faulting events may be important contributor to uplift of the Bago Yoma.

6. MECHANISM OF THE 2018 BAGO YOMA EARTHQUAKE

An earthquake with magnitude 5.1 occurred near Taikkyi on 13th March 2017 at 14:19:06 (UTC). The epicenter is situated at latitude 17.415°N, longitude 95.999°Eat focal depth 10 km (USGS). The main shock was initiated at approximately 33 km from southeast of Thayawady and 10 km northeast of Taikkyi (USGS) with rupture propagating southward for about (75) km towards Yangon. The causative fault of this earthquake is Taikkyi fault trending in NNW-SSE direction for (80) km length, with a mix of thrusting and right-lateral motion. An earthquake with magnitude 5.4 occurred near Thayet-Aunglan on 3rd April 2013 at 4:35: 45 PM (GMT). The epicenter is situated at latitude 19.24°N, longitude 95.66°E at focal depth 11 km. The shock was most severe near Thayet and Aunglan. An earthquake with M=5.2 occurred on 11th April, 2013 at depth 10.1km. Focal mechanism solution of this event gives thrust faulting (USGS). The causative fault of this earthquake is a fault named Shwepantaw fault trending in NNW-SSE direction, with a mix of thrusting and right- lateral motion.

Due to the eastward thrusting mechanism of the two earthquakes: Thayet-Aunglan and Taikkyi, ENE-WSW shortening gives rise crustal uplift, crustal thickening and crustal transport to the east. The 2013 Thayet-Aunglan earthquake and the 2017 Taikkyi earthquake might have unclamped the fault in the BagoYoma Range, which triggered the 2018 M 6.0 BagoYoma earthquake by oblique reverse movement associated with several aftershocks. Unclamping the fault would have locally lowered the resistance to sliding [13,14].

7. RESULTS AND DISCUSSION

Historical earthquake records in Central Myanmar Basin show that major events occurred along the Sagaing right-lateral fault and few events in Basin-Uplift Province. Seismic activity in this province is restricted to relatively shallow shocks with dextral faulting or normal faulting as a result of stresses generated by extensional deformation. To understand the geodynamics of mountain building of the Bago Yoma, it is important to investigate the tectonic setting of the range and its seismotectonic behaviors. The Bago Yoma earthquake provides an opportunity to evaluate the nature of mountain building process at Bago Yoma. In this paper, co-seismic deformation associated with the 2018 earthquake and the geometry of surface rupture are studied using interpretation of aerial photographs, topographic maps, satellite images, shaded relief map and digital elevation model (DEM) for regional deformation of the Bago Yoma area. The co-seismic deformationis characterized by reverse faulting and scarps developed upon flexure folds.

8. CONCLUSION

Dams are constructed on both side of Bago Yoma thrust-and-fold belt along the Sagaing fault on the east and along the 2017 Taikkyi earthquake fault and the 2013 Thayet-Aunglan earthquake fault on the west. Some of the dams are located on the Bago Yoma mountain. Location of dams on the higher ground may have encouraged infiltration of pore fluids into the fault plane causing the high-pressure fluid-driven seismicity and it indicates fault zone permeability in these areas. Since late Tertiary, the region has been subjected to crustal shortening associated with repeated seismic events in Bago Yoma mountain region. Deformation in Basin-Uplift province involves a combination of horizontal and vertical displacements on normal and strike-slip fault. Sagaing fault and the border faults of the basin are known to have generated earthquakes in the past 100 years and in the future.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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