Myanmar Earthquakes History (3rd Edition, August, 2017)

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To my teachers

from

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MYANMAR EARTHQUAKES HISTORY

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Preface

Although detailed historic account of earthquakes exist, many questions regarding the mode of deformation from the point of view of the plate tectonics remains unresolved. The author gathered the information by reinterpretation of the historical earthquakes and add to the previous understanding and provides a fresh perspective on inter-and intraplates seismogenic zones. Since ancient times, a series of earthquakes occurred along the Sagaing fault zone in a right-lateral strikes-slip sense including the related faults which are located at short distances to the west of the Sagaing fault. Co-seismic changes related to these earthquakes are summarized from the published literature (reference cited). The earthquakes of magnitude M>7.0 occurred along the Sagaing fault and other earthquakes M<7.0 occurred in plate interior settings. Despite being a small booklet among the books on the historical earthquakes in Myanmar, this booklet has been analyzed within the context of present-day understanding of earthquake seismology. A detailed morphotectonic study was carried out in this region using satellite remote sensing techniques to correlate the seismicity with tectonics. Much of the work presented in this book has been published as research papers in quarterly issue of the Tech Digest Magazine, Myanmar Engineering Society.

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Features inside:

Introduction

Myanmar represents an evolving continent of two crustal formation histories consisting of Burma plate and Indochina plate. Western Myanmar, west of Sagaing Fault (Burma plate) consist of three distinct lithotectonic entities of a continental fragment, a subduction-related accreted complex and a coastal area. Eastern Myanmar that is western continuation of Indochina plate is composed of two tectonostratigraphic terranes. Each terrane is fault-bounded. These terranes may have originated in the southern sites in late Mesozoic-early Tertiary time, than the present position during terrane assembling and accretion to the major continent. There are three collisional and accretionary episodes in Myanmar to have become the present configuration of tectonic terranes: (1) Inthanon zone of West Thailand-Than Lwin Belt of Eastern Myanmar- Changning-Menglian belt of West Yunnan (2)Shan Boundary belt in the west edge of Indochina plate; (3) Rakhine-Andaman-Nicober belt at the westernmost part of Myanmar. These accretionary episodes, ended in early Tertiary, have been followed by post-accretionary deformation of strike- slip faulting of Sagaing Fault in Myanmar; West Andaman Fault and Sumatra Fault System in Sumatra; spreading in Andaman back-arc basin resulting in the break-up of the northern part of Burma Plate (Myanmar) from that of Sumatra and disperse northward along Sagaing Fault since Neogene. Burma plate has been experiencing NNW-SSE extensional scheme in the Miocene, operated upon by the external couple of movements of two lithospheric plates: northward moving India plate in the west and southeasterly moving Indochina plate in the east. NNW-SSE extensional scheme has been followed by ENE-WSW compressional regime in the Plio-Pleistocene. Due to intraplate motion between India, Burma and Indochina plates, dextral shear movement along the Sagaing fault play an important role in Myanmar region. Extension in the ductile crust accommodates the brittle crust to pull apart. The crustal blocks were sliced from margin of lithospheric plates along the N-S trending dextral faults and ENE-WSW trending normal faults thus giving rise to many pull-apart basins in Central Myanmar. The Sagaing fault is a major right-lateral strike-slip fault which has long and straight traces across the entire length of Myanmar for 1000km. The rate of motion of the Burma plate with respect to the Sunda plate has a rate of 18-25mm/yr towards the north (Soquet et al.2006). The average trend of the Sagaing fault is 351° (N9°W) and the Sagaing fault accommodates part of the motion and the remainder of the motion is distributed on related faults within the Sagaing fault zone(Vigny et al., 2003). These faults are located at short distances to the west of the Sagaing fault in the Central Myanmar Basin.

Structurally, the Shan plateau belongs to the Indochina plate which is between the Red River fault and Papun – Three Pagoda fault. Southeastward extrusion of the Indochina plate controls the active tectonics of eastern Myanmar. The satellite imagery of the Shan plateau (eastern Myanmar) , east of Shan

Scarp show two tectonic domains: a series of longitudinal strike-slip faults in N-S direction forming step-like structure and a bookshelf-pattern of conjugate active strike-slip faults arranged in parallel in ENE-WSW direction. Active tectonics over much of eastern Myanmar are compatible with NE-SW- striking maximum stress and minimum stress striking NW-SE. In eastern Myanmar, ENE- or NE-oriented faults that dominate the crustal fabric are active as indicated by their sharpness of their traces on satellite imagery and the seismicity. Numerous events of earthquakes and geometry on active faults clearly show that the active tectonics of this region is dominated by strike-slip faulting and normal faulting. The stress fields of the region from the studies of focal mechanism solution of earthquakes (CMT from Harvard and epicenters from Engdhal, GIAC Report, Rangin(1996-1999) indicate that this area has been undergoing NW-SE extension and NE-SW compression. Active tectonics over much of eastern Myanmar are compatible with NE-SW-striking maximum stress and minimum stress striking NW-SE. Le Dain et al. summarized the historical earthquakes of Myanmar in 1984. The western boundary of the plateau is the NNW-SSE trending Shan Boundary fault forming precipitous scarp as triangular facets. The plateau has been dissected by a series of longitudinal step-faults trending in the N-S direction, forming blocks and depressions with the production of conspicuous landforms of great fault scarp trending in

Comparatively N-S oriented straight lines for many miles (Gorshkov,1959). The step-like structures are found approximately between longitudes 96°E and 98°E. Towards the east of such structures, at Loi-se hill range with the height of 5636 feet (latitude 20° 30' N-longitude 98° E) which is made up of Plateau Limestone trending N-S, Plateau Limestone is exposed, overlooking Than Lwin river where there is a gorge with 5000 feet deep as an enormous well-defined fault scarp of limestone on the west bank of the river (Pascoe,1959, pp.680). In the east bank, the plateau limestones are lying on the Pre-Cambrian basement rocks of Chaung Magyi Series. Beyond this particular fault scarp, the plateau limestones are found as steeply folded ranges with violent contortion (Pascoe, 1959, pp.681). These structures must be sigmoidal wrench structures and the sigmoidal bends may be a result of offset and drag along the Red River suture during extrusion of Indochina plate in 15Ma to 35Ma(Rangin,1996-1999). Their shape may be inherited from the origional grain of the Indosinian fold belt which marked the site of closure of Paleo-Tethys Ocean in Late Triassic-Jurassic age. This fault scarp along Loi-se range is situated to the west of Than Lwin river,approximately on Longitude 98°E. Between Latitude 98°4'N and 96°6'E , there is a longitudinal fault which passes through the Loi-ma haw Hill trending in N-S direction.

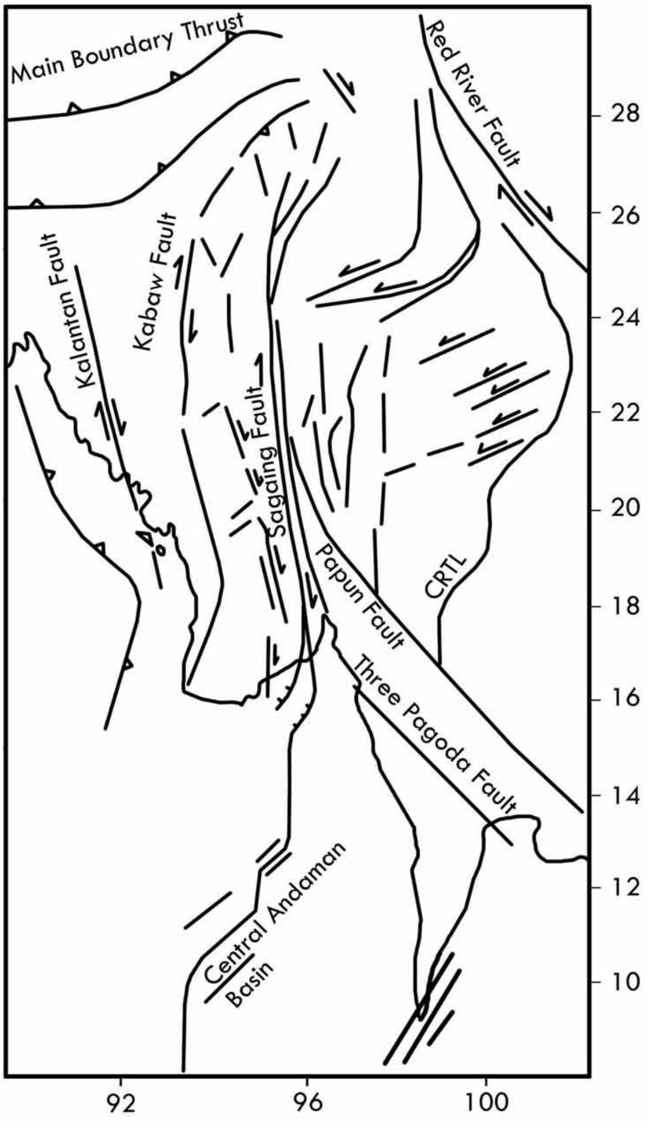


Fig.1.Tectonic Map of Myanmar

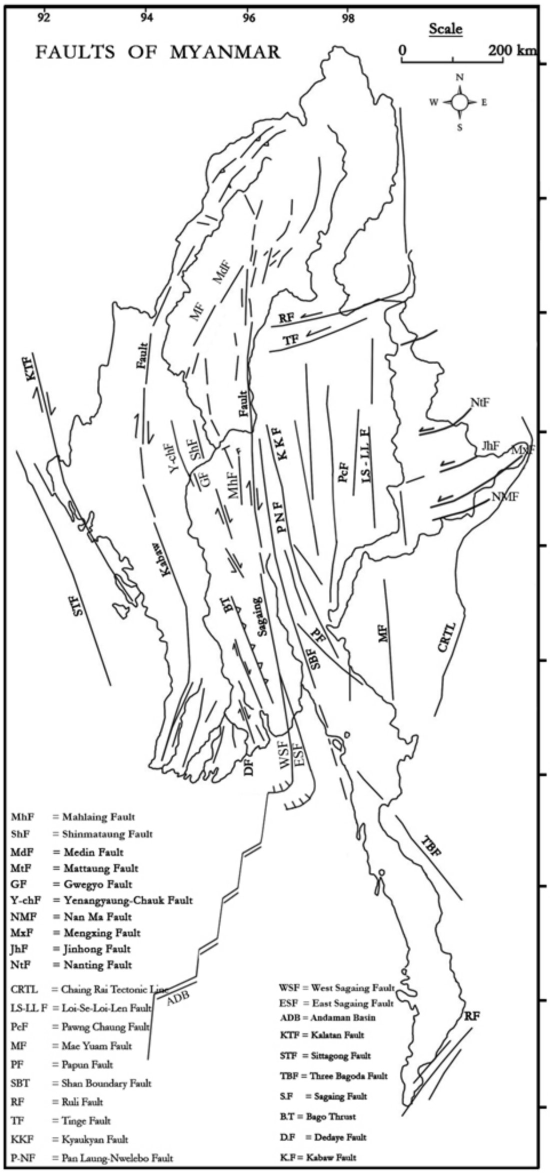


Fig.2. Faults of Myanmar

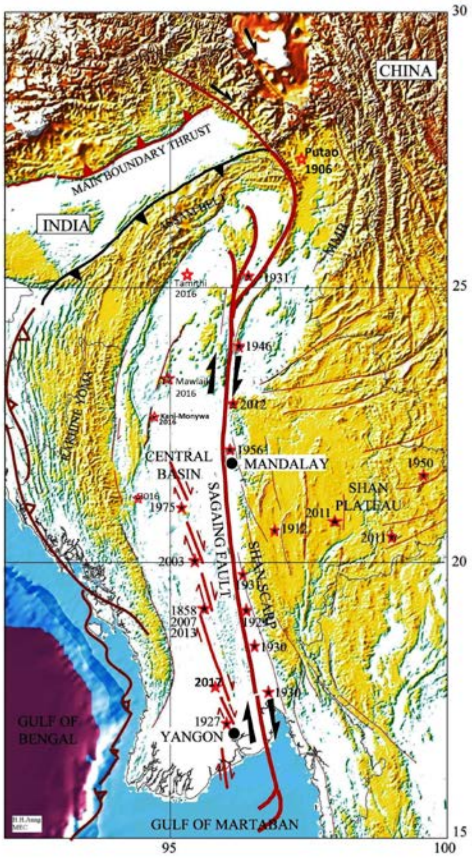
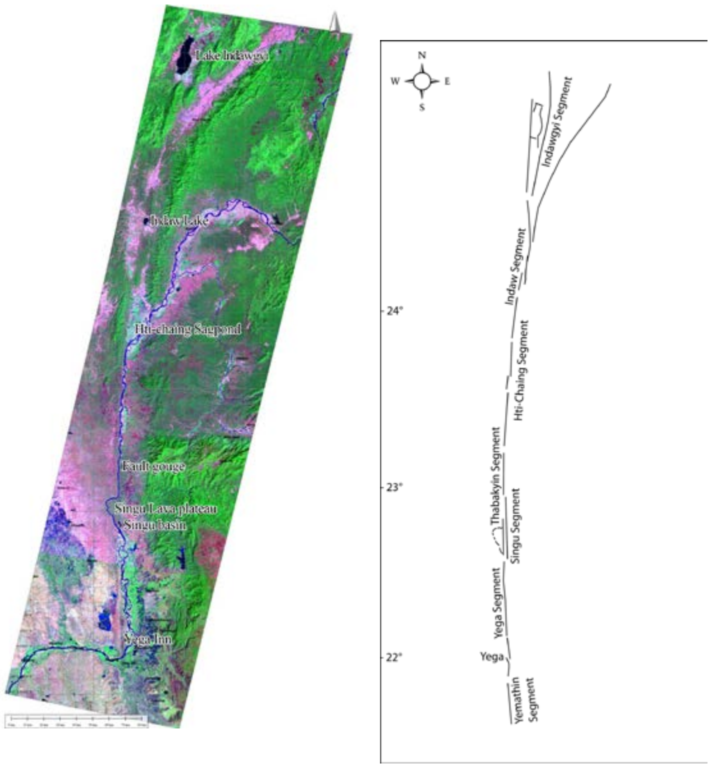


Fig.3. Topographic map showing the relation between Tectonics and seismicity in Myanmar region.

Due north of the Loi-se range, at about latitude 23°N in Northern Shan State, there is Loi-Han-Hun volcano with a mass of columnar basalt (olivine basalt), situated on Loi-len rang with the height of 8777 feet (latitude 22° 30’ N-longitude 98° E) (Chibbher, 1934, pp.303). Loi-len hill range has been composed of Plateau Limestone and trending in N-S direction overlying the older Paleozoic rocks and Pre-Cambrian Chaung Magyi rocks of slates and quartzites. Finally, it is concluded that the major fault which can be traced continuously on the satellite imageries, from Mae Yuam fault in the south (Thailand) to the north in Myanmar territory, along Loi-se hill range in Southern Shan State, passing through the limestone hill ranges in between Southern Shan State to Loi-len range in Northern Shan State can be regarded as the western boundary of Than Lwin belt. Here, the author has attempted to give a name to this boundary fault as Loi-se-Loi-len fault, the last fault which separated the step-fault structures in the west from the sigmoidal wrench structures in the east. The fault is consists of several fault segments with N-S orientation. The Loi-se_ Loi-len fault is under stress revealed by the prevalent occurrence of earthquakes near Namsam which is located in the west of the fault (Conference paper of Hla Hla Aung, IGCP 516, 2012). The Tarlay earthquake in March, 2011 (M 6.8) which occurred in eastern Myanmar indicates that Myanmar has entered a new active earthquake cycle. After 2011, the November 2012 Thabeikkyin earthquake (M6.8); the April 2013 Pyay-Thayet earthquake (M5.4); the November 2015 Monywa-Kani earthquake (M5.4) and the April 2016 Mawlaik earthquake (M6.9); the August 2016 Chauk earthquake (M6.8) occurred successively in Myanmar. The Mawlaik and the Chauk earthquakes which occurred in the India subducting slab provide a new insight into the nature of subduction zone earthquakes in Myanmar.

The Sagaing fault

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 (Curray et al., 1979; Le Dain et al., 1984; Yeats et al., 1997; Curray, 2005). The Sagaing Fault is linked with Central Andaman spreading center to the south (Curray et al., 1979). The Andaman Sea was formed by seafloor spreading along short ENE-striking spreading ridges that are offset by NNW-striking transform faults (Curray et al., 1978; Eguchu et al., 1979). The southern end of the Sagaing Fault would be the northern most part of these transform fault. Extension and rifting in the Central Andaman Basin began at around 11Ma and extension and sea floor spreading has been ongoing since 4-5 Ma (Khan & Chakraborty, 2005). That is consequently the best estimate for the age of the Sagaing Fault. Spreading in a 335° (N 25° W) direction, relative to present N, is at an average rate of 30 mm/yr and the northward component is 27 mm/yr (Curray, 2005). The rate of motion of the Burma plate with respect to the Sunda plate has a rate of 18-25mm/yr towards the north (Socquet et al. 2006). The average trend of the Sagaing Fault is 351° (N9°W) and the Sagaing Fault accommodates part of the motion while the remainder of the motion is distributed on other faults within a fault zone (Vigny et al., 2003). The NW-SE-oriented seafloor spreading direction agrees with the average trend of the Sagaing Fault. Moreover, the Sagaing Fault is the transform plate boundary with right-lateral motion. The NW-SE-oriented spreading along ridge segments in the Gulf of Mottama, which are rifting the Burma Plate northward with respect to the Sunda plate Myanmar region lies in seismic zone of Alpide-Hamalayan Belt. Earthquakes of varying magnitude have hit the region in the past. In the last 100 years, the significant earthquakes occurred in Myanmar are as follow: the Ava earthquake of 1839, the Maymyo earthquake of 1912 (M= 8.0,)the Swa earthquake of 1929 (M= 7.0), the Bago earthquake of 1930 (M=7.3), the Phyu earthquake of 1930 (M=7.0), the Kamaing earthquake of 1931 (M=7.6), the Sagaing earthquake 1956, the Tagaung earthquake of 1946(M 7.3), the Tarlay earthquake of 2011 (M=6.8), the Thabeikyn earthquake of 2012 (M 6.8). Myanmar has experienced many earthquakes and majority of these earthquake have depths < 15km with rumbling sound, depths of the other of 35km are reported from USGS earthquake catalog from 1973 onward. Isoseismal trend for these earthquakes are in fault direction. Present-day tectonics inferred from focal mechanism solution of earthquakes (USGS) shows preponderance of strike-slip faulting along NNW-SSE, NW-SE and ENE-WSW faults or reverse faulting due to uplift of tectonic blocks. Myanmar is under stress revealed by prevalent occurrence of earthquakes.



(a) (b)

Fig.4(a). Landsat TM image of the northern part of the Sagaing Fault. The fault can be divided into 5 segments, based on long-term geomorphic and structural features of the fault zone. These segments are as follow (from north to south): the Indawgyi, Indaw, Htichaing, Thabeikkyin ,Singu and Yega segments. These segments, each 50-180 km long and a half kilometer to 5 km wide are linked by step-overs or bends with 125 km long. The satellite image shows a series of tectonic lakes developed between these segments: Lake Indawgyi, Indaw Lake, Singu sag pond and Yega Inn and many other features in the northern part of Myanmar. (b) Line drawing of northern part of the Sagaing fault.

Geometry of the Sagaing Fault

The Sagaing Fault is a primary plate boundary along which most of the relative motion has occurred and will continue to occur for the geologic future. Rather than being a single major fault along which blocks move clearly past one another, the plate boundary is essentially sharing motion between fault segments arranged in a right-stepping en echelon pattern. To understand the complexity of the plate boundary system, first consider the geometry of the present day Sagaing Fault. The Sagaing Fault is a major right-lateral strike-slip fault which has long and straight traces along the entire length of Myanmar for more than1000km. The fault is distinct between Mandalay and Thabeikyin Township, but is much more difficult to observe southwards on satellite images where it crosses the lowlands of the Central Myanmar. Large-scale topographic maps, SRTM-DEM-based shaded relief maps and Landsat 7 band combination 742 as RGB (2003) and 1:24,000 scale aerial photographic maps are used for interpretation of the morphological features of the Sagaing Fault and related tectonic structures. Numerous small fault segments have been identified in map view which conveys an impression of en echelon pattern. Most of the segments along its length have ruptured in the past century, generating historical earthquakes.

Individual fault segments are continuous along their trace until a small offset separates one segment from the next, to one side of it. The intervening gap between the two segments creates small zones of extension or compression depending on whether it steps to the right or to the left. Such zones of compression or extension also exist at fault bends in the fault zone. These faults can be easily identified when the individual earthquakes struck on each fault segment. Fault geometry known as en echelon faulting leads to interesting consequences when faults rupture (Hough, 2004). This geometry of the segments produced by strike-slip faulting or thrust faulting during repeated earthquakes are separated by discontinuities that appear as step-overs or bends in map view. These segments are designated as (from the north to the south) the Indawgyi, Indaw, Htichaing, Thabeikkyin ,Singu,Yega, Yemethin, Pyinmana, Swa, Phyu, Shwedan, Zwegeik, Kabauk and coastal segments. Where fault segments overlap, extensional forces have created linear depressions between them. Along the Sagaing Fault, Lake Indawgyi, Indaw lake, a sag pond near Hti-chaing, another sag pond near Singu, Yega Inn, Shwedan Inn, Zwegaik Inn and Kabauk Inn, Bagan Inn, and more other sag ponds are forming as tectonic lakes created the fault by transtensional forces, and the localized pressure ridges such as Pale, Desunpa, Magyigyin, Sagaing, Minwun and Tagaung ridges at left-stepping fault segments are formed by transpressional forces (Fig.4).

Within the neotectonic framework of Myanmar, the Sagaing Fault 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. When the Sagaing Fault trend differs from the plate motion, dip slip faulting occurs and the plate motion becomes complex. Most of the NNW-striking faults that dominate the area appear to be presently active, as shown by recent seismicity which includes historical earthquakes.

Fans or Horsetail splays

At the northern end of the Sagaing Fault between 26°N and 27°N, the Sagaing Fault branches into various splays to form a compressive horse-tail structure 200 km from the east to the west. At the same time, the Indian Plate pushes the Burma Plate northeastwards. This fault connects the Himalayan Main Boundary Thrust in the north (Maurin, 2011).

At the southern end of the Sagaing Fault, at the latitude of Nyaunglebin-Bago (latitude 17°30’N), the Sagaing Fault branches into two main strands several kilometers apart. In the Mottama Gulf, the fault terminates as a horse-tail extensional system (Charmot-Rooke et al., 2001). An extensional deformation zone of 250 km wide from north to south exists in the Mottama Gulf (Rangin et al., 1999). The western branch of the fault, termed West Sagaing Fault terminates southwards in a cluster of normal faults separated by a series of pull-apart basins and a system of oblique transform faults that connect southwards with the Andaman spreading Centre (Curray et al., 2005). The fault branch located immediately to the east, termed East Sagaing Fault, is apparently covered by deep marine terraces and could be inactive.

Step-over/ Pull-apart basins

The most striking feature of the fault zone is perhaps its remarkably straight and distinct appearance on satellite images extending for 1000 km across much of the length of Myanmar. Most of the stretch along its course, the fault zone is clearly defined by both tectonic and topographic features.

At about 25°N, right-stepping fault segments form an extensional pull-apart basin called Lake Indawgyi. At 24°N, north of Hti-chaing, there is another fault segment forming a sag pond called Indaw Lake. At 23°N, west of Htichaing there is also a sag pond. Further to the south, at 22° 35'N, near Singu, the Singu basin with 1.5 km wide and 2 km long is observed. At latitude 21° 58'N, at 10km north of Sagaing right-stepping fault segments form an elongated basin called Yega Inn. Yega Inn is one of pull-apart basins with 1 km long and 500m wide, formed within the Sagaing Fault Zone.

Shwedan Inn (Inn is Myanmar word for lake), at 17°26'N is a tectonic depression or sag pong on the down-thrown side of the fault. The height of the fault scarp near the northern end of the Shwedan Inn is about 2.8m. A clear west-facing fault scarp extends south of Shwedan village. North and south of the Paingkyun Chaung, an elongated linear depression about 10 m wide and l m deep extends along the fault. Farther south, the Sagaing Fault bounds the eastern margin of the Zwegaik Inn at 17°01’N. The Kabauk Inn at 17°N is a pull-apart basin located at a right step of the Sagaing Fault (Tsutsumi et al., 2009). These basins characterize a step-over where the intervening region has been thrown into tension. A large earthquake tends to nucleate from the tip of the fault segment and then propagate along the fault plane where the accumulated stress is high enough to cause slip on the fault plane. Seismicity is consistent with the transfer of slip on one fault zone onto another segment on the right within the fault zone. (Hla Hla Aung, 2011)

Laterally offset surface features

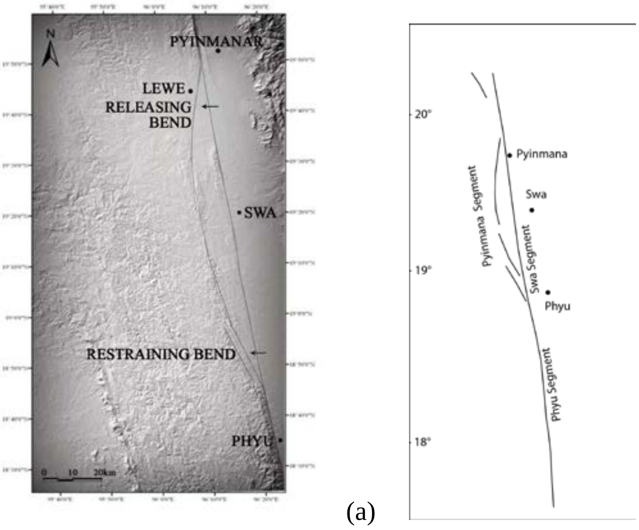
Near Sagaing City, the fault has brought Pegu sandstones (Miocene) in the west against the Irrawaddy Sandstones (Pliocene-Quartenary) in the east, and in the north near West Taungnyo village, the fault has brought sheared metamorphic rocks on the eastern side against the Pegu sandstones on the west, suggesting lateral displacement of the fault. Between Kebwet and Thabeikkyin, the Sagaing Fault forms a boundary between the older Mogok Series in the east and the Plio-Pleistocene sandstone of the Irrawaddy Formation on the west. A straight narrow, north-south trending fault trace can be observed between the main Sagaing ridge and the Minwun ridge just north of Sagaing.

Immediately north of Mandalay, at latitudes between 22°35’N and 22°45’N, the Singu lava plateau is dextrally displaced by the Sagaing Fault. This marker was used to test the finite displacement along the Sagaing Fault. These volcanic were dated by K/Ar method. The radiometric ages obtained for this volcanism on both sides of the fault range from 0.25 to 0.31 Ma for a cumulated displacement of 6.6km at the north of the volcanic field and 2.7 km in the south. This Singu volcanic plateau testifies to the fact that the extensional process is at work along the Sagaing Fault (Bertrand et al., 1998).

In the central part of the Sagaing Fault, the trace of the Sagaing fault is rather linear and simple along a line of low hills from Kyaukse to Thazi-Pyawbwe area. The detailed study also shows late-Cenozoic dextral slip along the NNW-SSE trending trace of the Sagaing Fault. For example, the Sinthe Chaung (chaung means stream in Myanmar) is an offset stream channel that can be found along the Sagaing Fault between latitude 20°00’ N and 20°10’ N.

Releasing / restraining bends

In zones where strike-slip faults are continuous, the strike of the faults may locally depart from a simple linear trend following a small circle on the Earth’s surface. In these areas, the curvature of the fault plane creates zones of localized shortening and extension according to whether the two sides of the bend converge or diverge. Pull-apart basins, zones of subsidence and deposition, and normal faults characterize releasing bends, whereas restraining bends display thrust faults, folds, and push-ups. These zones are similar to those that form in step-over. At diverging bends, localized area is 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 fault system. At a converging bend, a localized zone of subsidence occurs due to a combination of extension and dextral motion (Kearey, 2009). Lewe depression at releasing bend near Pyinmana and Khindengyi ridge at restraining bend, west of Phyu are observed on satellite images in the central part of the Sagaing fault zone (Fig.5). In the southern part of the Sagaing fault zone and in the Bago area, the Sagaing fault runs through the land of Bago area, creating a series of fault scarps, pressure ridges and sag ponds, where the fault segments can give rise to either zones of compression or extension. Such zones also exist at bends in the faults. The Bago itself is situated on a bedrock hill, the eastern margin of the hill is sharply defined by the Sagaing fault. The hill is a pressure ridge develops along left-stepping straight fault branch. Roughly parallel to and in the west of the Sagaing fault at 17°05'N, there is the Pale fault in N-S direction with a total length of 17km and to the south, it bends towards Sagaing fault with N 10° W. It is a restraining bend.



(a) (b)

Fig.5. (a) Shaded relief map showing geomorphic features along the central segment of the Sagaing Fault. Map location is between Pyinmana (18°30'N) and Phyu (19°35'N). (b) Sketches showing major active faults, releasing/restraing bends and fault-bounded wedges of rock form during the naturaal evolution of a double bend. Lewe depression at releasing bend near Pyinmana and Khindengyi ridge at restraining bend, west of Phyu are observed in shaded relief map.

To the south of Pale ridge, there is a linear depression called Zwegaik Inn,developed at right step over of the Sagaing fault. Epicentral location is the site of occurrence of Kabauk Inn (Inn is local name for a lake). It is a pull-apart basin marked by irregular depressions and oblique normal faults and formed in an extensional step-over between the fault segments. Releasing/restraining bends are located also at latitude 18° 30'N to 19° 35'N and latitude 17° 05'N to 17° 20'N (Fig.6).

Positive flower structures with faults that strike approximately in north-south direction can be found in northwest and southwest of Swa. In profile, typical tectonic inversion features show normal faulting in deeper part and reverse faulting in near surface area. An unconformity between the Pegu Group and the Irrawaddy Formation separates an earlier transtensional regime in Late Miocene from a later transpressional regime in Pliocene to Recent.

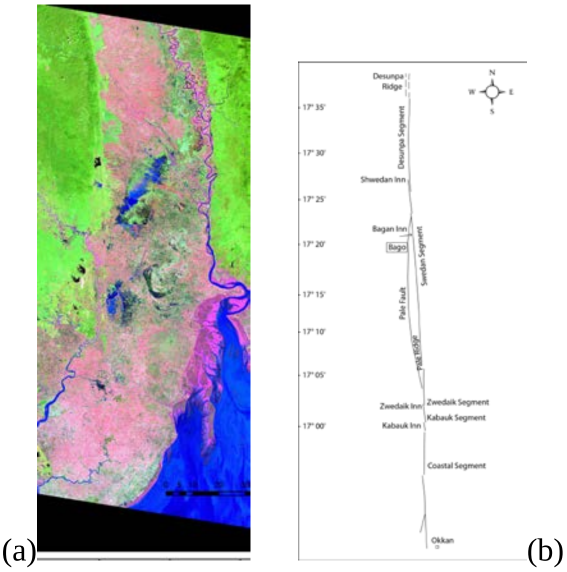


Fig. 6.(a).Landsat image of the southern part of the Sagaing Fault showing fault segments such as: Shwedan, Zwegeik, Kabauk and coastal segments. Where fault segments overlap, extensional forces have created linear depressions between them such as Shwedan Inn, Bagan Inn, Zwegaik Inn and Kabauk Inn. (b) Line drawing of southern part of the Sagaing fault.

Linear fault scarps

There are many linear fault scarps and localized pressure ridges in the Sagaing fault zone such as Desunpa, Magyigyin, Khendangyi, Sagaing ridge, Minwun ridge and Tagaung ridges.

In the Bago area, the Sagaing Fault is identified as continuous west-facing fault scarps. Fresh west-facing scarps exist for a 2.5 km along the stretch between Kanbe Chaung and Wagadok Chaung (Tsutsumi et al., 2009).

The Swa splay forms escarpment that varies in height from 4 to 7 m. The escarpment comprises a series of faceted spurs**.** These faceted spurs (GPS Location N19° 12.634´, E96° 14.374´, Facing – West) were the result of episodic fault movement and the facets are formed during periods of fault movement. The evidence of triangular facets and erosional benches, indicate that Swa splay is oblique strike-slip fault with both horizontal and vertical slip components.

The best location to observe pressure ridges within the Sagaing fault zone is the Mandalay region, just north of Sagaing City. Here, the Sagaing Fault is high lined by two N-S trending parallel pressure ridges, the Minwun ridge on the west and the Sagaing ridge on the east. Shutter ridges (Sagaing ridge and Minwun ridge) are common tectonic landforms near Sagaing City. These ridges are asymmetrical anticlines, made up of metamorphic and sedimentary rocks. Despite their N-S directions they display N30°W directions of the sedimentary bedding. These structures reflect the transpressional aspect of the ridges. A similar observation is near Yega village, an asymmetrical fold within the sandstones of the Pliocene-Quaternary Irrawaddy Formation with a N30°W trending axis. These ridges are cross-cut by N-S trending mylonitic zones along which is accommodated the motion of the Sagaing Fault.

Conclusion

The Sagaing Fault is a result of shear between the Burma and Sunda plates and it is similar to the San Andreas Fault between the Pacific and North American plates in California, the southwestern USA. Tectonic deformation has been taking place throughout the Miocene to the present. Structural analysis along the Sagaing Fault reveals several folds and faults, in varied orientations occurring along the fault, of which the NNW-direction is the most prominent. Some of them show considerable seismic activity as evident by epicentral location of earthquakes along the Sagaing Fault. From studies of fault characteristics within the Sagaing fault zone, the faults record both strike-slip deformation and dip-slip displacements and structures along the Sagaing Fault strongly reflect two distinct tectonic regimes. The first involved a combination of strike-slip motion and extension on north-northwest trending faults, leading to the formation of localized pull-apart basins. The second involved strike-slip motion and folding, possibly as a result of a change in the direction of motion in the transform regime.

Earthquakes that occurred along the Sagaing Fault and some sub-parallel faults are caused by the movement of huge crustal blocks of the earth’s crust and the fault is under stress as revealed by the prevalent occurrence of earthquakes. Although detailed historic account of earthquakes exist, many questions regarding the mode of deformation from the point of view of the plate tectonics remains unresolved. The author gathered the information by reinterpretation of the historical earthquakes and added to the previous understanding and provides a fresh perspective on seismogenic zone. The Sagaing fault zone illustrates many of the physiographic and structural features that are common to extensional step-overs and a series of contractional step-over. Tectonic-geomorphic features and seismic activity along the Sagaing Fault characterize the fault segments. These segments each 50-180 km long and a half kilometer -5 km wide are linked by step-over or bends with 125 km long. Many localized pull-apart basins and localized areas of uplift occur between these faults segments within the Sagaing fault zone. These studies of local tectonic geomorphic features and local geological structures show that all the historical earthquakes were associated with seismic amplification by small-scale topographic features such as localized scarps and localized basins. The seismic profiles in Swa area and many other parts along the Sagaing fault display flower structures developed at bends, in response to a combination of dextral motion and compression or extension across Sagaing Fault. In this seismic section near Swa, an unconformity between the Pegu Group (Late Miocene) and the Irrawaddy Formation (Pliocene-Quaternary) separates an earlier transtensional regime from later transpressional regime. This is estimated age of change in motion from strike-slip to transform. The active deformation and tectonic evolution of the plate boundary between the Burma and Sunda plates is important in the sense that it may generate large earthquakes along the Sagaing fault zone. The structures along the fault and other observations, testify that the Sagaing fault is a major continental strike-slip fault and a continental transform fault and these relationships illustrate how large strike-slip faults typically evolve very rapidly on timescales of tens to hundreds of thousand years. From the result of this study, step-overs that are observed along the Sagaing fault from south to north are at latitude 17° N, Kabauk In (1930 Bago Eq.); latitude17° 10’N, Zwedaik In; latitude17° 27’N, Shwedan In; Latitude 21° 58N, Yega In (1839 Eq.,1956 Eq.); latitude 22° 30N, a sag pond south of Singu plateau; latitude 23° N, a narrow fault gorge (2012 Thabeikkyin Eq.); latitude 24° N, a sag pond west of Hti-chaing (1949,1991 Tagaung Eq.); latitude 25.67°N-96° 15’E, Indawgyi lake(1931 Kamaing Eq. Mw=7.6, Depth 35km). Releasing/restraining bends are at latitude 18° 30N to 19° 35N (1930 Phyu Eq. /1931 Pyinmana Eq.); latitude 17° 05N to 17° 20’N and latitude 16°50’N96°31’ E. Study of earthquake events over the world indicates that magnitude of an earthquake depends on the length of fault segment. There are many linear fault scarp called the Khindengyi ridge(a visible scarp on satellite image, 1929 Swa Eq.) and localized pressure ridges in the Sagaing fault zone such as Pale ridge, Desunpa ridge, Magyigyin ridge, Sagaing ridge and Tagaung ridge. From detailed studies of these features, the length of each fault segment can be investigated. The length of fault segment controls earthquake magnitude. If a fault is 100km long, the earthquake would be closer to magnitude 7.5 (Hough, 2004) and it is important for modern earthquake assessment. There is a formula between the magnitude and fault length: log (L) =0.66 M -2.83 (Utsu, 1961), based on the length of five earthquakes (Hurukawa et al., 2011). There are at least a series of fifteen fault segments within the Sagaing fault zone, most of which had ruptured in the last century. These segments are as follow:

(1) The Indawgyi segment (Putao to Indawgyi) - 180km Lake Indawgyi
(2) The Indaw segment (Indawgyi to Indaw) - 100km Indaw lake
(3) The Hti-chaing segment (Indaw to Hti-chaing) - 60km Sag pond
(4) The Thabeikkyin segment (Hti-chaing to Thabeikkyin)- 100km narrow fault gorge
(5) The Singu segment (Thabeikkyin to Singu) - 50km pull-apart basin
(6) The Yega segment (Singu to Yega) - 60km pull-apart basin
(7) The Kyaukse segment (Yega to Kyaukse)-40km
(8) The Meiktila segment (Kyuakse to Meiktila)- 40km
(9) The Swa segment (Pyinmana to Swa)-80km Linear scarp
(10) The Pyinmana segment (Pyinmana to Phyu)- Releasing/ restraining bend

(11) The Phyu segment (Swa to Phyu)- 70km

(12) The Shwedan segment (Phyu to Shwedan)- 60km pull-apart basin

(13) The Zwedeik segment (Shwedan to Zwedeik) - 50km sag pond

(14) The Kabauk segment (Zwedeik to Kabauk) – 5km sag pond

(15) The coastal segment (Kabauk to coast)- 45km

Many fault-bounded geologic structures were produced by strike-slip faulting and grow by repeated seismic events which also produced multiple segments separated by discontinuities that appear as step-overs or bends in map view. The Sagaing fault is a region of active tectonics and geomorphic features associated with strike-slip faulting are easy to identify with interpretation of remote sensing images. The macro-seismic effects of the earthquakes in this book-let are summarized from Coggin Brown et al (1932), Chhibber (1934) and Satyabala (2002). The effects summarized in each section are from these publications in which some are given in quotes and the remaining is slightly modified in form.

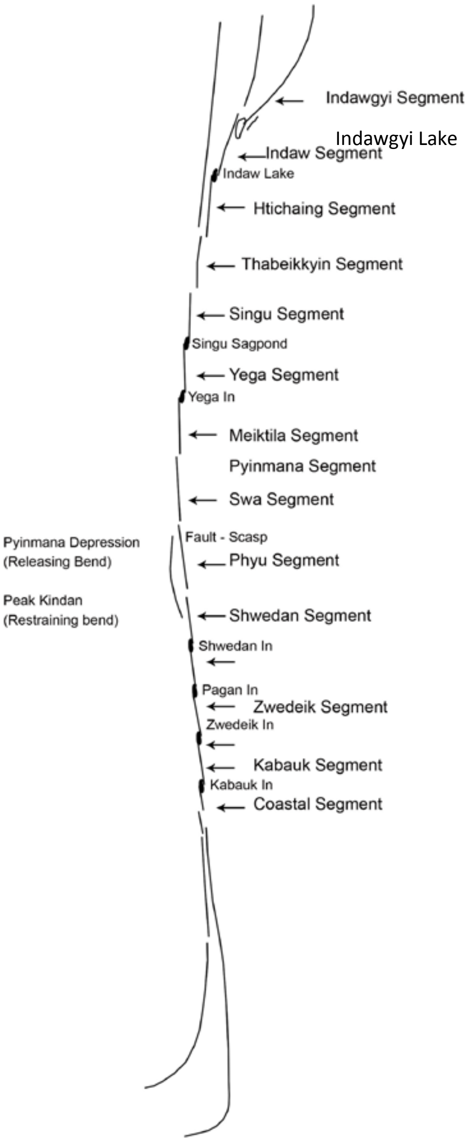


Fig.7. A detailed study along the fault using the satellite images and 1:24,000 scale aerial photographs together with 1:63360 scale topographic maps show that the fault is composed of several fault segments arranged in right-stepping, en echelon pattern. At least fifteen segments are recognized within the Sagaing fault zone as indicated by the occurrences of extensional and compressional tectonic geomorphic features between two fault segments, either right-stepping or left-stepping.

Date	Name	Lat.	Long.	Magnitute	Focal Depth	Mechanism	Source Characteristics
23 May 1912	May Myo Earthquake	21°N	97°E	8.0		Strike-slip ulting	Inlay lake (Pull- part basin)
8 Aug. 1929	Swa Earthquake	19°15'E	96°15'E	7.0		/	Fault Scarp
5 May 1930	Bago Earthquake	17°N	96°30'E	7.0		/	Kabauk In (Pull- part basin)
3 Dec. 1930	Phyu Earthquake	18°N	96°30'E	7.3		/	Restraining Bend
27 Jan. 1931	Kamaing Earthquake	25.6°N	96.8°E	7.3		/	Indawgyi lake ll-apart basin)
10 Aug. 1931	Pyinmana Earthquake					/	Releasing Bend
12 Aug. 1946	Tagaung Earthquake	23°30'N	96°E	7.5,7.75		/	Sag pond
16 Jul. 1956	Sagaing Earthquake	22°N	96°E	7.0		/	Yega In (Pull-apart basin)
8 Jul. 1975	Bagan Earthquake	21°30'N	94.7°E	6.8	10 Km	Thrusting	Salin basin
22 Sept. 2003	Taungdwingyi Earthquake	19.94°N	95.72°E	6.7	40 Km	/	Flower structure in Salin basin
24 Aug. 1858 2007	Thayet Earthquake	19°N	95°15'E	7.0, 5.5	10 Km	/	Pyay basin
22 Jun. 1923		22°75'N	98°75'E	7.3		/	
26 Dec. 1941		21°N	99°E	7.0		/	
2 Feb. 1950		22°N	100°E	7.0		/	
11 March 2011	Tarlay Earthquake	20.705°N	99.949°E	6.8	10 Km	/	Pull-apart basin
25 March 1992		20.7°N	97.1°E	5.7		/	
28 Oct. 1992		20.7°N	97.1°E	5.9		/	

Table1. Major historical earthquakes and recent seismicity in Myanmar are shown in this Table to correlate between seismicity and tectonics. Epicentral location coincides with small-scale geologic features. Seismic source characteristics are obtained from interpretation of satellite image. Seismic data are from the publication: Chhibber, 1934; Le Loup et al.1998 and Satyabala, 2002.

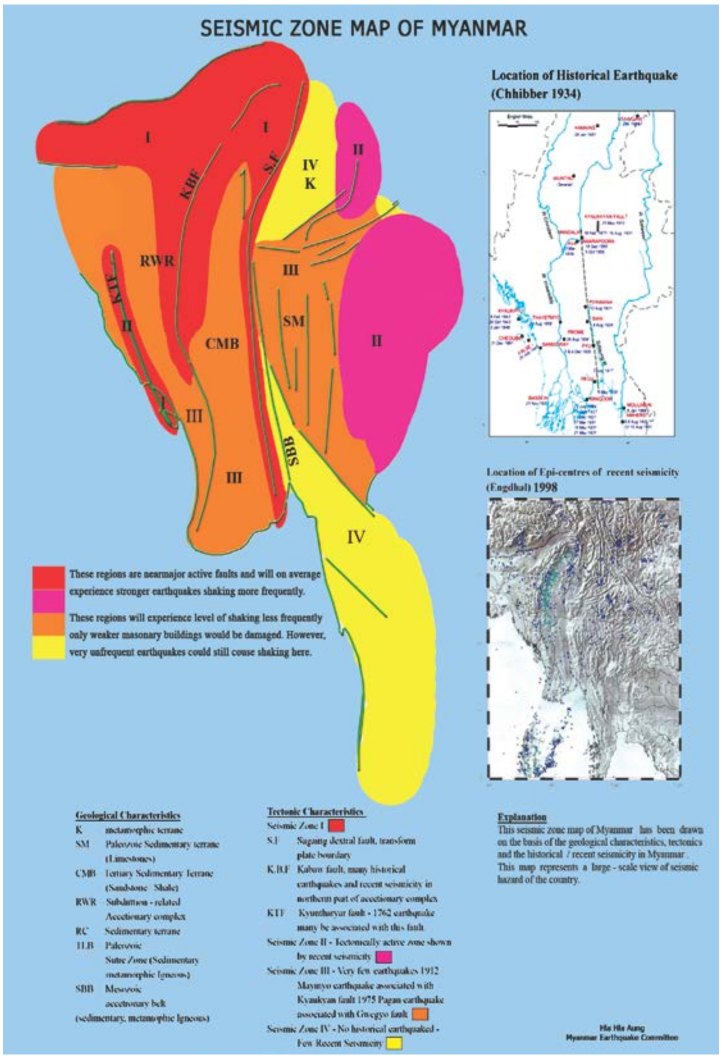


Fig.8. Seismic zone map of Myanmar, drawn by using Tectonic characteristics, Geologic characteristics, historical and recent seismicity of Myanmar (published in 2010, modified in 2011). The map represents a large-scale view of seismic hazard of the country.

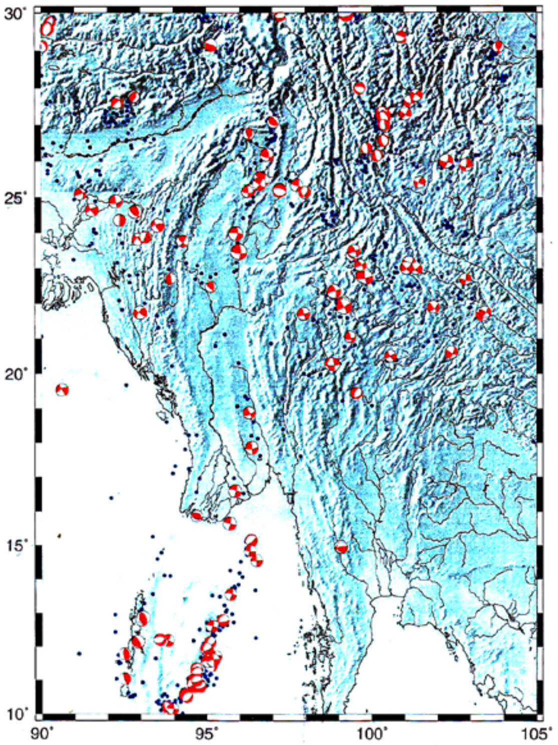


Fig.9. Shallow seismicity (0-40 km) of the Myanmar region
CMT from Harvard and epicenters from ENGDHALL (Souce:GIAC)

The 1929 Swa earthquake in Central Myanmar

Abstract: An earthquake of (7.0) magnitude occurred in Swa, a town located at (19º13'N-96º14'E), on the night of 8th August 1929, this was followed by a succession of minor tremors and caused damage to the buildings and railway tracks. Railroad tracks were bent, bridges and culverts collapsed, and

loaded trucks were overturned. The epicenter was situated at 19º15’N, 96 º 15’E,, six miles to the northwest of Swa. The satellite image reveals a prominent compressional linear ridge, NNW of Swa. The co-seismic surface deformation is characterized by oblique thrusting and scarps developed between the two fault strands. This earthquake was the first of a series of earthquakes in the years 1929 to 1932 that occurred along the Sagaing fault.The shock was felt in Yemethin, Paungde, Yenangyaung and Pyinmana and it was recorded on Bombay seismograph in India.

Keywords: tremors, epicenter, linear ridge, compression, thrusting, seismograph

Tectonic setting

The 1000 km-long N-S trending Sagaing fault is a large right-lateral strike-slip fault zone. This fault is the most conspicuous feature that can be seen on the Landsat imagery of Myanmar. The fault is distinct between Mandalay and Thabeikyin but is much more difficult to observe southwards on satellite images where it crosses the lowlands of the Central Basin. The Sagaing Fault is interpreted as a recent dextral strike slip fault and a continental transform plate boundary that separates the Burma plate from Sundaland plate (Curray et al.,1979; Le Dain et al.,1984;Yeats et al.,1997;Curray,2005). The Sagaing fault is linked with Central Andaman spreading center to the south (Curray et al., 1979). Positive flower structures with faults that strike approximately in north-south direction can be found in northwest and southwest of Swa. In profile, typical tectonic inversion features show normal faulting in deeper part and reverse faulting in near surface area. An unconformity between the Pegu Group and the Irrawaddy Formation separates an earlier transtensional regime in Late Miocene from a later transpressional regime in Pliocene to Recent.

A detailed study along the fault using the satellite images and 1:24,000 scale aerial photographs, together with 1:63360 scale topographic maps reveal an elongated ridge in NNW of Swa. It is a distinct linear feature defined by the Sagaing fault system (Fig.10).

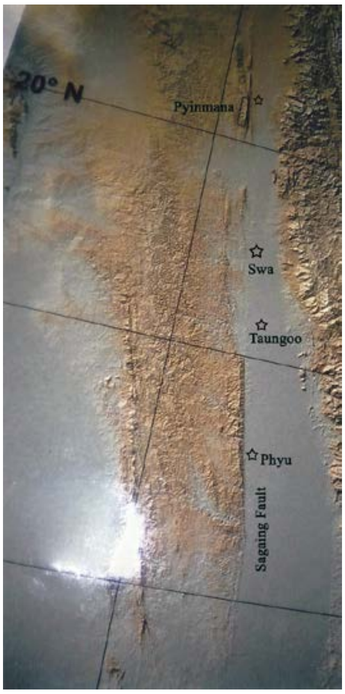


Fig.10. The satellite image reveals a prominent ridge northwest of Swa and another prominent ridge:Khindan Ridge at northwest of Phyu created by the Movenet of the Sagaing fault.

Co-seismic Deformation

The co-seismic surface deformations are summarized from Satyabala (2002). Rail joints were pulled out, breaking fish-plates and bolts. At some places, the rail track was twisted and bent. Four bridges were damaged and one of these was pushed up about 2 feet like a camel’s back. Two loaded trucks were also lifted off the track and thrown off one side. Large cracks appeared on the ground. Observation of surface deformation features associated with the 1929 Swa earthquake show the co-seismic displacement along the Sagaing fault zone, there exist a linear fault scarp at NW of Swa.

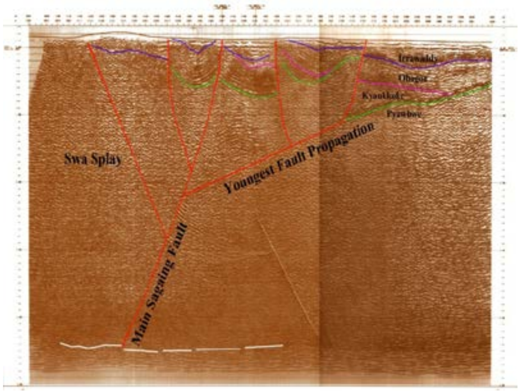


Fig.11 (a). Seismic line in E-W direction showing positive flower structure (Source:MOGE)

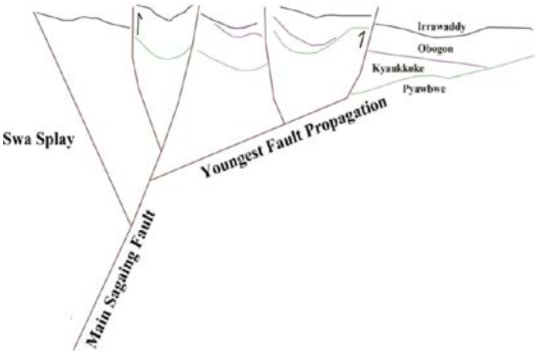


Fig.11 (b) Line drawing of seismic section

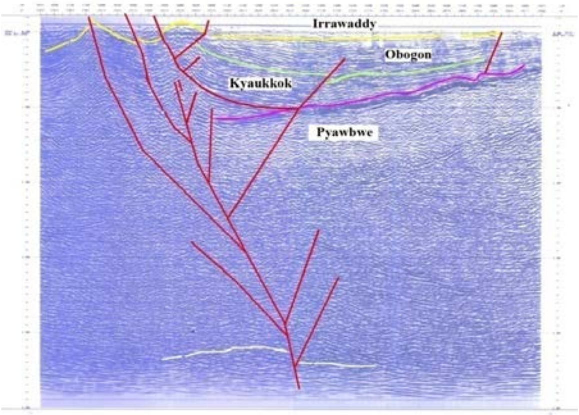


Fig.12 (a). Seismic line in E-W direction showing positive flower structure

(Source: MOGE)

Fig.12 (b) Line drawing of seismic section

Possible style of deformation

The satellite image reveals a prominent compressional ridge, NNW of Swa. The co-seismic surface deformation is characterized by oblique thrusting and the scarps developed between the two fault strands. Oblique thrusting results in the progressive formation of landforms such as linear scarps, fault escarpments, pressure ridges with a complex array of geomorphic expression (Yeats et al., 1997). These fault strands merge at depth near the epicenter region and form as positive flower structure (Fig.11and12). If a strike-slip fault is marked by an abrupt bend, complications arise. Bordering country rocks are required to adjust stress by stretching or shortening. Crustal shortening at bends is vertical uplift of the thickening blocks. Small-scale topographic features such as hills and ridges can amplify seismic amplitudes. Possible style of deformation is believed to be a combination of strike-slip faulting and thrusting along the Sagaing fault.

The 1930 Bago earthquake in southern part of the Sagaing fault

Abstract: The Pegu (Bago) earthquake occurred on May 5th 1930 that struck the town of Pegu causing great loss of life. A strong earthquake with M 7.3 occurred on the southern part of the Sagaing fault. The epicenter of this earthquake was at (17ºN, 96.5ºE), Ms=7.3 and origin time 13:45:27 hours GMT. This epicentral location is in the place of Kabauk In and the event was named after the nearest town Pegu(Bago). The earthquake caused great loss of life about 500 person killed in Bago and 50 person killed in Yangon respectively. It was felt with continually diminishing intensity, over a land area of approximately 220,000 square miles (570,000 sq. km.). The epicenter is in the Bago deltaic alluvial plain, in the south of the Bago-Sittoung canal. The most common liquefaction features are many large cracks and block fissures appeared in many areas such as Thanatpin in north of Bago and Kyauktan, Thongwa and Thanlyin in south of Bago along north-south direction. Intensity increases to the south to coastal area. In Rangoon, the southern portion of the city was built on alluvium and the damage was more than that in the north where the ground was composed of Tertiary rocks.

Keywords: Block fissure, liquefaction, strike-slip fault, normal fault, intensity, basin

Tectonic setting

The Sagaing fault runs through the land of Bago area, creating a series of fault scarps, pressure ridges and sag ponds, where the fault segments can give rise to either zones of compression or extension (Fig.13). Such zones also exist at bends in the faults. The Bago itself is situated on a bedrock hill; the eastern margin of the hill is sharply defined by the Sagaing fault. The hill is a pressure ridge develops along left-stepping straight fault branch. Roughly parallel to and in the west of the Sagaing fault, there is the Pale fault in N-S direction with a total length of 17km and to the south, it bends towards Sagaing fault with N 10° W. Epicentral location is the site of occurrence of Kabauk Inn (Inn is local name for a lake). It is a pull-apart basin marked by irregular depressions and oblique normal faults and formed in an extensional step-over between the fault segments. On 28th November 2014 an earthquake with M 5.1 occurred at 17.18 ° N and 96.66 ° E (DMH).

Fig.13. Relief map of Bago area showing pressure ridges and tectonic basins such as Desunpa ridge, Shwedan Inn, Pale ridge, Zwegeik Inn,Kabauk Inn and many others along the Sagaing fault. Epicenter of the May,1930Pegu (Bago) earthquake is at 17° N, 96.5° E, near Kabauk Inn

Co-seismic deformation

Co-seismic effect of this event was summarized from Geology of Burma by Chhibber, 1934 and Historical earthquakes of India and Burma by Satyabala (2002). The most common liquefaction features are many large cracks, ground subsidence and block fissures appeared in many areas such as Thanatpin in north of Bago and Kyauktan, Thongwa and Thanlyin in south of Bago along north-south direction. Sand blow and sand vents which erupted water and sand were found in many places and they even reached the coast. Graben-like ground deformations were formed between two ground fissures. Part of damage caused in Bago was due to subsidence (Chhibber, 1934).

The earthquake damage was disastrous. In Bago, the famous Shwemawdaw Pagoda was seen to sway and finally fall half sliding down its fractured base (Photo). In Yangon, the jeweled "hti" of the Shwedagon Pagoda was dislodged and left dangling from its summit. The "hti" of Sule Pagoda was bent over.

The photo shows the famous Shwemawdaw Pagoda fell half sliding down its fractured base due to 1930 the Pegu earthquake.

Possible style of deformation

Epicentral location is the site of occurrence of Kabauk Inn (Inn is local name for a lake). It is a pull-apart basin marked by irregular depressions and oblique normal faults and formed in an extensional step-over between the fault segments. A large earthquake tends to nucleate from the tip of the segment and then propagate along the fault plane where the accumulated stress is high to incur slip on the fault plane. Seismicity is consistent with the transfer of slip on one fault onto another fault segment to the right in this area.

The 1930 Phyu earthquake in central Myanmar

Abstract: The 4th December, 1930 Ms= 7.5 (Abe, 1981) Phyu earthquake at18:51:44 GMT, 1:22 a.m. (Myanmar Standard Time) was one of a series of earthquakes that occurred during the years 1929 to 1932 in Myanmar. Most of these earthquakes occurred along the southern part of the Sagaing fault. The town Phyu was shaken by this earthquake and it was felt over an area of 220,000 square mile of Myanmar region causing major destruction to buildings and killing 30 persons. Based on field observations along the Sagaing fault, the rupture consisted of Phyu segment and Pyinmana segment. The nucleation point of this rupture was defined by an epicenter at 18ºN, 96 1/2 º E. The event was named after the nearest town Phyu (18º 24’N, 96º 24’E). Co-seismic effects are severe buckling of railway line, twisted rails, large cracks and sand vents, damage to the foundation and floor of masonry buildings. Interpretation of surface deformation features indicates that the deformation mode

of this event is believed to be of thrusting associated with strike-slip faulting along the Sagaing fault.

Key words: surface deformation, rupture, thrusting, strike-slip faulting, twisted rails

Tectonic Setting

The Sagaing Fault is a primary plate boundary along which most of the relative motion has occurred and will continue to occur for the geologic future. In the central part of the Sagaing Fault, the trace of the Sagaing fault is rather linear and simple along a line of low hills from Kyaukse to Thazi-Pyawbwe area. The detailed study also shows late-Cenozoic dextral slip along the NNW-SSE trending trace of the Sagaing Fault. For example, the Sinthe Chaung (chaung means stream in Myanmar) is an offset stream channel that can be found along the Sagaing Fault between latitude 20°00’ N and 20°10’ N. Lewe depression at releasing bend near Pyinmana and Khindengyi ridge at restraining bend, west of Phyu are observed on satellite images in the central part of the Sagaing fault zone. A detailed study along the fault using the satellite images and 1:24,000 scale aerial photographs, together with 1:63360 scale topographic maps show that the fault is composed of several fault segments arranged in en echelon pattern. Pull-apart basins, zones of subsidence and deposition, and normal faults characterize releasing bends whereas restraining bends display thrust faults, folds, and push-ups. These zones are similar to those that form in step-overs. These ranges have localized uplifted area 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 fault system.

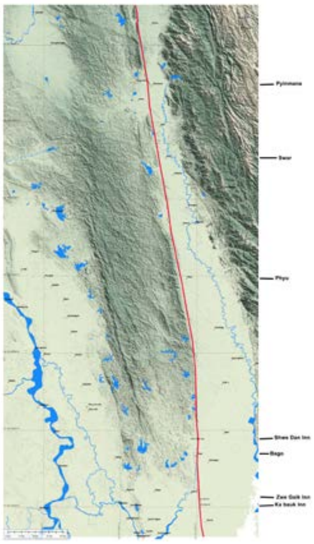


Fig.14.Relief map showing tectonic features
Along the Sagaing fault between Swa-Phyu area

Co-seismic Deformation

The most affected area is in a small limited area to the west and WSW of Pyu (18º24’N, 96º24’E), in the vicinity of Kindangyi (18º28’N, 96º24’E) where the earthquake was extremely severe. The peak Khengdan may be taken as approximately the center of the most shaken area. The approximate limits of the epicentral tract to the north and south of Kindangyi respectively are region west of Zeyawadi (18º33’N, 96º26’E) and northwest of Penwegon (18º12’N, 96º36'E) give some indication of the approximate limits of the epicentral tract. Co-seismic effects are severe buckling of railway line, twisted rails, large cracks and sand vents, damage to the foundation and floor of masonry buildings. Mud and water had spouted to heights of 18-20 feet, like a fountain, from the cracks. Fissuring of alluvial ground and issue of sand and water from crater lets are prominent features in all areas felt by this severe earthquake.

Possible style of deformation

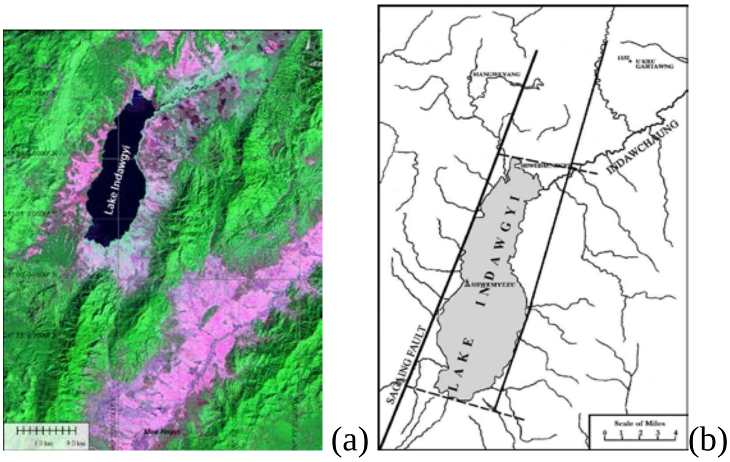
The maximum intensity lies in and about the foot of the hills which border the town on the west. There is a well-defined, remarkably straight wall-like ridge of Kindangyi which runs in W 9 º N of Phyu. At the peak Khendan with the height of 1754 feet (534m), a diverging bend from the main Sagaing fault is observed on the satellite images (Fig.14). When there is diverging bend in a strike–slip fault zone, bordering country rocks are refined to adjust stress buildups by shortening. It is called restraining bend and are common places to response to crustal uplift of thickened blocks formed by folding or thrusting. Possible mode of deformation is believed to be a combination of strike-slip faulting and thrusting at the restraining bend within the Sagaing fault zone. The Phyu earthquake occurred about seven months after the Bago earthquake and the fault zones of the two events are linked with segments. To explore the relations between the events, Coulomb failure stress changes for the

Sagaing fault caused by the May 1930 Pegu (Bago) earthquake calculated by Coulomb 2.6 (Toda et al., 1998). The result shows that stress increased by several bars immediately north of the May earthquake rupture. Previous studies demonstrated that a stress increase on the order of a few bars is large enough to trigger failure on the nearby favorably oriented faults. (e.g., Stein et al., 1992; Toda et al., 2005). Therefore, it is possible that the May earthquake triggered the December earthquake (Tsutsumi, 2009). Some research results show that the positive Coulomb failure stress produced by the big earthquake encourages the subsequent moderate earthquake occurrence and negative one may postpone the earthquake occurrence (Wang et al.2010). Basing on this result, it shows that Phyu area locates in positive front of Coulomb failure stress change. Sometimes, stress change produced by big earthquake extends up to more than 1000km. The Kamaing earthquake occurred on 27 January, 1931, two months after the 4 December Phyu earthquake. All three earthquakes are linked with several segments along the Sagaing fault.

Other earthquakes that occurred along the Sagaing fault zone

The 1931 Kamaing Earthquake

The Kamaing earthquake occurred on 27th January 1931at 25 º 60'N, 96 º 80'E, with magnitude Ms=7.6. It was a disastrous earthquake which caused development of big fissure sometimes several feet long in alluvial area, accompanied with southings of sand and water. Epicenter was in the east of the Indawgyi Lake, very closed to the Sagaing fault. The epicentral tract is very hilly and its average height is between 2000-3000 feet above sea-level. Its maximum height is 4982 feet above sea-level. The hill slopes were scarred by big cracks and block fissures were also observed. Big fissures with several hundreds feet long developed in alluvial tracts, accompanied by spouting of sand and water. Numerous landslips and rockfalls occurred in the epicentral tract. Lake Indawgyi is a typical fault-bounded lake formed between the two fault segments within the Sagaing fault zone. It is long and its length with (33) km and the width (12) km oriented along the fault indicating continued fault motion on the Sagaing fault (Fig.15).



.Fig.15.(a)LANDSAT TM Image of Lake Indawgyi. (b)Map of the Lake Indawgyi in the northern part of the Sagaing fault. Earthquakes usually occur near the lake when the plate motion transfers from one fault to another fault.

The 1931 Pyinmana Earthquake

The earthquake occurred on 10th August 1931 at 4:50 PM and it shook the town Pyinmana, 91 miles North of Phyu. This was a violent earthquake and felt at Meiktila, Yemethin, PyawBwe, Lewe and Mandalay in the North and Bago to the South. But Swa and Phyu area had been free from disturbance. Cracks were developed in the brick buildings and some bridges were raised by about 3 to 10 inches. Near Pyinmana, a releasing bend occurred (Fig.16). In fault zones where strike-slip faults are continuous, the strike of the faults may locally form a simple linear trend following a small circle on the Earth’s surface. In these areas, the curvature of the fault plane creates zones of localized shortening and extension according to whether the two sides of the bend coverage or diverge (Kearey, 2009).

These zones are similar to those that form in step-overs. Pull-apart basins, zones of subsidence and deposition, and normal faults characterize releasing bends. Such bends on the major strike-slip faults invite high concentration of strain. It is a releasing bend where fault-bounded graben is formed by extensional deformation.

Fig.16. Shaded relief Map of Pyinmana-Phyu area, the Sagaing fault can easily be visible; trending in NNW-SSE direction Pyinmana-Lewe area itself is a large depression created by releasing bend in the Sagaing fault system.

The 1946 and 1991 Tagaung Earthquakes

Earthquakes on 12th September 1946 (M 7.5) and 5th January1991 (M 7.1) occurred at 23º50’N, 96ºE respectively. Landslides occurred and large fissures and ground cracks, sand blows were formed. Pagodas and some buildings collapsed at Tagaung, Htichaing, Kawlin, Thabeikyin and surrounding areas. Two people killed.

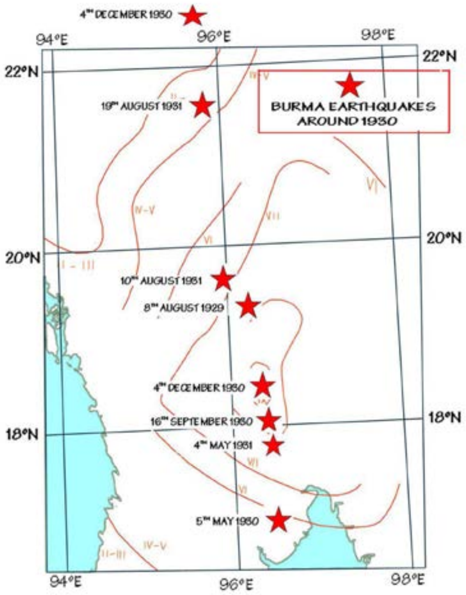


Fig.17. Isoseismals of earthquakes that occurred during 1929 to 1931 follow the trend of the Sagaing fault (Map from Satyabala, 2002)

The 1956 Sagaing earthquake in northern Myanmar

Abstract: A strong earthquake with M 7.0 occured on 16th July 1956 at 9:40 pm on the northern part of the Sagaing fault. The epicentral location is 21°58’ N, 95°50’ E (USGS, NEIC), north of Sagaing. This epicenter is in the place of Yega In and the event was named after the nearest town Sagaing. The area has historical background of many earthquakes which include the 23th March of Ava (Inwa) earthquake of 1839. The earthquake caused great loss of life about 300 to 400 people killed in 1839 and 40 to 50 person killed in 1956 respectively. This powerful earthquake destroyed many famous pagodas in Inwa, Amarapura, Tada-U, Sagaing and Mandalay. The Mingun Pagoda, the largest masses of solid brickwork in the world was damaged with fissures by this destructive earthquake but the earthquake could not topple the pagoda. School buildings, monasteries and some government buildings across the regions were also destroyed. The mechanism of this devastating earthquake is right-lateral strike-slip faulting on the Sagaing fault and the extensional normal faulting at the occurrence of tectonic geomorphic feature of a sag pond or a pull-apart basin near the epicenter of this earthquake.

Key words: Pagodas, school buildings, magnitude, shaking, sag pond, strike-slip fault

Tectonic Setting

The Sagaing fault runs through Myanmar from north to south for more than 1000 km and has created a series of sag ponds and scarps along the fault. The Sagaing fault is clearly visible on the satellite image from the northern terminus in Kachin State to Mandalay in the south for about 450 km. A detailed study along the fault using the satellite images and 1:24,000 scale aerial photographs, together with 1:63360 scale topographic maps show that the fault is composed of several fault segments arranged in en echelon pattern. When one fault segment steps to the right, the fault rupture creates a zone of extension between the two fault segments. Normal faults exist where the extensional forces are pulling the crust apart and converting into an inland lake that extends along the fault. The Yega In (In means literal translation of a basin) itself is a typical fault-bounded lake formed by the lateral movement of the Sagaing fault associated with vertical motion, in which sediments collect in the depression. It is located at 21° 58’N, 95° 50’E and 1000m long/ 500m wide. The segment of the Sagaing fault on the east runs N-S from the eastern side of Yega In to northward and the western segment extends from Yega village through the Sagaing city and then farther southward to the central lowland area. The Sagaing fault earns its name by cutting through Sagaing city (Fig.18).

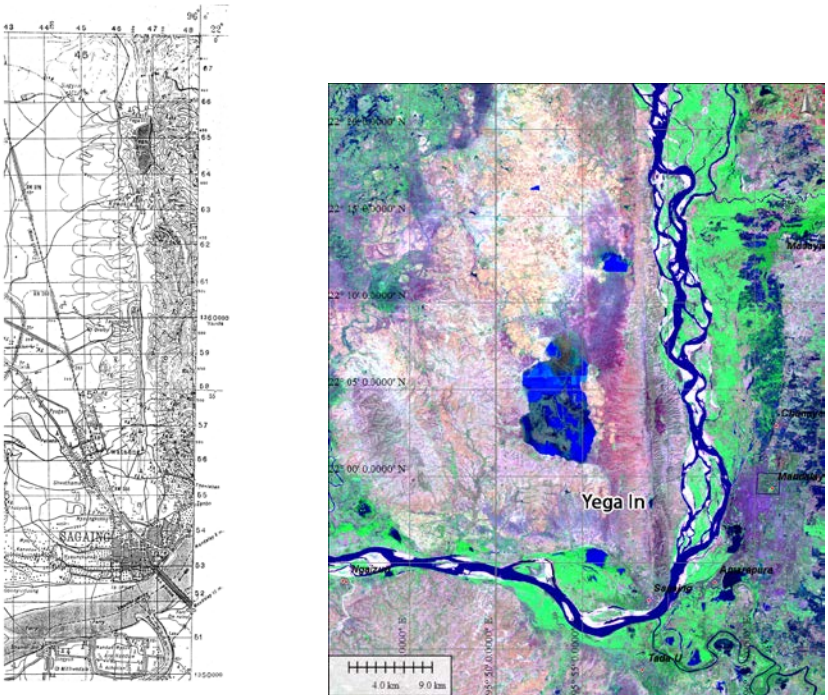


Fig.18 (a). Topographic map and satellite image showing the location of Yega In (black shaded area). The straight trace of the Sagaing fault can be identified in the map on the west and east side of Yega In. Mandalay is in the east and Sagaing and Inwa are in the south of Yega In. Each of these cities is only a few miles away from Yega In. (b) LANDSAT TM image of Yega Inn.

Co-seismic effects by the event

The town of Inwa, Sagaing and Mandalay were severely hit by this earthquake. Pagodas and city walls were damaged. The Ayeyarwady river flow was reversed for some times, river water flood and fish were killed by the quake. Mingun Pagoda the world largest brick stupa was shattered by this earthquake. The Mingun Pagoda is located in Mingun at 21°55’N- 96°E, just across from Mandalay on the opposite bank of Ayeyarwady river. It is approximately 11 km west of Mandalay. The construction was halted in 1819 as a one-third completed structure otherwise that would soar 150 m high. The 1839 Ava (Inwa) earthquake leveled the city and damaged the pagoda with huge cracks but could not toppled it (Fig.19). The earthquake caused great loss of life about 300 to 400 people killed in 1839 and 40 to 50 person killed in 1956 respectively. Large cracks appeared in the ground parallel to the direction of the trend of the Sagaing fault and from which water and sand were ejected forming heaps of sand. Upper part of pagodas fell sliding down. School buildings and monasteries were badly damaged. In Mandalay, Shwebo, Inwa, Amrapura and Sagaing, masonry buildings, all of which were damaged, and some completely destroyed.

Fig.19. The Mingun Pagoda the world's largest brick stupa was damaged by the 1839 Ava earthquake and the 1956 Sagaing earthquake.

Possible Style of Deformation

The ancient city: Ava (Yatana-pura) or Innwa is located at 21°52’N-96°01’E, 20 miles southwest of Mandalay above 285’ above sea level. The city is built on lake-filled sediment at the junction of Ayeyarwady river and Myit-nge river. There are (9) natural lakes or inns of which (4) inns are filled with sediment, so-called man-made land area to build a capital city in A.D.1364. Ava became a capital city of the Burmese Empire and (31) kings ruled Ava over a period of (400) years. Ava (Innwa) sits on the soft earth material which can amplify the seismic waves. Sagaing city is located at 21°52’ N, 95°58’ E (USGS, NEIC), on the Ayeyarwady river, 20 km southwest of Mandalay on the opposite bank of the river. More than a dozen earthquakes including the 1839 Ava earthquake and 1956 Sagaing earthquake ruptured the segment of the Sagaing fault system that bound the Yega In and caused significant damage throughout the whole region of Sagaing. The Yega In was formed by the lateral movement of the Sagaing fault associated with vertical motion, its length oriented along the fault, in which soft sediments collect. Seismic waves can be amplified in the soft sediments leading to strong shaking of the surface in the basin. This fault segment is believed to be a causative fault for the 1839 Ava (Inwa) earthquake and 1956 Sagaing earthquake. Therefore, the deformation mode for these earthquakes is inferred basically to be a combination of normal and strike-slip faulting. The ancient cities like Ava (Yatana-pura), Sagaing (Zayarpura), Mandalay (Yadanarpon) have already developed near the Yega In and they have been destroyed by earthquakes repeatedly through history.

The 1975 Bagan earthquake in central Myanmar

Absract

On July 8th, 1975, at 12:04:42 (UTC) an earthquake of magnitude approximately 6.8 (CMT determination) occurred at 21°50’N and 94°70’E, near Bagan (USGS Report), 100km (65 miles) southwest of Mandalay. Depth of hypocenter is 112 km (ISC) and focal mechanism is thrusting (USGS). The 1975 Bagan event was the first ever known earthquake that occurred in subducting slab of India plate in Myanmar. The epicenter is in the sparsely populated region (Source: NEIC and CMT). Within epicentral tract, the intensity of the earthquake was severe which involves partial or total destruction of pagodas. The 1975 earthquake occurred on 8th, July, 1975 and the town of Bagan was severely hit by this earthquake. The town was ruined with a loss of at least one live and one injury. Pagan, the land of pagodas was destroyed by this earthquake and many pagodas and temples were damaged within seconds. Some of pagodas are being left intact and withstand to maintain the role of its past glory as historical monuments in Southeast Asia. The earthquake was felt in much of central Myanmar and extended to northeastern India and Bangladesh.

Key words: magnitude, depth, epicenter, thrust fault, building, pagoda

Co-seismic effect of the 1975 earthquake event

The ancient city, Thiri Pyitssaya or Pagan is located in the heart of dry desolate desert-like plains in the Dry Zone of Myanmar, the very center of the country, covering an area of a little over 25 square miles, in the northwest of Mt.Popa. Pagan became a capital city of the Burmese Empire and fourteen kings ruled Pagan over a period of 290 years from A.D.1044-A.D. 1334 (U Khin Maung Nyunt). Many Buddhist temples and pagodas were built on the stretches of sandy wind-swept plains and Pagan became a stronghold of Buddhism and was well known as the seat of Buddhist learning and culture among its contemporaries in Southeast Asia. Pagan, the land of pagodas was destroyed by an earthquake with magnitude 6.8, in 1975 and many pagodas and temples were damaged within seconds (Fig.20 & 21). Some of pagodas are being left intact and withstand to maintain the role of its past glory as historical monuments in Southeast Asia. Previous investigations were done by Person, 1977, Gosavi, 1977, and Chaudary, 1976 and their concluded remark is as follow: *The earthquake was about 100 km southwest of Mandalay in the vicinity of Pagan. Damage to the ancient monuments was about 90 percent mostly located near Ayeyarwady river. At Chauk oil fields, three oil rigs were toppled. The quake was centered in a sparsely populated region and there was only one death and one injury. It was also felt* *throughout central Myanmar, Yakhine area and northeastern India and Bengladesh.*

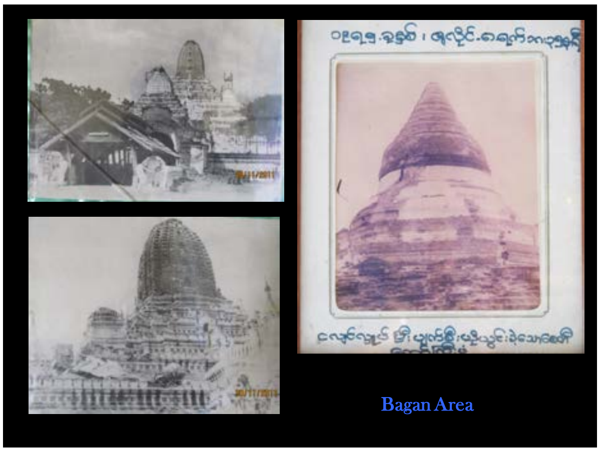


Fig. 20. Damage of pagodas by the 1975 Pagan earthquake (Lin Thu Aung)

Fig.21. Damage of pagodas by the 1975 Pagan earthquake.

The 2003 Taungdwingyi Earthquake of central Myanmar

Abstract: On September 22nd 2003, at 18:16:13 (UTC) an earthquake of magnitude approximately 6.6 (CMT determination) at depth 10km occurred near Taungdwingyi at 19.90°N- 95.73°E (USGS Report), 110km (65 miles) south of Meiktila. The epicenter is clearly west of the Sagaing fault (Source:NEIC and CMT). Within epicentral tract, the intensity of the earthquake was severe which involves partial or total destruction of some buildings, monasteries, and pagodas. The 2003 earthquake occurred on 22nd September,2003 and the town of Taungdwingyi was severely hit by this earthquake. The town was ruined with a loss of at least (7) lives. The earthquake was felt in much of central Myanmar and extended to northern Thailand.

Key words: magnitude, depth, epicenter, strike-slip fault, building, pagoda

Tectonic Setting

The Central Myanmar Basin is a N-S oriented, elongated belt for 1100 km in Myanmar and another 1000km in Andaman sea. The basin is dominated by NNW-oriented and NE- to ENE-trending faults. The dominance of NE-to ENE-to EW trending faults is suggestive of a NNW-SSE striking extensional stress direction. This extensional stress appears to have favored the formation of normal faults. The terrane is bounded to the west by the Kabaw fault and to the east by the Sagaing fault. The terrane has been sliced into several crustal blocks from margin of lithospheric plate by normal faulting. These blocks are moving laterally as a result of northward movement of the India plate with respect to the Sundaland plate, in which some blocks are being compressed and uplifted and some are being stretched and sagging, forming Basin-Uplift province along the Central Myanmar Basin containing the sub-basins and uplifts. The Basin-Uplift province constitutes of Hukawng basin-26° N Uplift- Chindwin basin - 22° N Uplift - Salin basin - 20° N Uplift - Pyay basin to Ayeyawady Delta basin to the south (Bender,1983). Salin basin is one of the pull-apart basins and it runs for more than 200km in the N-S direction between 20°N Uplift and 22° N Uplift. The east edge of the basin is bounded with a NNW-SSE trending dextral strike-slip fault accompanied by a series of narrow elongated anticlines. To the east of these anticlines, a further belt of anticlines exposed in the plains to the north of Taungdwingyi. To the north of 20° N uplift, the Salin basin runs in NNW and N-S direction and the generally NW-SE and NNW-SSE trending folds are elongated and narrow and are cut by a great number of faults. The Chauk-Yenangyat asymmetrical fold with an east dipping thrust fault on the eastern flank and countless transverse faults with a ENE-WSW strike and NE and NW oriented diagonal faults break the anticline into individual sections. The Salin basin begins with 20°N uplift and ends in the north at a structural uplift, the 22° N Uplift (Bender,1983).

Fig.22.Photo shows damage of pagoda in Taungdwingyi by 2003 earthquake (Source:MEC)

Fig.23.Photo shows ground failure in Taungdwingyi

Co-seismic Effect of the 2003 Event

The 2003 earthquake occurred on 22nd September,2003 and the town of Taungdwingyi was severely hit by this earthquake. The town was ruined with a loss of at least (7) lives. The railway line between Taungdwingyi and Pyinmana was badly damaged: bridges were cracked and sheared. Large crack opened across the line. Embankments of the line were dropped some inches. Upper part of pagodas fell sliding down (Fig.22). Large cracks appeared in the ground and from which water and sand were ejected forming heaps of sand (Fig.23). School buildings and monasteries were badly damaged. Seismic data from the southeastern region of the Salin basin, 60 km north-east of Sinbaungwe shows a positive flower structure with faults that strike approximately N-S direction. The seismic section that mentioned in Pivnik, 1999 Pg.1850), coincide with the epicentral location in the vicinity of Taungdwingyi. The seismic section displays the various splays of a strike-slip fault, a bounding fault of the Salin basin on the east side, where rocks are squeezed upward and outward from the fault zone to form a positive flower structure as a localized ridge in Taungdwingyi area (Fig.24). It is a transpressional push- up and basin inversion.

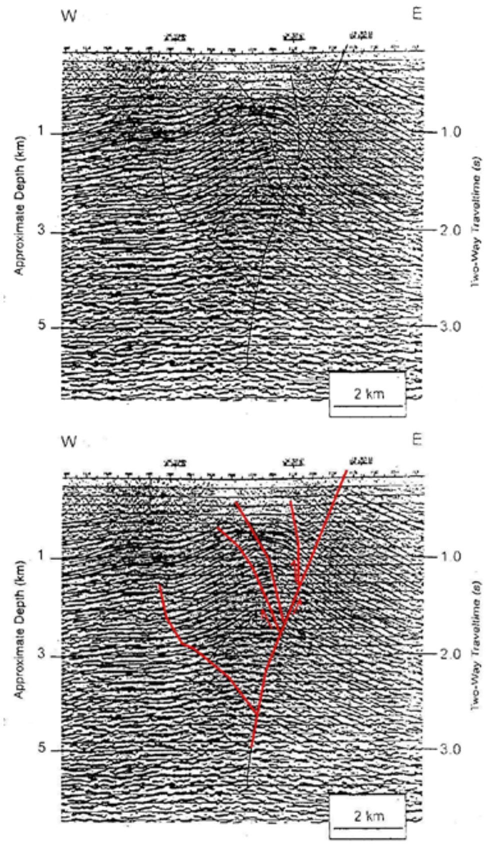


Fig.24(a) and 24 (b). Seismic sections in east-west direction in Taungdwingyi are 60 km north-east of Sinboungwe, showing a positive flower structure with fault that strike approximately N-S (data from Pivnik, 1998)

Such kind of structural uplift is a site of crowding which invites high concentration of strain. Earthquake focal mechanism for the 2003 event show strike-slip solution on a branch of the Sagaing fault system where crustal material are squeezed upward forming a localized ridge between the basin bounding fault on the east and several upward-branching faults with reverse offsets in the west. Periodic uplifting of these tectonic faults could be the cause for seismicity in Taungdwingyi area. The earthquake epicenter coincides with the site of occurrence of the localized ridge formed by a combination of shortening and strike-slip faulting.

Conclusion

Geographically, Taungdwingyi is situated in central Myanmar. Tectonically, the town is located in the Salin basin in the west of Sagaing fault. Structurally, the town is located very close to a major strand of the Sagaing fault, which bounds the Salin basin. There are many en echelon folds in this region trending NNW_SSE. Seismically, Taungdwingyi fall in seismic zone III of Seismic Zones Map of Myanmar (Aung,2010). The intraplate stress field derived from combination of focal mechanism and fault orientations show a NNW-oriented extension and a ENE-striking compression. Intraplate stresses cause earthquakes on particular faults so intraplate seismicity migrates within continental deformation zone. The Yangon Earthquake (M=7,1927); the Pagan Earthquake (M=6.8, 1975); the Taungdwingyi Earthquake (M=6.6, 2003) and the Thayet Earthquake (M= 7.0, 1858 and M=5.4,2007) are the continental intraplate earthquakes that have occurred within the transfer zone.

The 2012 Thabeikkyin earthquake in Northern Myanmar

Abstract: A strong earthquake with magnitude of 6.8 occurred on 11th November 2012 at 7:42 am at 9.9 km depth on the Sagaing fault. The epicentral location is 23.009° N, 95.884° E (Source:USGS, NEIC), 45 miles north north-east of Shwebo. This epicentral location is in the place of Thabeikkyin and the event was named after the nearest town Thebeikkyin . Two aftershocks with magnitude 5.0 occurred at 59 miles north of Mandalay, 23 miles northeast of Shwebo, 36 miles west of Mogok and 4 miles southwest of Thabeikkyin and 53 miles north of Mandalay, 10 miles northeast of Shwebo, 41 miles west of Mogok, 12 miles southwest of Thabeikkyin. The area has historical background of earthquakes which includes September, 1930 earthquake at latitude 23° N/longitude 96° E; Feb.1936 earthquake at 23° N/ 96° E (M=5.9) and 23° N/96° E; Sept.1947 earthquake at 23.9° N/96.2° E; March,1955 earthquake at 23° N 96° E (M=4.7); 1958 earthquake at 23.5° N/ 96.5° E. School buildings and some government buildings across the regions were also destroyed. According to the latest official reports, a moderate earthquake of 5.8 hit 5 miles northeast of Shwebo at 5 hours 26 mins, 20 secs, (MST) and more than 20 aftershock followed in the epicentral tract. The level of earthquake shaking in terms of a range of intensities is more severe in Thabeikkyin and Singu regions. The Thabeikyin event show manifestation of seismic amplification due to the topography. The damage was distributed linearly up to Singu area south of the epicenter. The

mechanism of this devastating earthquake is a combination of right-lateral strike-slip motion with contraction in the Sagaing fault zone.

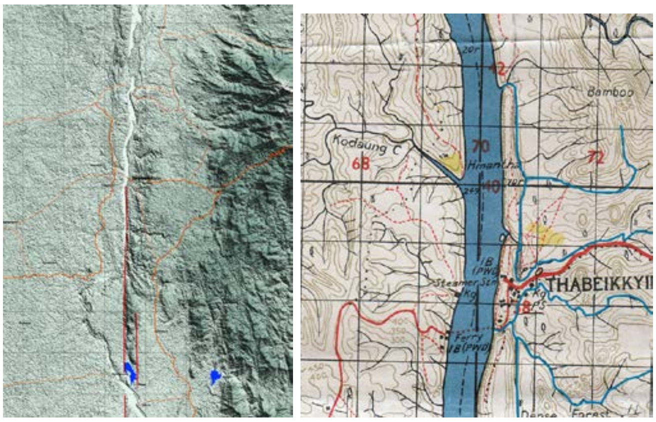
Key words: Pagodas, school buildings, bridge, shaking, strike-slip fault, step-over

Tectonic setting

The Sagaing Fault is a primary plate boundary along which most of the relative motion has occurred and will continue to occur for the geologic future. Rather than being a single major fault along which blocks move clearly past one another, the plate boundary is essentially sharing motion between fault segments arranged in en echelon pattern. To understand the complexity of the plate boundary system, first consider the geometry of the present day Sagaing Fault. Large-scale topographic maps, SRTM-DEM-based shaded relief maps and Landsat 7 band combination 742 as RGB (2003) and 1:24,000 scale aerial photographic maps are used for interpretation of the morphological features of the Sagaing Fault and related tectonic structures. Numerous small fault segments have been identified in map view which conveys an impression of en echelon pattern. The right-lateral movement along the fault caused several earthquakes in the past such as Kamaing earthquake(Lake Indawgyi) in 1931; Tagaung earthquake in 1946,1999; Thabeikkyin earthquake in 1931; Shwebo earthquake in 1931; Sagaing earthquake in 1956; Pyinmana earthquake in 1931; Swa earthquake in 1929; Phyu earthquake in 1930; Bago earthquake in 1930.

Co-seismic Effect of the 2012 Event

The followings are the data from field observations (personal communication) and official reports in the New Light of Myanmar. The 2012 Thabeikkyin earthquake occurred on 11 November, 2012 . The epicentral location is 23.009° N, 95.884° E (Source:USGS, NEIC), 45 miles northnorth-east of Shwebo. This epicentral location is in the place of Thabeikkyin and the event was named after the nearest town Thebeikkyin. The town of Thabeikkyin and Singu were severely hit by this earthquake. Large cracks appeared in the ground parallel to the direction of the trend of the Sagaing fault and from which water and sand were ejected forming heaps of sand. Upper part of pagodas fell sliding down. School buildings and monastries were badly damaged. In Thabeikkyin township, nearly 100 houses were damaged. In Moenyin township, three Pagoda were destroyed. At Singu area, school buildings fell down and some tilted over towards west (MEC) (Fig.26). One witness from Thabeikkyin stated that the earthquake started with swaying floor of the house then followed by main shock.



(a) (b)

Fig.25.Geographic location of Thabeikkyin city on the relief map (a)and topographic map (b). A sharp linear ridge can be clearly visible from the vicinity of latitude 23°30’N to Singu in the south. The streams cannot enter into the Ayeyawady River near Thabeikkyin. due to existence of the ridge.

At Thabeikkyin and Singu, the shock have been intense and lasted seven minutes as it was in the epicentral tract of M=6.8. The preliminary shocks were of a few second and these were noticed by some local people. Yet even there it was strong enough to destroy utterly most of the brick buildings in the towns. Pagodas, temples were completely destroyed. Masonry dwelling houses were generally shattered though portions of the walls were left standing sometimes. In some extreme cases two-storied houses appeared to have been literally hurled to the ground, falling almost flat in low heaps bricks, plaster and splintered beams shattered. Foundations of heavy column were cracked and shifted. Walls, pillars, water towers and piles of bricks were thrown over.

Fig.26. Tilted position of a school is observed during field survey in Thabeikkyin (Source: MEC)

In Mandalay, Shwebo, Inwa, Amrapura and Sagaing, Thabeikkyin and Singu, masonry buildings, all of which were damaged, and some almost completely destroyed. The brick foundations of the timber posts supporting the houses were badly cracked horizontally. Foundations of buildings were fractured and the upper broken portions pushed over their vases. The top section of the high local Pagodas collapsed. At many places, buildings which were tall, narrow brick and plaster structure; of this structure walls fell bodily outwards and were badly broken. High Pagodas were cracked at the top and smaller ones thrown over. The shock was very strong and severe cracking of houses resulted in many case, every wall of brick–built fell. Large waves were created in the Ayeyarwady River and the water flooded the bank carrying boats and objects. Fissuring of ground and issue of sand and water from the fissure are found (Fig.27). Part of a bridge called Yadanar Thingaha was fell off their trusses and dropped down into the river (Fig.28). Foundation bed of the approaching road to the bridge is cracked for 1 foot with considerable depth. Small fissures are found running parallel to the general north and south trend of the Sagaing fault. The region was to have eight grades of the Modified Mercalli Intensity (MMI) scale, based on damaged constructions and ground surface effects.

Intensity VIII (MMI): Observation of shaking and damage: Everyone had difficulty standing and walking and felt prominent dizzy and some vomiting. Water jumped up. Some or many masonry buildings, including stone, brick and mud destroyed or totally collapsed and the amount of destroyed or collapsing buildings is obviously more near the epicenter. The frames of most masonry buildings suffered heavy damage including substantial cracking and partial collapsing of stone and brick walls and extensive collapsing/toppling of low connected stone fences. Some small landslides occurred on steep slopes of hills or river banks, cracks developed in ground or hillside up to width and depth of several or 10s of centimeters.

Fig.27. Co-seismic surface deformation: a N-S trending long fissure on the road (Source: MEC)

Fig.28. The photo shows a damage of Yardanathingaha Bridge (MEC)

Possible style of deformation

In northern Myanmar, the Ayeyawady River flows placidly and majestically from the second defile below Bamaw and enters the third defile near Thabeikyin. Here from latitude 23°30'N near Tagaung, it follows a straight course through a narrow, deep gorge between the steep ridges and hills until Singu (Fig.25). The Thabeikyin event show manifestation of seismic amplification due to the topography. The damage was distributed linearly up to Singu area south of the epicenter. All of these reflected the different basic geological conditions. The factors controlling the damage caused by earthquakes are the characteristics of the geological structure. Earthquake damage is severe in Thabeikkyin and Singu regions near the Sagaing fault. A very narrow linear fault scarp with its steeply dipping on both faces about 20 km long (22°40'N-22°55'N) is observed, just where the Ayeyarwady River fallow the fault zone southward. Morphology of the scarp suggests that the Thabeikkyin earthquake may have associated with amplification by small-scale topographic features such as hills and ridges. The focal mechanism solution of this earthquake (USGS) suggests a strike-slip motion with contraction. Therefore, the deformation mode for Thabeikkyin earthquake is inferred basically to be a combination of thrust and strike-slip faulting.

According to the reports from Department of Meteorology and Hydrology , there were more than five clusters of earthquakes occurred in surrounding area of Lake Indawgyi, in July, August and September and November, 2012: (1).11th July,2012, 60 miles west of Myitkyina, 230 miles north of Mandalay M=5.1 (2). 23rd July,2012, 20 miles north of Monhyin, 210 miles north of Mandalay M=5.1 (3). 3rd August 2012,80 miles northwest of Myitkyina,280 miles north of Mandalay, M=5.0 (4). 20th August 2012, 130 miles northwest of Myitkyina, 220 miles north of Mandalay, M=4.6 (5). 23rd September 2012, 45 miles west of Myitkyina, 245 miles north of Mandalay, M=4.5 (6). 30th November 2012, 74 miles northwest of Myitkyina, 265 miles north of Mandalay, M=4.3. On November 11, 2012, an earthquake of Thabeikkyin with magnitude 6.8 occurred. All these earthquakes were caused by the right-lateral strike-slip movement of the Sagaing fault.

Conclusion

The Sagaing fault is (1000) km long, trending N-S direction. The 1931 Kamaing earthquake (M=7.6), 1946 and 1999 Tagaung earthquakes (M=7.5), 1956 Sagaing earthquake (M=7.0) occurred in the past along the northern part of the Sagaing fault for 450 km long. The damage was distributed linearly up to Singu area south of the epicenter. All of these reflected the different basic geological conditions. The factors controlling the damage caused by earthquakes are the characteristics of the geological structure. Earthquake damage is severe in Thabeikkyin and Singu regions near the Sagaing fault. A very narrow linear fault scarp with its steeply dipping on both faces about 20 km long (22°40’N-22°55’N) is observed, just where the Ayeyarwady River fallow the fault zone southward. Morphology of the scarp suggests that the Thabeikkyin earthquake may have associated with amplification by small-scale topographic features such as hills and ridges. The focal mechanism solution of this earthquake (USGS) suggests a strike-slip faulting. Therefore, the deformation mode for Thabeikkyin earthquake is inferred basically to be a combination of thrust and strike-slip faulting. The frequency level of earthquakes in the past and the repeatability of the seismic hazards are important factors in determining the risk of earthquake hazards.

The 2011 Tarlay Earthquake of eastern Myanmar

Abstract: An earthquake of 6.8 magnitude occurred in eastern Shan State in Myanmar at 20:29:30 Myanmar Standard Time (01:55:12 PM UTC) on 24th March,2011. It was a violent earthquake. Six after-shocks occurred the same year. Its epicenter was situated in 20km west of Tarlay (20.705°N-99.949°E) at depth(10 km) and its magnitude was 6.8. The earthquake damage was disastrous. There were earthquake cracks, arch bend, erupting sand and gush water, etc. in many places. As a result of the strong earthquake, 224-305 houses were seriously damaged, (74) people were killed, (124) injured. Tarlay is located very close to Nan Ma fault, one of the bookshelf faults in Than Lwin suture zone. The geological structure around the town is complex. Mong Lin, Nar Yawng, Kya-Ku-Ni village-tracts are among the most affected areas. The shock was felt in Northern Thailand in the south and Laos in the east.

Key words: Damage, liquefaction, structure, bookshelf fault, earthquake

Tectonic Setting

Tarlay area is located in Than Lwin suture zone between Loi-se-Loi-len fault and Chiang Rai Tectonic Line (Hla Hla Aung, 2009). The geomorphology of the Than Lwin suture zone indicates a youthful topography characterized by deep gorges, narrow V-shaped valleys, rapids and waterfalls suggesting that this region might be undergoing drastic deformation since Neogene. The presence of bookshelf faults and seismicity in the region points to the rejuvenation of tectonic process. Strike-slip faults in NE-ENE-striking direction and normal faults in N-NNE-striking direction represent themselves as tectonic lineaments. The stress fields of the region from the studies of focal mechanism solution of earthquakes (CMT from Harvard and epicenters from Engdhal, GIAC Report,Rangin 1996-1999) indicate that this area has been undergoing NW-SE extension and NE-SW compression. The 2011 Tarlay earthquake is a significant event that occurred in a plate-interior setting.

Introduction

The 2011 Tarlay earthquake is a significant event that occurred in a plate-interior setting. The focal mechanism solution of this earthquake (USGS) suggests a left-lateral strike-slip faulting.

Tarlay is sited very close to the localized rift basin where a fault segment of the Nan Ma fault steps to the left of adjacent fault. The 2011 earthquake event showed that earthquake along a ENE-WSW striking Nan Ma fault was dominated by left- lateral strike-slip faulting which, in turn generate the NNE-SSW trending normal fault to down faulting. Seismicity is consistent with the transfer of slip from one fault segment to another fault segment on the left (Fig.29).

A detailed morphotectonic study was carried out in the area using satellite image to correlate the seismicity with tectonics. From the studies, it is found that there are two prominent lineaments striking NNE-SSW and ENE-WSW in the region. NNE-SSW lineaments are normal fault character and they are developed by NW-SE tensional stress and ENE-WSW lineaments are formed by NE-SW compression. NNE-SSW fractures represent the transfer fault for the ENE-WSW fractures in this area. Horizontal movement along the sinistral strike-slip fault generates the normal fault to down faulting. Periodic movement along these normal fault lineaments has given rise to seismicity in the area.

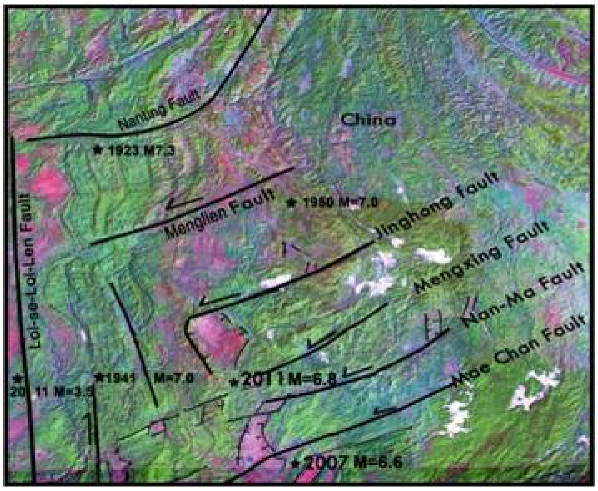


Fig.29. Map shows sharpness of topographic feature and active faults in easternmost part of Shan State and occurrence of earthquakes associated with extensional basin.

Coseismic effects of the 2011 Tarlay Event

The most common co-seismic features were sand boils, ground rift, rise of ground, ground subsidence. All these phenomena appear either together, in isolated spots or in linear structures. There were ground surface cracks in many places. Sand boil and gushing water are often associated with ground rifts. The volume of sand extruded was large and found in the paddy fields. In Tarlay, many ground fissures appeared on the Tarlay Road. Graben –like step depression was formed between two ground rifts. Wells overflowed, some fell in, and some subsided in many places. Liquefaction affected many paddy fields mostly in Tarlay, Kyar-ku-ni and Nar Yawng villages (Fig.30). Morphological changes leading to migration of spring from Nar Yawng village to Kyar-ku ni village and sinking of the ground are found in the area due to this earthquake event. Serious damage, such as building collapse, slant split are found in the region. The houses near the road were out of the perpendicular and slant split. At the sides of the road, a step zone occurs. A ground fissure system appeared on the Tarlay Road. Ground displacement is found in the paddy field.

Fig.30. Liquefaction feature by the Tarlay earthquake

Possible style of deformation

The damage was distributed linearly east and west of the epicenter. Some of the ground seismic damage appears over a large area. Buildings are damaged in different ways. Some buildings collapse, some split open and others settle unevenly. All of these reflect the different basic geological conditions. The factors controlling the damage caused by earthquakes are the characteristics of the geological structure. Earthquake damage is severe in regions near the Nan-Ma fault.

In the area of Tarchi-leik, Tarlay area is located very close to a localized depression where a fault segment step to the adjacent fault segment on the left. The north and south sides of the depression are bounded with strike-slip faults and east and west sides are bounded with irregular margins of normal faults. All of the active fractures are inherited from Neogene bookshelf faulting. The frequency level of earthquakes in the past and the repeatability of the seismic hazards are important factors in determining the risk of earthquake hazards. Earthquake damage is most frequently associated with shallow engineering geology.

Conclusion

Earthquake disasters are related to the local site specific characteristics and seismic stress field. Co-seismic changes like migration of spring and stream, sinking of the ground are common styles of deformation during compressional earthquake. The 2011 earthquake event showed that movement along a ENE-WSW striking Nan Ma fault was dominated by left- lateral strike-slip faulting which, in turn generate the NNE-SSW trending normal fault to down faulting. Tarlay is sited very close to the localized rift basin. The focal mechanism solution of this earthquake (USGS) suggests a strike-slip faulting. Therefore, the deformation mode for Tarlay area is inferred basically to be a combination of normal and strike-slip faulting.

The 2013 Yangon earthquake in the Ayeyarwady Delta Basin

Abstract: An earthquake of M=3.4 occurred in 9 miles north of Yangon, 13 miles north-northwest of Thanlyin,20 miles northeast of Twante at 08:07:03 pm on 30th January,2013. Its epicenter was situated at 16.950°N, 96.127°E and at depth 10 km (6.2 miles) (USGS, NEIC). It was a slight earthquake and vibrations were felt in the region of Yangon. In 17 December, 1927, an earthquake with magnitude 7.0 hit Yangon and caused certain amount of damages. It was felt 15,000 sq.km from Kyangin to Dedaye along the western slope of Bago Yoma. In Yangon, the shock was much severer causing widespread alarm and damage to concrete buildings. Focal mechanism solution of this event is a strike-slip faulting (USGS). In July, 1930 Bago earthquake with M=7.3 effected Yangon, vibration spread caused damage to the buildings and 500 persons in Bago and 50 persons were killed in Yangon respectively. The last record of significant earthquakes that struck Yangon is on 30th September,1978 with M=5.7 at 10 km depth.

Introdution

Yangon is located between latitudes 16° 45’ N-17° 4’N and longitudes 96°1’E-96° 20’E, on the southeastern corner of the Ayeyarwady Delta basin, at the mouth of three rivers: Yangon, Ngamoyeik and Bago rivers and 34km from the sea in the coastal area. It has a tropical Monsoon climate with annual precipitation of 2366 mm. It has population of about 5 million people. Due to the annual increase of population, the size of the city has expanded several times than its prewar size. When population increases, urban development expands. Yangon’s pride: the Shwedagon Pagoda was built on the top of Singuttara Hill , on the southern spur of Bago Yoma (Fig.31).

Tectonic setting

Yangon region is tectonically located on the southern spur of the NNW-SSE trending Bago anticlinal ridge which lies immediately on the western site of Sagaing Fault. Bago Yoma is a ridge of both geological and geomorphic prominence ridge with 400 miles long and 40 miles wide and is composed of Miocene rocks. Bago Yoma extends toward south into the gulf of Motamma and might be connected to Alcock Rise. Yangon is 35km in the west of Sagaing fault. The Bago Yoma, Sagaing fault and Central Andaman spreading centre are the most significant structures of shear band of Sagaing fault with 100km width.

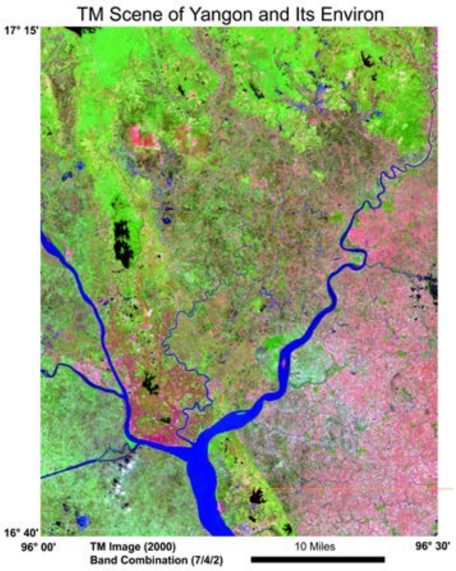


Fig.31. LNDSAT TM image of Yangon area, epicenter was situated south of Hlawga Lake, at 16.950°N, 96.127°E and at depth 10 km (6.2 miles) (USGS, NEIC).

Yangon area is underlain by alluvial deposits (Pliestocene to Recent), the non-marine fluvial-tile sediments of Irrawady formation (Pliocene) and hard, massive sandstone of Pegu series (early- late Miocene). Alluvial deposits are composed of gravel, clay, silts, sands and laterite which lies upon the eroded surface of Irrawaddy formation at 3-4.6m above sea level. The central part of Yangon area is occupied by the anticlinal ridge as a backbone (Fig.32).

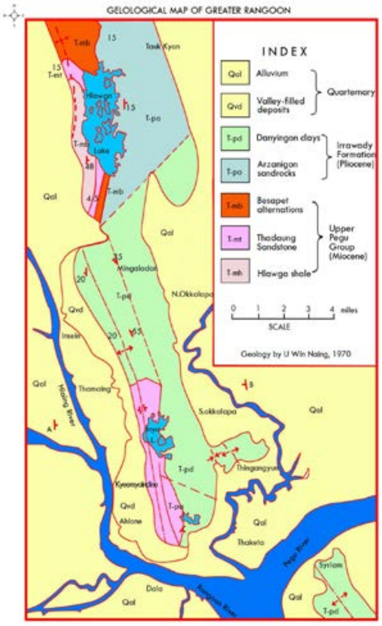


Fig.32. Geological Map of Yangon area(W.Naing,1979)

Possible style of deformation

From the study of seismic profiles in the shelf area of Ayeyarwady Delta basin, ENE-WSW trending normal faults are recently inverted and it is possible the inversion is still active (Rangin,1996-1999), as in Salin basin (Pivnik,1999). Most of the Ayeyarwady Delta basin is covered with alluvium so that surface geology can only be found in very few areas. Structure and geology are deciphered mainly on the basis of seismic profile. NNW-SSE trending folds and NNE-SSW striking transverse faults occur in Yangon area (Fig.32). The Ayeyawady basin is one of the rift basins in N-S trending elongated Central Myanmar Basin. It is bounded with NNW-SSE trending fault to the east and a fault that separates the basin from Rakhine Yoma in the west. These basin bounding faults are capable of triggering earthquakes in the region. Historical and recent earthquakes have shaken the Yangon including the M7.0 1927 earthquake and the M5.7 1978 earthquake. These earthquakes reflect the existence of a blind fault underneath the soft sediments of Yangon region. The Yangon earthquake ruptured this fault and this fault has no name, so that the author attempts to give a name to this fault as Yangon fault.

Concluding Remark

The cause of earthquake damage is due to both the geological condition of an area and the foundation of the building itself. Ground shaking and movement along the faults are hazards for an area. The shaking can break power lines, pipelines, buildings, roads, bridges and other structures that are very close to the fault. So the simplest strategy would be not to build near the fault zones. However, many ancient cites of Myanmar such as Tagaung, Ava (Inwa), Sagaing, Taungoo, Bago and Bagan have already developed near major faults and they have been destroyed by earthquakes repeatedly through history. Designing earthquake- resistance buildings or building codes is a great challenge for the buildings to withstand strong earthquakes. A further complication is that the same building codes cannot be applied everywhere. Neither all earthquakes produce the same pattern of ground motion nor can all geological structure be the same in a country. It is also important to consider type of soil on which the structures is built. Buildings built on the bed rocks seem to suffer far less damage than those built on deep soil. Because ground shaking is amplified by seismic waves within any sedimentary basin. The liquefaction is a major cause of damage to the building where the ground is covered with alluvial soil and in filled land near the coast.

Preliminary Report on the Thayet-Aunglan Earthquake in Central Myanmar

Abstract

An earthquake with magnitude 5.4 occured 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 felt by nearby cities of Aunglan (Myayde), Thayet, Nay Pyi Daw and Pyay. It is 54 km from east of Aunglan, 57 km east of Thayet, 66 km south-west of Nay Pyi Taw and 74 km north-east of Pyay (USGS, NEIC). The shock was most severe near Thayet and Aunglan. After that, average magnitude of 4.0 earthquakes took place on the following days and another earthquake with M=5.2 occurred on 11th April, 2013 at depth 10.1km. Focal mechanism solution of this event gives thrust faulting (USGS). Some houses were collapsed in villages and slight damage to lower part of Bade dam. This earthquake was named, the Aunglan earthquake as the town is closest to the epicenter of the event. The causative fault of this earthquake is a

fault trending in NNW-SSE direction, with a mix of thrusting and right- lateral motion. Thrust fault exist where compressional forces are squeezing the crust to shorten and thicken due to vertical motion. If a region is under compression, crustal blocks try to escape with lateral motion.

Keywords: thrust, strike-slip fault, damage, compression, epicenter, shock

Tectonic setting

This earthquake is the significant earthquake which has occurred in plate-interior setting. The earliest earthquake on record in “Geology of Burma” by Chhibber,1934, which affected the central Myanmar, are an earthquake of 24th August and another earthquake of 26th August of the same year, 1858, respectively. The towns: Pyay, Thayet, Aunglan are situated in the Pyay basin, one of sub-basins in N-S elongated Central Myanmar Basin. Pyay basin is in the N-S direction and it is 80 km long, in the northern part of the Ayeyarwady Delta basin,. Additionally, it is a narrow E-W extension between Rakhine Western Ranges to the west and Bago Yoma to the east, which form the Pyay Embayment. ENE- striking transverse faults as well as NW-SE and NE-SW trending diagonal faults are present in the basin. Asymmetrical folds with special culmination along their crests in NW-SE or NNW-SSE are found in the basin.West-dipping overthrusts with vertical displacement of up to 1000 m are found in the basin. The 20° N uplift area with locally exposed

Oligocene rocks separate the Pyay basin from the Salin basin in the north (Bender,1983).

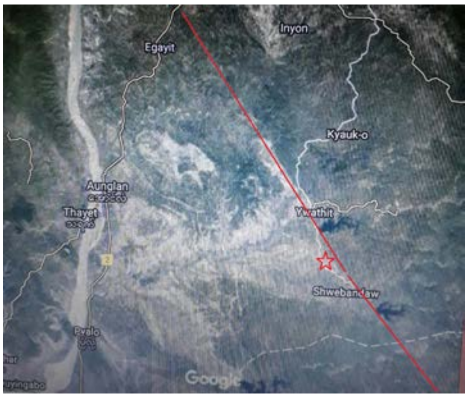


Fig.33. Location of epicenter of the Aunglan earthquake in the ENE of Shwebandaw Indicated with a star, near a fault trace, background map from Google, Bwetkyi Dam in the north and Bade Dam in the south can be seen on the map.

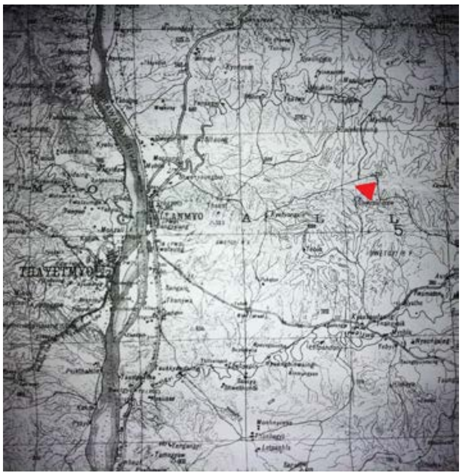


Fig.34. Topographic map showing location of Aunglan earthquake
In the ENE of Shwebandaw indicated with a red arrow.

Possible style of deformation

Based on historical accounts, the earliest seismic record was in 1858, a destructive earthquake also occured near Thayet-Aunglan with magnitude 7.0. Tops of Pagodas were knocked down, houses collapsed due to this destructive earthquake at that time. Mud was brought up to the surface of the water where the Ayeyarwady River is shallow. The bed of the river was distinctly seen to rise out of the water and to resume its old level after the shock was passed. Intensity decreased southward and the general direction of motion appears to have been from ENE to WSW. Tops of pagodas were torn off and fell to the south-west (Chhibber,1934). Thrust movement along the preexisting detachment surface during basin inversion under compressional stresses could be the cause for seismicity in Aunglan area. The NNW-SSE trending fault located in the east of Aunglan, very closed to Ngayangyaw village and Shwepandaw village, accommodates a mix of thrust and right-lateral motion (Fig.33,34). Such deformation style may be characteristics of rift-related environments under compressional stresses. In this tectonically active continental rift setting, the majority of strain is accommodated along border faults of the basins. These faults are easy to find when the individual earthquakes struck on each fault. Focal mechanism solution of earthquakes and fault orientations give strong extension axis in an NNW-SSE direction and maximum compression axis direction in an E-W or ENE-

WSW. Depth distribution of earthquakes shows that the majority of earthquakes occur at depth from 0-40 km (CMT from Harvard and epicenters from ENGDAHL) (Rangin,1996-1999).

Conclusion

The Yangon Earthquake (M=7, 1927); the Pagan Earthquake (M=6.8, 1975); the Taungdwingyi Earthquake (M=6.6, depth-10 km(NEIC), 2003) and the Earthquakes (M=7.0, 1858; M=5.4, depth-14 km, 2007(USGS) and recent earthquake near Aunglan (M=5.4, 2013; Depth=11 km), define the faults that bound the basins in Central Myanmar Basin, respectively. Seismicity in Central Myanmar Basin occur as a result of the stresses and strain set up within the plate, on the pre-existing normal and strike-slip faults that have an appropriate orientation with respect to the present day stress field.

The 1912 Maymyo earthquake in eastern Myanmar

Abstract: The M = 8, I_{max} = IX Maymyo earthquake of May 23, 1912 is the most powerful earthquake in Myanmar. It occurred at about 3 a.m and the shock was felt widely throughout the eastern part of Myanmar, in Western part of Northern Shan state and Southern Shan state over an area of approximately 375, 000 square mile. It disturbed recording instruments throughout the world. This earthquake should be named the Taunggyi earthquake instead of Maymyo because the epicenter of this event is very close to Taunggyi. The epicenter is located at 21°N 97°E. The vibration cost damage in all parts of Maymyo. There was no loss of lives due to the scanty population in this region and their traditional way of housing style. The major exist of the elongated isoseismal line trends in a general NS direction, coincides nearly with the Kyaukkyan fault. The Kyaukkyan fault is a major right-lateral strike-slip fault for 500km in N-S direction from the vicinity Yawksauk in Northern Shan state to the Eastern margin of the Innlay lake in Southern Shan State. Mode of deformation is believed to be right-lateral strike-slip faulting.

Keywords: epicenter, vibration, population, isoseismal line, deformation

Tectonic setting

In eastern Myanmar, a vast plateau is covered with dolomitic and calcitic limestone with immense thickness, from west Yunnan at about latitude 24°N through the whole Shan Plateau and to the south to latitude 20° 20' N, where it narrows (Chhibber, 1934) and then expands again and continues to the south to western Thailand. The western boundary of the plateau is the NNW-SSE trending Shan Boundary fault forming precipitous scarp as triangular facets. The plateau has been dissected by a series of longitudinal step-faults trending in the N-S direction, forming blocks and depressions with the production of conspicuous landforms of great fault scarp trending in comparatively N-S oriented straight lines for many miles (Gorshkov, 1959). The Kyaukkyan fault is one of these longitudinal faults in Shan Plateau. Kyaukkyan Fault is a right lateral active strike-slip fault trending in north- south direction. The length of the fault is about 500km. The northern end is terminated in Mogok metamorphic belt and the southern end merges into the Papun Fault. Current stress field in western plateau is N-S extension and E-W compression (Fig.35).

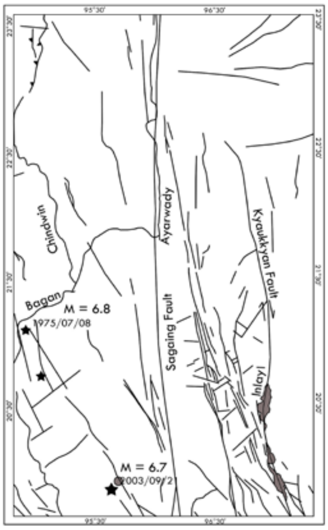


Fig.35. Map showing the longitudinal faults at the western part of Shan Plateau, on the east of the Sagaing fault, drawn from satellite image. The Kyaukkyan fault can be visible in the map (Source: MEC).

Fig.36. Map of Inlay lake

Co-seismic surface deformation

Co-seismic surface deformation features are summarized from the literature: Geology of Burma by Chhibber 1934. The most severely affected area lay partly in the Northern Shan State and partly in the Southern Shan State and the greater parts of Maymyo, Kyaukse, Meikhtila, Yamathin, Shwebo and ruby mines. Nearly every brick building in many parts of the region were badly cracked and about 60 Pagodas collapsed. There were numerous foreshocks and aftershocks and railroad tracks bent near fault but little deformed elsewhere. The shock was felt in India, Thailand and China. Huge landslides were common in many parts along the Kyaukkyan fault.

Possible mode of deformation

The Maymyo earthquake was one of the prominent events along normal and strike-slip faults that occurred widely about Shan Plateau before and after the Maymyo earthquake in 1912. Inlay Lake was the result of East- West-directed compression and North-South-directed extension. The Inlay Lake is a pull-apart basin formed by the transtensional process (Fig.36). The movement along the Kyaukkyan fault produced significant earthquake of the 1912 Maymyo earthquake in western part of Shan Plateau. Active deformation and seismicity within the Shan Plateau represent an important component of the active intracontinental tectonics of SE Asia.

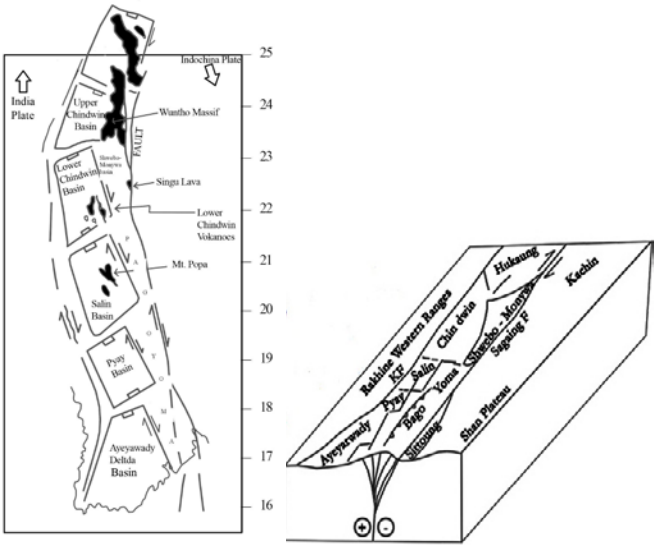
The 2015 Monywa-Kani Earthquake of central Myanmar

Abstract: On November 27th 2015, at 18:34:13 (UTC) an earthquake of magnitude 5.4 (CMT determination) occurred at depth of 23 km near Kani at 22.6144°N- 95.040°E (USGS Report), 60km (35 miles) northwest of Monywa. The epicenter is located in Shwebo-Monywa basin. The earthquake is one of the continental intraplate earthquakes that have occurred within the transfer zone. Within epicentral tract, the intensity of the earthquake was severe which involves partial destruction of some buildings, monasteries, and pagodas. The Monywa-Kani earthquake is believed to be due to basin inversion at transpressional push- up near western bounding fault of the Shwebo-Monywa basin.

Key words: magnitude, depth, epicenter, transfer zone, building, pagoda

Tectonic Setting

The Central Myanmar Basin is a N-S oriented, elongated belt for 1100 km in Myanmar and another 1000km in Andaman sea. The basin is dominated by NNW-oriented and NE- to ENE-trending faults. The dominance of NE- to ENE-to EW trending faults is suggestive of a NNW-SSE striking extensional stress direction. This extensional stress appears to have favored the formation of normal faults. The N-S oriented belt of tectonic blocks is bounded to the west by the Kabaw fault and to the east by the Sagaing fault. The terrane has been sliced into several crustal blocks from margin of lithospheric plate by normal faulting. These blocks are moving laterally as a result of northward movement of the India plate with respect to the Sundaland plate, in which some blocks are being compressed and uplifted and some are being stretched and sagging, forming Basin-Uplift province along the Central Myanmar Basin containing the sub-basins and uplifts. The Basin-Uplift province constitutes of Putao basin, Hukawng basin-26° N Uplift- Chindwin basin - 22° N Uplift - Salin basin - 20° N Uplift - Pyay basin to Ayeyawady Delta basin to the south (Bender,1983). The Shwebo-Monywa basin is oblique to the Sagaing fault to the east and bounded by a series of faults in N-S, NNE-SSW and NE-SW direction such as Shinmataung fault, Medin fault and Mettaung fault to the west. To the south, the Sittoung basin is located between Bago Yoma to the west and the Shan Boundary fault on the east. Bago anticlinorium to the east of Pyay basin has been formed between Bago fault and Sagaing fault due to crustal shortening and topographic uplift related to a series of contractional step-overs. It is the largest push-up for 400 miles long and 40 miles wide in the Central Myanmar Basin (Bender, 1983) (Fig.37a and 37b).



(a). (b).

Fig.37a. Map showing distribution of basins in N-S trending transfer zone between the India and Indochina plates. Fig.37b. A block diagram showing how pull-apart basins are formed relation to the movement along the Sagaing fault. (based on data from Bender,1983)

Fig.38. Map showing epicenters of earthquakes in Myanmar

Intraplate stresses cause earthquakes on particular faults so intraplate seismicity migrates within continental deformation zone. The Gwegyo Earthquake (M=4.8, 2016); the Taungdwingyi Earthquake (M=6.6, 2003) and the Thayet Earthquake (M= 7.0, 1858 and M=5.4,2007); The Yangon Earthquake (M=7,1927); are the continental intraplate earthquakes that have occurred within the transfer zone between two lithospheric plates of the India to the west and Sunda to the east (Fig.38).

Conclusion

Geographically, Monywa and Kani are situated in central Myanmar. Tectonically, the towns are located in the Shwebo-Monywa basin in the west of Sagaing fault. Structurally, the town, Kani is located very close to a major strand of the Sagaing fault, which bounds the Shwebo-Monywa basin in the west. There are many en echelon folds in this region trending NNW_SSE. Seismically, Kani falls in seismic zone III of Seismic Zones Map of Myanmar (Aung, 2010). Possible style of deformation is believed to be a combination of strike-slip faulting and thrusting due to basin inversion.

The 2016 M 4.7 Gwegyo earthquake in Central Myanmar

An earthquake occurred on 7th March, 2016 with M 4.8 at 20.93°N 94.96°E, northeast of Chauk.

Tectonic setting

The Central Myanmar Basin is a N-S oriented, elongated belt for 1100 km in Myanmar and another 1000km in Andaman sea. The basin is dominated by NNW-oriented and NE- to ENE-trending faults. The dominance of NE-to ENE-to EW trending faults is suggestive of a NNW-SSE striking extensional stress direction. This extensional stress appears to have favored the formation of normal faults. The terrane is bounded to the west by the Kabaw fault and to the east by the Sagaing fault. The terrane has been sliced into several crustal blocks from margin of lithospheric plate by normal faulting. These blocks are moving laterally as a result of northward movement of the India plate with respect to the Sundaland plate, in which some blocks are being compressed and uplifted and some are being stretched and sagging, forming Basin-Uplift province along the Central Myanmar Basin. The Basin-Uplift province constitutes of Hukawng basin-26° N Uplift- Chindwin basin - 22° N Uplift - Salin basin - 20° N Uplift - Pyay basin to Ayeyawady Delta basin to the south (Bender,1983). Salin basin is one of the pull-apart basins and it runs for more than 200km in the N-S direction between 20°N Uplift and 22° N Uplift. The east edge of the basin is bounded with a NNW-SSE trending dextral strike-slip fault accompanied by a series of narrow elongated anticlines. To the north of 20° N uplift, the Salin basin runs in NNW and N-S direction and the generally NW-SE and NNW-SSE trending folds are elongated and narrow and are cut by a great number of faults. The Chauk-Yenangyat asymmetrical fold with an east dipping thrust fault on the eastern flank and countless transverse faults with a ENE-WSW strike and NE and NW oriented diagonal faults break the anticline into individual sections. Pagan is situated in the Salin basin which begins with 20°N uplift and ends in the north at a structural uplift, the 22° N Uplift (Fig.39).

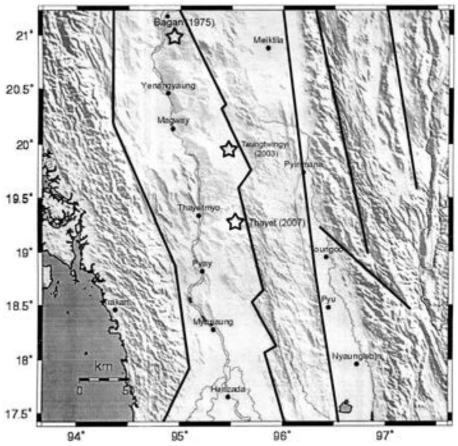


Fig.40. Gwegyo village is situated in the south of Gwegyo thrust and SSE of Bagan in the Salin. Pyay-Thayet is in the Pyay basin in the south of Salin basin. Earthquake occurrences are shown as star in Central Myanmar Basin.

Fig.40(a) Google Earth map of Gwegyo village and Gwegyo Thrust Trending NNW-SSE direction

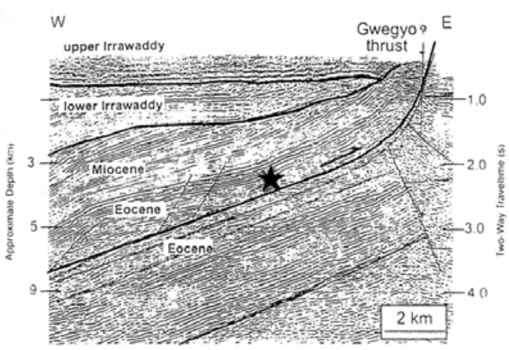


Fig.40(b). Seismic section in E-W direction across the Gwegyo thrust (Pivnik, 1998). A model of fault- propagation folds during basin inversion under compressional regime.

Possible Style of deformation and the causative factor of earthquake in Gwegyo village

The author proposed a model for the Gwegyo earthquake event based on tectonic inversion and development of fault propagation fold of the hanging wall of the Gwegyo thrust.(Fig.40,a). According to Pivnik, (1999), the Gwegyo thrust sheet extends for over 50km along the NNW-oriented strike from Ngashantaung to

Tuyintaung in the north , with the dip 10° west. The thrust is exposed at Tetma, Nyaungnigyin and at Zigyibin. The Gwegyo thrust fault cut the eastern flank of NW-SE trending Gwegyo anticline. Evidence for eastward tectonic transport over west-dipping, low-angle thrust fault is graphically documented on stereo-net and fracture patterns associated with thrust faults indicate compressional strain (Pivnik,1999) (Fig.40.b). The structural geology of the Gwegyo thrust show that the regional decollement layer is the Tabyin formation of the Eocene age. In the compressional field in the Salin basin since Plio-Pleistocene, the NNW-SSE trending Gwegyo thrust flattening at depth have behaved as detachment surface. The Tabyin formation is located at 15,000 m (15km) in Central Myanmar (pg.162, Bender,1983). Thrust movement along the preexisting detachment surface during basin inversion under compressional stresses could be the cause for seismicity in the area. Such deformation style may be characteristics of rift-related environments under compressional stresses. The relation between intensity and the observed surface deformation zone suggest that the deformation correspond to a broad zone of up warping under compressive stresses. The model of fault propagation from the boundary of the Salin basin to a deep detachment surface suggested that the estimated epicenter occurs to the southeast of Pagan, approximately at 15 km depth. This event epicenter is at 20.93°N 94.96°E, northeast of Chauk (Fig.41). Gwegyo village is located south of Gwegyo Thrust fault. Thrust movement along the preexisting detachment surface of Gwegyo fault at depth during basin inversion under compressional stresses could be the cause for seismicity in Gwegyo area. Such deformation style may be characteristics of rift-related environments under compressional stresses.

Fig.41. Source: Map from Google Earth showing epicenter Location of an earthquake, Gwegyo village, southeast of Bagan

Conclusion

Geographically, both Gwegyo village and Taungdwingyi (Taungdwingyi Earthquake, 2003) are situated in central Myanmar. Tectonically, they are located in the Salin basin in the west of Sagaing fault. Structurally, the towns are located very close to a major strand of the Sagaing fault in NW-SE direction, which bounds the Salin basin. There are many en echelon folds in this region trending NNW_SSE. Seismically, Gwegyo village and Taungdwingyi fall in seismic zone III of Seismic Zones Map of Myanmar. Seismicity in the Central Myanmar Basin terrane may be due to the severe crustal movement through the Basin-and-Uplift structure along the transfer zone for 1000km length.

The intraplate stress field derived from combination of focal mechanism and fault orientations show a NNW-oriented extension and a ENE-striking compression. Intraplate stresses cause earthquakes on particular faults so intraplate seismicity migrates within continental deformation zone.

The 2016 Mawlaik Earthquake of Central Myanmar

Abstract: On April 13th 2016, at 8:25 (Local Time) an earthquake of magnitude 6.9 (CMT determination) occurred at depth of 134 km, at 23.133°N- 94.900°E (USGS Report), 74 Km southeast of Mawlaik, 165 km west of Mogok. The epicenter is located in Shwebo-Monywa basin, near the town Thakekyin. An aftershock with M 4.6 occurred on 14th April, 2016 at 12:12:53 (Local Time), 23.820°N 94.183°E, 31 km northwest of Mawlaik, at depth 67.65 km (42.04 mile). Another aftershock with M=4.7 at 120 km southwest of Monyin (24.507°N/95.53°E) on 22nd April, 2016 occurred north-northeast of the previous epicentral location of Mawlaik earthquake. Within epicentral tract, the intensity of the earthquake was severe which involves partial destruction of some buildings, monasteries, and pagodas. As a result of strong earthquake, its violent seismic wave made much of Myanmar region shake to the south in Yangon and to India in the west. The moment tensor from USGS Earthquake Report gives oblique reverse faulting. The 2016 Mawlaik

earthquake which occurred at depth of 134 km is believed to be an intraplate subduction zone earthquake in Myanmar.

Key words: magnitude, depth, epicenter, transfer zone, building, pagoda

Tectonic Setting

Rakhine Western Range terrane is a subduction- related accretionary complex, composed of two different geologic units, normally a large turbidites-bearing belt of Chin flysch which constitutes the main section (Cretaceous, Eocene-Neogene) in the western part and a narrow, intermittently out-cropping zone of an Upper Cretaceous sequences, meta-morphic rocks, serpentinites mélanges (early Campanian), Triassic Halobia schist (Kanpetlet schist) and ophiolites at the eastern margin of RWR. This ophiolites were considered to be the remnants of Neo-Tethys seafloor obducted during Middle Eocene. Triassic Halobian schist and an upper Cretaceous sequence and emplacement of serpentinite mélanges along the eastern margin of Western Range terrane probably took place in the early Campanian. Structural trend swings from the NE-SW direction in the Naga Hills to NW-SE along the Rakhine Range and Chin Hills. The Kabaw fault System demarcated this terrane from CBB terrane to the east. The Kabaw fault dips moderately to the east (Pivnik,et al.,1998) and runs at the eastern foot of the Naga Hills, Chin Hills and continues to the western margin of the Ayeyawady delta basin in the south. The Rakhine Western Ranges was formed by the collision of the India and Burma tectonic plates at a relative rate of 60 mm/yr. A large amount of the motion is driving the uplift of the Rakhine Western Ranges. The boundary region between these two plates has a history of large and great earthquakes, making it one of the most seismically hazardous regions in the world (Fig.42.(a).

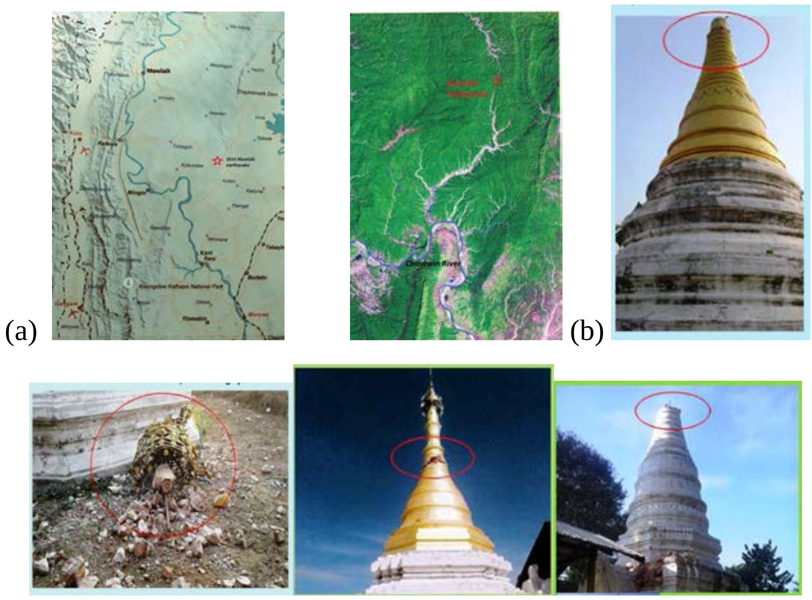


Fig.42 (a). Location of Mawlaik earthquake epicenter (Fig.42.b)Mosaic of pagodas in Kani area showing damages only at the upper part of pagodas by Mawlaik earthquake

Possible style of Deformation

In northern Myanmar, a northeast-dipping Indian plate is thrusting under Burma plate below the northern Rakhine Western Ranges at the speed of 60mm/yr. It was clearly evidenced in tomographic images derived from P-waves seismic events done by Spakman, Utrecht University (Rangin,1999 GIAC Report). Moment tensor solution of this earthquake gives oblique reverse faulting (USGS Report, 13, 4, 2016). The fact that many pagodas damaged by the M6.9 earthquake remained intact suggests that such deformation style may be characteristics of up-ward movement under compressional stresses (Fig.42b). The earthquake spread to a wide area across the country and neighboring countries like Bengladesh and India The focal mechanism, according to USGS Report gives oblique reverse movement in a deep zone with 134 km which implies that the event occurred in the subducting slab of India plate.

Conclusion

The M 6.9 Mawlaik earthquake was an intraplate subduction zone earthquake event that occurred within a year of 2016. Based on interpretation of post- earthquake damages in surrounding area and field survey in surrounding areas, the geometry, geomorphology and kinematics of co-seismic rupture as well as geologic hazards along the subduction zone indicate neotectonic deformation due to the reorganization of interplate motion between India and Burma. Detailed investigation indicates that the Mawlaik earthquake occurred along the N-S trending megathrust of the subduction zone. The main surface rupture zone of Mawlaik earthquake on the segment of megathrust is approximately (250) km in length. Such deformation style may be characteristics of the environments under compressional stresses. The earthquake was felt in much of central Myanmar and extended to northeastern India and Bangladesh.

The 2016 M 6.8 Chauk earthquake in Myanmar

Abstract

The 6.8 magnitude megathrust earthquake occurred on 24th August 2016 at deep depth of 84.1km with epicenter 20° 919' N 94° 579'E, 25 km west of Chauk lasting 1 minute. Focal mechanism solution of this event is given as compressional faulting (USGS) in subducting slab of India plate. It spread to location across the western part of the Sagaing fault including Yakhine coastal region in the west, Central Myanmar in the east. The M 6.8 Chauk earthquake was one of two Subduction zone earthquake events that occurred within a year of 2016. Based on interpretation of post- earthquake damages in Bagan area and field survey in surrounding areas, most of the upper portion of the pagodas fell down but the pagodas remained intact to the ground as before. Felt report said that the earth uplifted suddenly to carry up hundreds of Bagan pagodas and came down slowly, then lateral shaking took place. Detailed investigation indicates that the Chauk earthquake and the Mawlaik earthquake occurred along the N-S trending megathrust. The main surface rupture zone of Mawlaik earthquake on the segment of megathrust is approximately (250) km in length and the Chauk earthquake on another segment is approximately (180) km, respectively.The Chauk earthquake provides new insight into the nature of subduction zone earthquake in Myanmar. The seismological studies obtained from USGS earthquake report indicates that the main shock was initiated at 25km W of the town Chauk, with the rupture propagating N-S for about (200) km. Such deformation style may be characteristics of

the environments under compressional stresses. The earthquake was felt in much of central Myanmar and extended to northeastern India and Bangladesh.

Keywords: subduction zone, rupture,compression, megathrust,

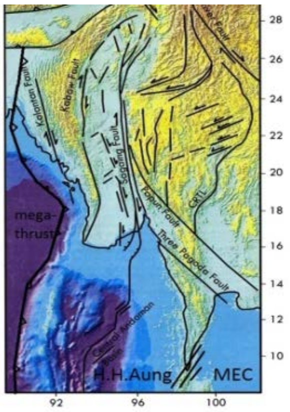
Tectonic setting

Hard collition between India and Burma plate during Oligocene to Miocene (45Ma-35Ma) and Rakhine Western Ranges became uplifted during Middle Miocene to Upper Miocene (Curray et al.2005). India plate is subducting obliquely beneath Burma plate along Sunda subduction zone consisting of four trenches: Indo-Myanmar trench, Andaman–Nicobar trench, and Sumatra trench (Fig.44 and 45). Northward and northeastward movement of India oceanic crust is the most important part for tectonic of Burma in Tertiary time.

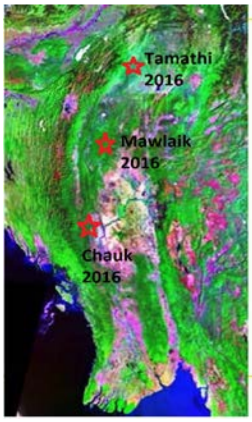
This Rakhine Western Ranges is a subduction- related outgrowth continent, composed of two different geologic units, normally a broad flysch belt which constitutes the main section, and a narrow, intermittently out-cropping zone of metamorphic rocks and ophiolites. These ophiolites were considered to be the remnants of Neo-Tethys seafloor obducted during subduction. Structural trend swings from the NE-SW direction in the Naga Hills to NW-SE along the Rakhine Range and Chin Hills. Kabaw Fault System demarcated this terrane from Central Burma Basin terrane.

Co-seismic effect of the 2016 Chauk earthquake event

Many Buddhist temples and pagodas were built on the stretches of sandy wind-swept plains and Pagan became a stronghold of Buddhism and was well known as the seat of Buddhist learning and culture among its contemporaries in Southeast Asia. Pagan, the land of pagodas was destroyed by an earthquake with magnitude 6.8, in 1975 and many pagodas and temples were damaged within seconds. Some of pagodas are being left intact and withstand to maintain the role of its past glory as historical monuments in Southeast Asia. Due to this Chauk earthquake, approximate numbers of pagodas (400) out of (4000) stupas and temples were damaged, the same as the previous 1975 Bagan earthquake. Pagodas left intact and withstand as before.



(a)



(b)

Fig.43(a).Megathrust on the west of Yakhine coast trending in N-S direction

Fig.43(b)Epicentral location of intraplate subduction zone earthquakes

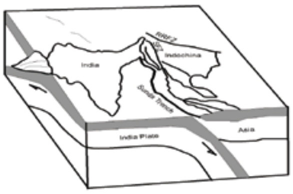


Fig.45 (a)

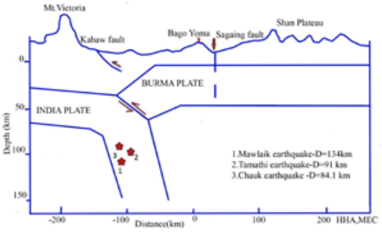


Fig.44(b)

Fig.44(a).Generalized configuration of India and Burma plates in relation to megathrust. 45(b): The three intermediate earthquakes occurred in subducting slab of India plate Within one year,2016

Fig.45. Mud eruption in Yakhine area and Minbu area during Chauk earthquake

One of the characteristics of subduction zone earthquake is eruptions which can produce fast-moving mudflows as well as high-lofted ash clouds (Fig.45) Subduction contain many of Earth’s most remarkable geologic structures, from deepest oceanic trenches to steaming volcanoes (*EOS* vol.97,no.16*)*.

Possible style of deformation

The 6.8 magnitude megathrust earthquake occurred on 24th August 2016 at deep depth of 84.1km with epicenter 20° 919' N 94° 579'E, 25 km west of Chauk lasting 1 minute. Focal mechanism solution of this event is given as compressional faulting (USGS) in subducting slab of India plate. The geometry of surface rupture zones by compressional faulting during this 2016 chauk earthquake is similar to that produced by the oblique reverse faulting during the 1975 Bagan earthquake. The 1975 Bagan, the April 2016 Mawlaik, the August 2016 Chauk and the October 2016 Tamathi earthquakes occurred at different segments of the Sunda megathrust.

The March 2017 M 5.1 Taikkyi Earthquake in north of Yangon

Abstract: 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°E at focal depth 10 km (USGS). The shock was felt by nearby cities of Thayawady, Okkan, Mhawbi and Yangon region. 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 shock was most severe near Taikkyi. After that, an earthquake with average magnitude of 4.8 took place on the same evening. Several aftershocks with average magnitude of less than 4.5 occurred on following days. The important observation from satellite imagery, topographic map, aerial photograph and field investigation are introduced to better understand the relation between seismicity and tectonics. To better understand the seismic hazard posed by the fault, the surface trace of the fault has been mapped by interpretation of Landsat TM

images and shaded relief map. Taikkyi fault is an active reserve fault with right lateral strike-slip component, as a result of basin inversion. It is a basin bounding fault of the Ayeyarwady Delta Basin. Some old houses were collapsed in villages and slight damage to pagodas. This earthquake was named, the Taikkyi earthquake as the town is closest to the epicenter of the event. 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. Thrust fault exist where compressional forces are squeezing the crust to shorten and thicken due to vertical motion. If a region is under compression, crustal blocks try to escape with lateral motion. The horizontal slip rate of CMB is 8mm / yr from GPS analysis (GIAC project, 1999), while coseismic horizontal slip rate during 2017 Taikkyi earthquake is at least 2 m, obtained from 10 rupture traces along water pipeline of Gyobyu Reservoir. The recurrent interval of 2017 earthquake would be 250 year.

Keywords: thrust, strike-slip fault, damage, compression, epicenter, inversion, slip rate

Tectonic setting

This earthquake is the significant earthquake which has occurred in plate-interior setting. The earlier earthquake is an earthquake in 2nd January, 2006 with M 4.4. The town is situated 65 km north of Yangon in the Ayeyarwady Delta basin. The basin is one of sub-basins in N-S elongated Central Myanmar Basin. The faults are recently inverted and it is possible the inversion is still active (Rangin,1996-1999), as in Salin and Pyay basin (Pivnik,1999). Most of the Ayeyarwady Delta basin is covered with alluvium so that surface geology can only be found in very few areas. Structure and geology are deciphered mainly on the basis of seismic profile. NNW-SSE trending folds and NNE-SSW striking transverse faults occur in Taikkyi area. The Ayeyawady basin is one of the rift basins in N-S trending elongated Central Myanmar Basin. It is bounded with NNW-SSE trending fault to the east and a fault that separates the basin from Rakhine Yoma in the west. These basin bounding faults are capable of triggering earthquakes in the region. The Taikkyi earthquake ruptured this fault and the author attempts to give a name to this fault as Taikkyi fault. The present-day deformation field of the Basin-Uplift province is revealed by the pattern of seismicity of horizontal velocity estimates data derived from GPS, which show 8 mm/yr between basin and uplift (Rangin, 1996-1999).

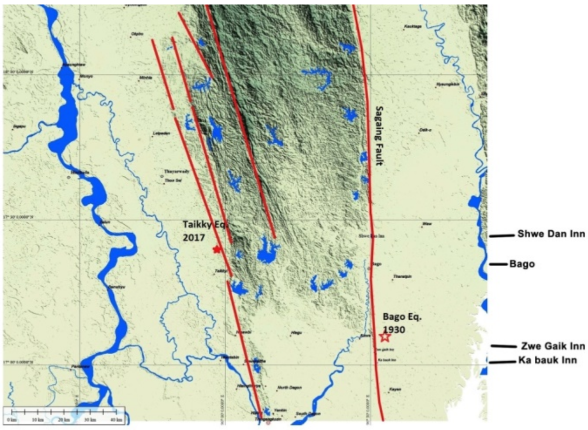


Fig46. Shaded relief map showing regional tectonic features in the vicinity of Bago Yoma

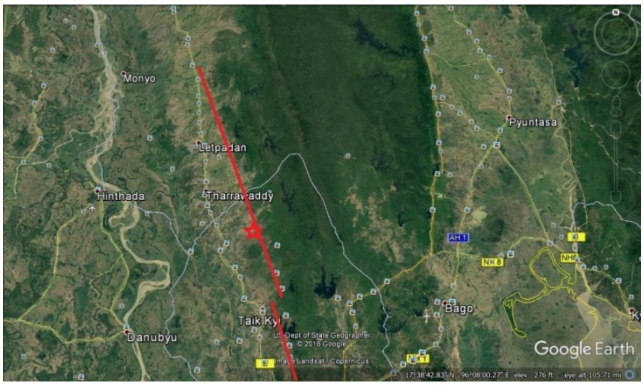


Fig.47. Google Earth map showing Taikkyi fault and its related topographic features

Geological Background

The important observation from satellite imagery, topographic map, aerial photograph and field investigation are introduced to better understand the relation between seismicity and tectonics. To better understand the seismic hazard posed by the fault, the surface trace of the fault has been mapped by interpretation of Landsat TM images and shaded relief map. The Taikkyi fault is an active reserve fault with right lateral strike-slip component, as a result of basin inversion. It is a basin bounding fault of the Ayeyarwady Delta Basin. It is located at the west base of the Bago Yoma trending in NNW-SSE direction with 80 km length (Fig.46,47). The Central Basins of Myanmar are affected by a significant tectonic inversion during the late Miocene (Pivnik et al.,1999). This inversion is mainly marked by right lateral strike-slip faulting and thrusting or reserve faulting along the NW-SE trending faults affecting the basins in Central Myanmar Basin. The NNW-SSE trending (N140°) strike-slip faults are reactivated as thrust with

NE- or SW vergenc (Rangin et al.,1996-1999). The geological structure of Taikkyi area is underlain by alluvial deposits of Bago Yoma fan . The alluvial deposits can be found in the flood plains and they have the texture of gravel, clay, silts, sand and laterite , which lies upon the eroded surface of Irrawaddy formation and the hard compact sandstone and shale of Pegu series (Fig.48). From the geology point of view, it can be concerned for the initial review of faster displacement possibility in some area such as in the eastern part of the town where the top soil is clays.

Fig. 48. Topographic map, northeast of Taikkyi show the relationship of drainage to tectonics in the Bago Yoma mountains. Here most streams show significant change in direction with right-angular course where they cross resistant beds such as sandstones.

The Bago Yoma, about 660 km long and 60 km wide is dominated by N-S striking thrusts that verge to the east and a series of anticlines. 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

(Bender, 1983).The Bago Yoma is an anticlinorium that has formed between the Pegu fault in the west and the Sagaing fault in the east. 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, thrust faults and surface uplifts. The Bago Yoma is a broad, low ridge composed mainly of Miocene rocks and Pliocene sedimentary rocks and the largest push-up in Myanmar. Bago Yoma represents a group of anticlinal folds. The axis of the western BagoYoma anticline approaches Yangon and eastern fold extends to Thanlyin. 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 (Gorshkov, 1959). Crustal uplift and thrusting has 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 mountains by transpressional push-up and basin inversion in late Tertiary. Analysis of 2017 Taikkyi earthquake provides several new insights into Pegu Yoma mountain building.

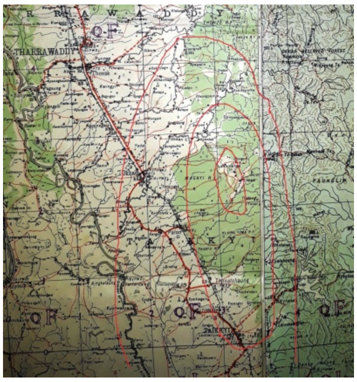


Fig.49. Isoseismal show three grades of the Modified Mercalli Intensity scale VI, VII, VIII,

Surface Deformation associated with the Taikkyi earthquake

At 8:49 06 p.m. on 13th March 2017, a moderate earthquake M 5.1 (USGS) occurred in Taikkyi. Its epicenter location is 33 km southeast of Thayarwady at 17.415°N and 95.999°E and focal depth is 10km (USGS). After that at 22:19:04 p.m. an aftershock of magnitude 4.7 followed the main shock on the same day. The earthquake spread a wide area including Thayarwaddi, Okkan in the north, TawLaTi, Aphauk in the west, Yangon in the South and surrounding area of west of Bago Yoma. We rushed toTaikkyi and to the mountain front of Bago Yoma at Lahamange Inn to search for a scarp and to get data for a thrust earthquake. Three day survey was made of the epicentral region after the earthquake and direct interview was made for the felt report. The region surveyed was found to have three grades of the Modified Mercalli Intensity scale : VI, VII, VIII, based on people’s perception, indoor effects, damaged buildings, and ground survey effect (Fig.49). The rupture is offset by a mile inferring that the rupture has involved too distinct parallel faults forming step-over at Lahamange Inn. A small number of simply constructed houses and aged buildings were collapsed. Upper portion of some pagodas are fallen down. Position of objects in monastery was shifted and brick fences are fallen down. Some portion of water pipe-line from Gyophyu Reservoir to Yangon has been uplifted and shifted. On the road which runs in NS direction that the rupture has cut, the two sides of the fault had been squeezed together by shortening. The pavement of the road while cracked remain mostly smooth. It is due to that the ground motion was strong enough to fling up the road as the fault rupture beneath it. The overall width all the pavement was reduced and shortened (Fig.50). People of Taikkyi strongly and distinctly felt the quake. Local people from Lhamange village Kinpadi village, Oakkan, Taikyi, Tawlati villages are interviewed for a felt report of ground deformation during Taikkyi earthquake. U Saw Hlaing from Okkan and U Thein Aye from Lahamange village explained that the main shock was very powerful and the villagers felt like that an elephant had hit their houses with great fury. He also told us that the water in a half-filled tank with 5-6-5 feet had splashed water several times during the quake. The Lahamange Inn may be taken as approximately the center of the most shaken area (MMI VIII). The Lahamange Inn (Inn means lake in Myanmar) is a rhomb-shaped tectonic depression or sag pond that formed at right-step segment of the Taikkyi fault. It is one mile wide and one mile long. The height of the fault scarp on the east- and northeast of the Inn is (3)m.   Intensity (MMI VII) was reached in the town Taikkyi where the shaking was severe.

Isoseimals followed the trace of the Taikyi fault in elongated pattern of NNW-SSE direction (Fig.47). Aftershock activity of the Taikky earthquake was distributed over much of Taikkyi area. The activity migrated southward to near Mhawbi.

Possible style of deformation

An earthquake also occurred near Taikkyi with magnitude 4.4 in 2006. Tops of Pagodas were knocked down, houses collapsed due to this earthquake at that time Intensity decreased southward and the general direction of motion appears to have been from ENE to WSW. Tops of pagodas were torn off and fell to the ground. Thrust movement along the preexisting detachment surface during basin inversion under compressional stresses could be the cause for seismicity in Taikkyi area. The NNW-SSE trending fault located in the east of Taikkyi, very closed to Kinpadi village, accommodates a mix of thrust and right-lateral motion. Such deformation style may be characteristics of rift-related environments under compressional stresses. In this tectonically active continental rift setting, the majority of strain is accommodated along border faults of the basins. These faults are easy to find when the individual earthquakes struck on each fault such as an earthquake of 2006 on Gwegyo earthquake on Gwegyo thrust, Taungdwingyi earthquake (2003), Aunglan earthquake (2007,2013), Taikkyi earthquake (2006,2017) and Yangon earthquake (1927, 1978). Focal mechanism solution of earthquakes and fault orientations give strong extension axis in an NNW-SSE direction and maximum compression axis direction in an E-W or

ENE- WSW. Depth distribution of earthquakes shows that the majority of earthquakes occur at depth from 0-40 km (CMT from Harvard and epicenters from ENGDAHL) (Rangin,1996-1999). The length of the fault is approximately 80 km which implies that it can potentially rupture in large earthquake.

Fig.50 (a). Slight damage to pagoda by the 2017 Taikkyi earthquake (b)Damage to the concrete road and (c) Gyophyu water pipeline by the rupture beneath the surface

The horizontal slip rate of CMB is 8mm / yr from GPS analysis (GIAC project), while coseismic horizontal slip during 2017 Taikkyi earthquake is at least 2 m, obtained from 10 rupture traces along water pipeline of Gyobyu Reservoir (Fig.48). The recurrent interval of 2017 earthquake would be 250 year. Coulomb failure stress changes for Taikkyi fault caused by the 2017 Taikkyi earthquake was calculated for status of stress. (personal comm.Chan,2017). The result shows that stress increased by several bars (0-0.10)unit bars to the north and to the south of Taikkyi earthquake rupture (Fig. 49). Such a stress increase on the order of a few bars is large enough to trigger failure on the nearby favorably oriented faults (Stein et al.,1992; Toda et al.,2005).

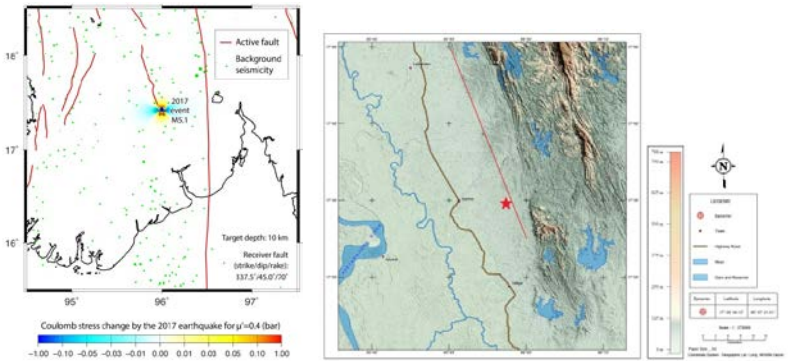


Fig.51. (a)Positive Coulomb Failure Stress change on the main fault

Conclusion

Geographically, Taikkyi is situated in central Myanmar. Tectonically, it is located in the Ayeyarwady Delta basin in the west of Sagaing fault. Structurally, the town is located very close to a major strand of the Sagaing fault in NW-SE direction, which bounds the Pyay basin. There are many en echelon folds in this region trending NNW_SSE. Seismically, Taikkyi falls in seismic zone III of Seismic Zones Map of Myanmar (Aung,2009).

Seismicity in the Central Myanmar Basin terrane which includes the Ayeyarwady Delta basin, Pyay basin, Salin basin, Chindwin basin and the Hukawn basin in the north. may be due to the severe crustal movement through the Basin-and-Uplift structure along the transfer zone for 1000km length. The intraplate stress field derived from combination of focal mechanism and fault orientations show a NNW-oriented extension and a ENE-striking compression. Intraplate stresses cause earthquakes on particular faults NNW-SSE direction so as intraplate seismicity of the Gwegyo earthquake (7.3.2016 M 4.7,estimated depth 15km), the Taungdwingyi earthquake (22.9.2003 M 6.8 D 10km), the Thayet-Aunglan Earthquake (3.4.2013 M 5.4 D 11km), the Taikkyi earthquake (13.3.2017 M 5.1 D 10km), and the Yangon earthquake (30.1.2013 M3.4 D10km) migrates within continental deformation zone. In this tectonically active continental rift setting, the majority of strain is accommodated along border faults of the basins. These faults are easy to find when the individual earthquakes struck on each fault. Possible mode of deformation is believed to be a combination of reverse faulting and strike-slip faulting due to basin inversion under compressional regime.

Acknowledgement

The author appreciates the concerning on the study from U Myint Zaw Than, Deputy Head of Water & Sanitation Department , Yangon City Development Committee and party. The author greatly acknowledges U Tin Hlaing and U Than Aye from Okkan for their valuable information about Taikkyi earthquake.

Concluding Remarks on seismicity of Myanmar

Myanmar region is highly seismic and it lies in the zone of the Alpine-Himalayan- Indonesia Seismic Belt. A detailed morphotectonic study using satellite image interpretation and observation of co-seismic surface deformation features were carried out to correlate the mode of deformation and characteristics of source area of the historical earthquakes. It is found that earthquake disasters are related to the seismic stress field and the small-scale geological structures at source area. Asia constitutes three broad active deformation zones: the Arabia-Eurasia convergence zone in the west, the India-Asia convergence zone in the central, and East-Southeast Asia convergence zone caused by the Indian, Sunda, Australian, Philippine Sea and Pacific subduction in the east. The most illustrative effect of India-Asia oblique convergence has been the formation of the Burma plate and post-collision northward movement of India plate is responsible for the active deformation and seismicity on the Burma plate. The structure in Shan Plateau which is western part of the Indochina plate shows the trace of regional compression during extrusion of the Indochina plate along the Red River Fault. The tectonic deformation in this area is continuously active, which is reflected by the frequent occurrence of earthquakes.

Consequently, active deformation and seismicity within Myanmar region is widespread and most large earthquakes occur at known active fault zones. A number of large events have struck Myanmar region during last century and recently, a M=6.8

event at Tarlay in Shan State on 24th March, 2011 and a M=6.8 event along the Sagaing fault zone on 11th November, 2012 occurred. The houses in most part of Myanmar are mainly of light timber construction and are practically earthquake proof.

Myanmar is undergoing active deformation at present and past for several millions of years. Seismicity in Myanmar suggests information on active deformation. Myanmar is a site of large earthquake as indicated by historical records and recent investigation. This book addresses two important aspects of the earthquakes in Myanmar: the style of surface deformation and mode of deformation reinterpreted from the earthquake history. It also indicate the existence of many fault segments within the seismic zones in Myanmar. Seismic activity provides information on the active deformation in Myanmar. Myanmar is part of a long active seismic belt extending from the Himalaya to Sunda trench. Recent studies and reinterpretation of historical and recent earthquakes suggest the possibility that seismic activity may be alternating between several fault segments within the seismic zones, although the overall deformation rate may remain constant. Shallow earthquakes (0-40km) predominantly occur on a combination of strike-slip and normal faults or on a combination of strike-slip and thrusting faults, including the Sagaing and Kyaukkyan faults and faults in eastern Shan plateau within Myanmar. Between 1929 and 1991, seven M7.0+ earthquakes occurred along the right-lateral Sagaing Fault, resulting in severe damage in Myanmar including the generation of landslides, liquefaction and the loss of many lives. Deep earthquakes (>200km) have also been known to occur in the northwestern part of Myanmar, these are thought to be due to the subduction of the northeastwards dipping of India plate along the Kabaw fault at the foothill of Naga-Chin Hill. The Burma plate has been experiencing a NNW-SSE extensional scheme in the Miocene and ENE-WSW compressive regime since Neogene. The Burma plate is composed of three tectonic terranes, each of which are significantly different in geologic history, stratigraphy, tectonic and paleontological indicators. Their boundaries between them are major active faults from west to east: the Kyunthayar Fault, Kabaw Fault and Sagaing Fault. The Kyunthayar Fault or the Kalatan fault is trending NNW - SSE and it has shear sense of lateral movement. Kabaw Fault is considered to a reverse or thrust fault but a later investigation show right lateral displacement. The Sagaing Fault is transform fault and transform plate boundary between the Burma plate and the Indochina plate. Eastern Myanmar is western part of the Indochina plate, composed of two tectonic terranes of the Shan Massif terrane and Than Lwin Belt. The boundary between them is the Loise-Loilen fault trending nearly N-S direction. Both of the terrane are experiencing NW-SE extensional scheme and NE-SW directed crustal shortening recently. Active deformation will be continuing to take place in Myanmar region from the result of reorganization of interplates between the India, Indochina and Eurasian plates. Myanmar is undergoing active deformation at present and past several millions of years. Seismicity in Myanmar suggests information on active deformation. Myanmar is a site of large earthquake as indicated by historical records and recent investigation. According to the historical records and location of recent earthquake epicenters, Kabaw fault, Sagaing fault, Kyaukyan fault and Loise-Loilen strike ‐ slip fault in Shan State are identified as major active faults. Some other fault related to the extensional deformation and compressive regime is also active faults in Myanmar. The present mode of deformation in Myanmar is predominantly strike-slip faulting associated with normal or thrust faulting. For seismic hazard assessment, understanding the ground shaking is essential. Study of large earthquakes indicate that the severity of earthquake shaking depends significantly on earthquake magnitude, the attenuation of seismic waves and the amplification of seismic waves due to the local geological structure.

Recently a series of successive earthquakes occurred in different parts of Myanmar since 2011until 2017 with magnitude 6.8. It indicates that Myanmar has entered a new active earthquake cycle. For creating society safe and secure from earthquake/tsunami hazards , Myanmar need more seismic station and GPS station than those already installed and cooperative support from foreign institution to carry out the active fault study and related research. To have safe society for the people of Myanmar and to mitigate the earthquake/tsunami hazards in this region, a continuous space-based geodetic survey is an absolute need to the nation.

Data and Resources

All data used in this book were obtained from published sources listed in the references and some from limited field investigations. Satellite images are provided by Ko Toe Win Thein.

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Biodata of the author

The author graduated with a Bachelor of Science in Geology in 1968 from the University of Yangon. She earned a M.Sc. in Geology from the same University. In addition to formal degree program , she attended a diploma course at International Institute for Geo-information Science and Earth Observation (ITC) in the Netherlands under the UNDP Fellowship program and was awarded Diploma in Advanced Cartography in 1975. She conducted lectures at Geology Department, University of Yangon from the year 1969 to 1993. She is currently a Patron and Senior Researcher of Myanmar Earthquake Committee, Myanmar Engineering Society and is working as a Senior Researcher since 2007. She attended several local workshops and academic conferences and seminars both in and outside the country. She has published more than thirty articles (Myanmar language) in journal such as TechDigest journal and magazine. She has also international publications on seismicity of Myanmar for Advances in Geosciences (World Scientific Publishing Co.Pte.Ltd.). She is the author of *Earthquake Education and Book for Preparedness* (in Myanmar language) and *Tectonic Style and Deformation Pattern of Terranes in Myanmar* (in English). She also wrote handbooks for geology students: *Handbook for Structural Geology Practicals, 1990 and Handbook for Stratigraphic Practicals, 2004.*

PROFESSIONAL AFFILIATION

1. Member of Myanmar Earthquake Committee, Myanmar Engineering Society
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ARTICLES IN MYANMAR LANGUAGE(in domestic journal www.mes.org.mm)

1 .Historical earthquakes of Myanmar Tech Digest Journal Vol. 2 No.9 2006

2. Historical earthquakes of Myanmar Tech Digest Journal Vol. 2 No.10 2006

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5. Earthquakes and the Sagaing Fault Tech Digest Journal Vol. 2 No. 15 2006

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ARTICLES IN ENGLISH (in domestic journal www.mes.org.mm)

1. The 2011 Tarlay Earthquake in Eastern Myanmar Vol.4 No.4 2012

2. The 1929 Swa earthquake (preprint under review)

3. The 1930 Bago earthquake in southern Myanmar (TechDigest Quarterly Magazine, vol.6/no.3, April, 2014))

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5. Other earthquakes that occurred along the Sagaing fault. (preprint)

6. The 1956 Sagaing earthquake in northern Myanmar (TechDigest Quarterly Magazine, vol.6/no.2,January, 2014))

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14. Tour Guide for Geo-tourist along the Sagaing fault Tech Digest Quarterly Magazine vol.6/no. October, 2014

ARTICLES IN NEWS PAPER: The New Light Of Myanmar

1. Mitigation of earthquake and education
2. Mitigation of earthquake and preparedness
3. Interview after the 2012 Thabeikkyin Earthquake

BOOKS IN MYANMAR LANGUAGE

1. Guide for Structural practical for geology students
2. Guide for Stratigraphic practical for geology students
3. Earthquake Education
4. Preparedness

BOOKS IN ENGLISH

1. Tectonic Style and Deformation Pattern of Terranes in Myanmar (Printed in Myanmar)
2. Myanmar Earthquakes History (Printed in Myanmar)

LIST OF INTERNATIONAL PUBLICATIONS

1. Earthquake Potential in Myanmar : Advances in Geosciences, vol.13 Solid Earth Section ,2009 ,pp.265-280, www.asiaoceania.org

2. Studies and Constant observations of Potential source areas for Future Earthquake in Myanmar, Proceedings of the International Symposium on Restoration Program from Giant Earthquakes and Tsunamis, Phuket, Thailand, pp123-133, 2008

3. Recognition of Paleo-Tethys suture zone in Eastern Myanmar : Acta Geoscientific Sinica, vol.30 supplement, pp.1-3, Sept.2009, www.cagsbulletin.com

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5. Seismicity in Central Myanmar Basin and Regional Tensional Stress, Advances in Geosciences vol. 26, Solid Earth Section, 2010 www.asiaoceania.org

6. Potential seismicity of Yangon Region, Advances in Geosciences,vol.26,SolidEarthSection,2010. www.asiaoceania.org

7. Reinterpretation of Historical Earthquakes for the period 1929-1931, Myanmar, Advances in Geosciences, vol.31,Solid Earth Section,2011. www.asiaoceania.org

8. The Tarlay Earthquake and Active Tectonics in Paleo-Tethys Suture Zone, Myanmar, Vol.33 Supp.1:4-6, Acta Geosciences Sinica, Oct.2012

9. Tectonic evolution of the Sagaing fault (under review) for SprigerOpen

10. Tectonic Geomorphology of the Sagaing fault (submitted to IGCP589,2014)

11. Delineation of the western boundary of Paleo-Tethys suture Zone in Myanmar, Vol.33 Supp.1:4-6, Acta Geosciences Sinica, Nov.2015

PAPER and POSTER PRESENTATION AT INTERNATIONAL CONFERENCES

Papers presented at International Conferences

1. 4th Asia Oceania Geo Sciences International Conference (AOGS2007), August,2007, Bangkok, Thailand Title of Presentation: Earthquake Potential in Myanmar (published), www.asiaoceania.org

2. 5thAsia Oceania Geo Sciences International Conference(AOGS2008), June, 2008,Busan, Korea Title of Presentation: Northward Translation of Crustal blocks indicated by Lateral sedimentary facies changes in Myanmar (Case study: Ayeyarwady Delta Basin), Abstract Volume, pp386

3. International Symposia on Geosciences Resources and Environments of Asia Terranes, GREAT2008, 4th IGCP 516 and 5th APSEG, November, 2008, Bangkok, Thailand Title of presentation: Reconstruction of Tectonic Terranes in Myanmar territory (Abstract Volume,pp)

4. 6th Asia Oceania Geo Sciences International Conference(AOGS2009), August, 2009, Singapore Titles of presentation: (a) Potential seismicity of Yangon Region (in press), Abstract Volume, pp 291 (b) Early Tertiary Collisional Event marked by Unique linear granitic belt of SE Asia (Abstract Volume, pp 290)

5. 5th International Symposium of IGCP 516, Geological Anatomy of East and East Asia: Paleogeography and Environment in Eastern Tethys, September, 2009,Kunming, China Title of Presentation: Recognition of Paleo-Tethys suture zone in Eastern Myanmar (published)

6. Poster Presentation for International Symposium on Giant Earthquakes and Tsunamis, January, 2008, Phuket, Thailand

7. 7thAsiaOceaniaGeoSciencesInternational Conference(AOGS2010), June, 2010 Hyderabad, India: Titles of Presentation (a) The Volcanic Occurrences in Relation to Tectonic, Myanmar, Abstract Volume, pp308 (b) Seismicity in Central Myanmar Basin and Regional Tensional Stress (in press), Abstract Volume, pp 308

8. 6th Symposium of the IGCP516, E & S Asia, 2010: International Geological Correlation Project 516 (IGCP516), Geological Anatomy of East and South Asia, 9-14 Nov.2010, Kuala Lumpur, Malaysia. Title of Presentation: Carboniferous-Permian sequences and fauna from Paleo-Tethys suture zone in Than Lwin Belt, Esatern Myanmar, Abstract Volume, pp47

9. 8th AsiaOceaniaGeoSciences International Conference (AOGS2011), August, 2011, Taipei, Taiwan. Title of Presentation: Reinterpretation of Historical Earthquakes for the years 1929-1931, Myanmar, www.asiaoceania.org

10. 33rd Asian Conference on Remote Sensing (ACRS2012), Nov.26-30,Pattaya, Thailand

11. Disaster Risk Reduction study to Japan, 2012. Title of Presentation: DRR Education in Universities of Myanmar

12. Joint Project Team Meeting (JAXA), Bangkok, Thailand, November, 2013. Title of Presentation: Hazard Profile in Myanmar

13. Asia-Pacific Disaster Management Expert Meeting, Daejeon, Korea, 30th-June-1st July, 2014, Title of Presentation: Hazard Profile of Myanmar

14. 1st MES-EIT Joint seminar on DAM TECHNOLOGIES, Chaophya-Park Hotel, BKK, 26 August, 2014. Title of Presentation: Tectonic Geomorphology of the Sagaing fault

15. 35th Asian Conference on Remote sensing (ACRS2014), Oct.27-31, Nay Pyi Daw, Myanmar

16. 2nd Joint Project Team Meeting for Sentinel Asia STEP-3 (JPTM2014), Nov.19-21, Yangon, Myanmar

Title of Presentation : Remote Sensing Application for Seismic Hazard Assessment in Myanmar

17. Seminar on Seismic Aspects of Dam Design organized by MNCOLD,18.1.2015: Title of Presentation-Coulomb failure stress change and b-value mapping in Bago-Phyu region

18. 12th AsiaOceaniaGeoSciences International Conference (AOGS2015), August, 2015, Singapore: Title of Presentation: The triggering on regional seismicity by Ms 7.3 5th May Pegu earthquake in Myanmar, www.asiaoceania.org

19. 5th Symposium of the IGCP589, E & S Asia, 2016: International Geological Correlation Project 589 (IGCP589), Geological Anatomy of East and South Asia, 9-14 Nov.2015, Bangkok, Thailand, Title of Presentation: Delineation of western boundary of Paleo-Tethys suture zone in Myanmar; Abstract Volume, pp47

20. Seminar on Workplace Safety Area (BuildTech2016), Yangon, Myanmar. Title of presentation: Hazard Profile of Myanmar

21. Joint Project Team Meeting (JAXA), Hanoi, Vietnam January, 2017. Title of Presentation: The 2016 Bagan earthquake in Myanmar

22. The 6th International workshop on Seismotectonics in Myanmar and Earthquake Risk Management (SMERM2017),5-6 July 2017, Yangon, Myanmar; Abstract Vol. pg.7

Title of presentation: A Continental Intraplate Earthquake, the Taikkyi Earthquake

ONGOING RESEARCH WORKS

1. The Kabaw fault and its sub-surface configuration
2. Continental intraplate earthquakes of Myanmar
3. The intraplate subduction zone earthquakes in Myanmar
4. Risk Assessment for Dam Construction

The author visiting the Great Wall in China