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AN INTEGRATED DESIGN FOR EARTHQUAKE ENERGY RELEASE AND FORECAST MODEL DEVELOPMENT

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ABSTRACT

The seismogenic behaviour observed by the recent strain energy release has been studied by dividing the region into in the six geo ت tectonic block in North-East India. It has been found that the Arakan ت Yoma to be seismically active followed by Naga Hills region. It also shown that the probability of occurring an earthquake is more in the Shillong Plateau than the other five tectonic blocks. For the region as a whole there is the probability that an earthquake of intensity is determined for unifyingپslip − dependent law determined from strain energy bearing capacity of the region. Moreover, it has also been found that if strain energy released by a tectonic block is large it might affect the stress building process in the rocks of adjacent tectonic blocks. The iso-strain release map depicted areas of high and low seismic activity. We also identified a zone of future earthquake activity in the Indo-Myanmar border based on the study and developed an integrated functional block diagrams as part of the study. The first part of block identified the observational scenario of earthquake activity using precursory activity while the second is a knowledge drive expert system to identify the root cause of earthquake activity in any geo-tectonic region.

INTRODUCTION

The sizes of earthquakes are measured using well-defined, measurable quantities such as seismic moment and released or transformed elastic energy. No simple calculative measures exist for analysis of the nature of nucleation and strain energy released in earthquakes and eruptions some promising avenues of research such as "remote triggering" of earthquakes and the newly discovered Episodic Tremor and Slip (ETS) that may lead to success in the future indicates robust areas of elevated strain rates where data coverage is strong. The proposed study is a novel method for the observation of seismicity rate changes magnitudes events that would be expected to occur depending on the recurrence time of the recent events based on the size analyzed by the seismic moment and the effect of the dynamic strains as the region shows increase in moment rate and seismic strain energy release rate as a nucleation locking has taken place and earthquake is likely to occur in the vicinity. The seismic moment and the elastic energy transformed during an earthquake are directly related to measureable parameters. For example, the seismic moment is related to the area of the fault rupture, the average displacement or slip during the rupture, and an elastic constant that provides quantitative measure for integrated earthquake warning methodology in the forecast model design. For earthquakes and eruptions, elastic energy derives from two sources: (1) the strain energy stored in the volcano/fault zone before rupture, and (2) the external applied load (force, pressure, stress, displacement) on the volcano/fault zone. Earthquake genesis is based on the it is constrained by scaling laws of rupture along fault planes, relating, length, seismogenic layer depth, stress drop and slip per event. secondly we need to identify the historical data based on the data set, time period and rise of earthquake correlation strain accumulation rates inferred from aftershocks , limited length of the fault and the maximum strain energy that can stored in the different types of rocks before reaching their failure points. Longer instantaneous fault ruptures release more energy in one shock and thus generate a larger earthquake of greater magnitude. Based on the study conducted in Dutta et al.(2012a), pressure increases with increasing depth from the surface affecting the strain energy release pattern for a tectonic earthquake on a fault where pore pressure is affected by compressive stress. Tectonic stresses produce an increase in the elastic energy stored by the rocks up to one limit defined by its strength. When this strength is exceeded a rupture is produced and an earthquake is triggered. So, there is one upper bound to the energy that can be stored, and so to the seismic moment magnitude, defined by the rock strength. The elastic energy that is transformed during earthquakes into other types of energy, partly seismic waves (kinetic energy) and heat, can be calculated using well-tested formulas from fracture mechanics including the Gutenberg تRichter Method. The most imminent method to determine the physical quantities related to the rupture for the size of the nucleation zone and the slip acceleration is found to be scale- dependant with the shear rupture energy whereby the square root of the energy ŁEب is proportional to the strain rebounded during an earthquake that generates the earthquake. The part of the elastic energy ŁEب is considered to be stored up during the earthquake preparation stage affecting causal nature of the residual strain release pattern. There is a well known relation between the Gutenberg ت Richter magnitude (M_s) and the seismic energy ŁEب which can be used for finding the relationship with moment magnitude (M_w):

$$\log E = 11.8 + 1.5 M_s \qquad (1)$$

We also know that $M_s = (M_W - 0.81)/0.92 = 1.087\, M_W - 0.88$, where the moment magnitude M_W is known. Then, it putting in equation 1 it is found that

$$\log Es = 11.8 + 1.5\,(1.087\, M_W - 0.88) = 11.8 + 1.63\, M_W - 1.32;$$

$$\log E_s^{0.5} = 0.815\, M_W + 5.24 \qquad (2)$$

where $E_s^{0.5}$ is the equivalent to the strain release due to the elastic forces during the preparation stage of the earthquake. Thus, finally we have:

$$E_s = 10(1.63\, M_w + 10.48) \qquad (3)$$

Once the derivation for the energy release is found in equation 2, we can estimate a linear relationship of the magnitude with rupture length (L_m) identification which has been established by (Kasahara, 1981) as shown in equation 3 to identify the affected source zone where the nucleation had taken place.

$$\text{Log } L_m = 3.2 + 0.5\, M_s \text{ (Kasahara, 1981)} \qquad (4)$$

$$\text{Log } L_m = 3.2 + 0.5(1.087\, M_W - 0.88)$$

$$\text{Log } L_m = 2.76 + 0.5435 M_w$$

$$L_m = 10(0.5435 M_w + 2.76) \qquad (5)$$

SEISMIC EVALUATION AND PREDICTION OF THE TECTONIC BEHAVIOR IN NORTH-EAST INDIA

The study region is North-East India and its adjoining region demarcated by latitude (22^0 N ت30^0N) and longitude (89^0 E ت98^0E). Northeastern India and its adjoining territories display tectonically distinct geological domains occurring in intimate spatial association. Rocks representing the entire span from archean to recent, occur in this very small region. Eocene (Disang) sediments of trench facies occur in juxtaposition with those of platform facies (Jaintia) of stable shelf condition; Neogene Siwalik fore-deep molasse in front of the Himalaya and Tipam molasse of Upper Assam basin in front of the Indo ت

Myanmaar mobile belt occur in close proximity and are separated by the Brahmaputra alluvium. The Shillong area is a part of a complex tectonic domain located between latitude 24 and 28ﺥN and longitude 89 and 97ﺥE belongs to northeast part of India bounded by Himalayan orogenic belt to the north, Indo-Myanmar Ranges to the east, crustal-scale Dauki fault to its south and the Yamuna-Brahmaputra lineament to the west. The complex tectonics of the Shillong basin and the causative rock source has been numerically modeled earlier by Chowdhury and Khan (2012) for finding tectonic stress distribution that occur as a consequence of the catastrophic failure in the rocks, which have undergone strain thereby resulting in faults. These forces produce space-time fluctuations of strain around many small to large faults in the Shillong plateau (Mishra, 2014) which occur in the upper crust. Some of the faults have been intermittently active and show recurrence of earthquakes.

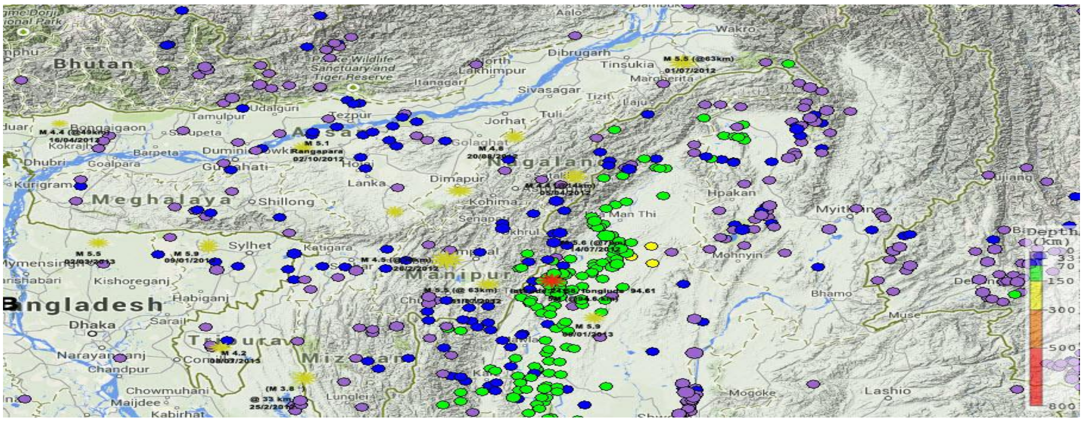


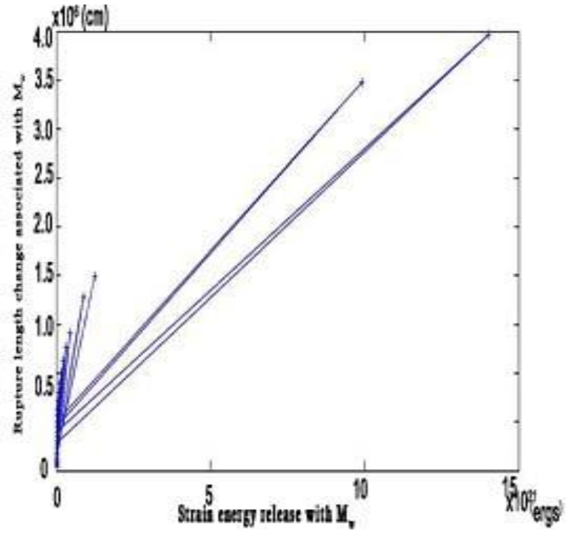
Figure 1. A seismic map showing the recent occurrence of earthquakes along with the depth of occurrence for the earthquakes in Shillong Plateau where yellow stars indicate stronger earthquakes as taken from IRIS Earthquake Browser (in reference), 2009-August, 2014(Dutta, 2014)

In the present study, we calculated the $E_s^{0.5}$ values for 5 years for the Shillong Plateau from 2009-2014 for the catalogue from IRIS comprising of more than 500 events over the five years taken from (11th July, 2009 to 16th August, 2014 for all events having Magnitude M≥3.6 within Latitude (22.51ﺥN-28.43ﺥN) and Longitude (87.77ﺥN to 99.37ﺥE). It has been observed in geological expeditions from 1936 in the Himalayas that in the north ـeastern part of India it has been observed that instead of the gradual subsidence of the alluvial plain, there is a longitudinal upheaval along the Siwalik Border. The anti-clinal warping illustrates that a tectonic movement in the recent stages has continued. The thrusting that occurs in the Himalayas is a type of thrusting from North to South or North-East to South-East The occurrence rate of intra-plate earthquake (Mw ≥ 4.2) with a shallow depth between (5 km -48 km) depth causing a wide-spread ground shaking, which has increased in recent time, 150 such occurrences has been noticed between 2012 and 2014 with the latest incident of M5.0 last recorded on 16th August, 2014 at the Manipur-Myanmar border at a depth of 96.5 kilometers in depth as shown in Figure1 in (star) red. The figure does not indicate that all accommodated strain has been released, so there may be a chance that larger earthquake may occur; when, where and magnitude is unknown. To statistically analyze the seismicity data, an earthquake catalogue was collected from the publically available catalogue maintained by the Incorporated Research Institutions for Seismology (IRIS) as shown in Figure1 for the Shillong plateau and the adjoining areas in order to identify the release of the stress patterns. We inferred that if the magnitudes of all earthquakes occurring in any fault system over a period are known then a plot of the fault displacement (strain) during that time period gives strain release characteristics and their corresponding rupture length behavior patterns. If we restrict our goal to finding an analytical expression capable of representing the traction evolution within the cohesive zone during the dynamic earthquake propagation, then a slip − dependent law is a candid solution for earthquake forecast. It is imperative to lead the scientific development for a holistic earthquake warning system for mitigating earthquake hazards based on a complete knowledge of earthquake nucleation processes and the strength of its rupture propagation in varied seismo-tectonic settings. In this case, a بuni fyingپslip − dependent law means that we only reproduce the traction evolution independently of the physical mechanisms that control the constitutive process. Slow earthquakes refer to fault slip episodes at seismogenic depth occurring with some accompanying seismic radiation in the normal frequency bands; silent earthquakes are not accompanied by seismic radiation in the normal frequency bands; the nature of creep events results from the complex fracture of the near-surface fault material at depths typically shallower than several hundred meters rather than fault failure at the seismogenic depths. We can also identify the maximum strain bearing capacity of the rock based on the exhaustion of the maximum accumulated strain caused by earthquakes. The problem with seismic pre-earthquake signals is that, in order to produce any reasonably detectable seismic signal, catastrophic ruptures have to take place in the crust (Wells and Coppersmith, 1994). The seismic moment depends on the average slip (displacement at rupture) and rupture area, as well as the driving shear stress (roughly stress drop) during the earthquake. The maximum rupture area relates to the strike dimension ('length') and dip dimension ('height' or 'width') of the rupture (slip) plane, and so does the slip. The maximum values of all these factors, and thus the moment, depend on the size of the seismogenic fault zone (or part of the zone) within which the earthquake occurs. For an earthquake to rupture the entire seismogenic fault zone, the local stress field in the entire zone must be everywhere favorable to that type of fault slip, that is, stress-homogenized. There are certainly limits to how large a rock body - seismogenic fault zone or part of it - can develop stresses (that, in turn, relate to the strain energy stored in the body, a part of the elastic energy) that are everywhere similar and generally favorable to a given type of slip at a particular time (the time of the earthquake). Thus the dimensions of the rock body/fault zone with favorable stresses for a particular earthquake at a particular time put limits on the maximum rupture area and slip and thus the moment (and the moment magnitude) of the earthquakes generated (Gudmundsson,2014). Due to the limited length of the fault and the maximum strain energy that can stored in the different types of rocks before reaching their failure points. But physically speaking, it is constrained by scaling laws of rupture along fault planes, relating, length, seismogenic layer depth, stress drop and slip per event. bypass this scaling laws if the right concatenation of asperity breakages add to a much larger event. Tectonic stresses produce an increase in the elastic energy stored by the rocks up to one limit defined by its strength. When this strength is exceeded a rupture is produced and an earthquake is triggered. So, there is one upper bound to the energy that can be stored, and so to the seismic moment magnitude, defined by the rock strength. A statistical analysis of the 2011 pre-Sikkim earthquake seismicity and with the post Sikkim Earthquake data to search for evidence of anomalous seismicity following the event, which shows that there is probable chance for the imminent large earthquake to occur in the future in Shillong plateau and adjoining Indo-Myanmar Border and the entire North-east region. The examination of seismicity rate changes as shown in Figure1 that reveals the fact that there is an increase of slope as shown in Figure2b compared to that of in Figure2a, indicating that a larger rupture length gets affected for the emission of strain release for pre and post-earthquake occurrence based on the M6.9 Sikkim, 2011. We also identified that temporal variation of the nucleation event for any thrust fault earthquake can establish a relation with crustal seismicity as Mogi (1985) as

$$\text{Log } t_a = 0.06 + M_p \qquad (6)$$

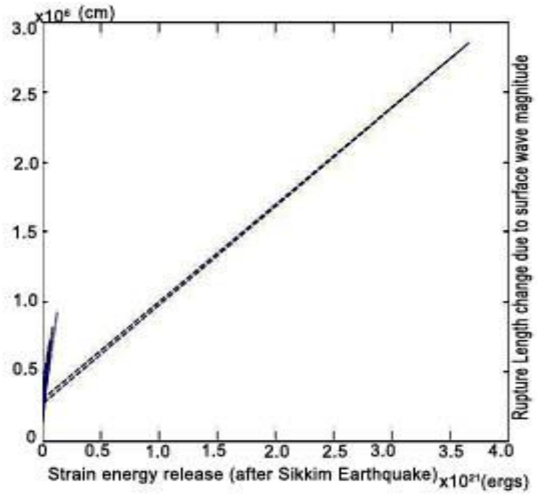
where t_a is the nucleation period and M_p is the magnitude of the preceding foreshock. As from Figure 2 and Figure3, it can be deduced that most of the earthquakes that occurred in the Shillong Plateau were بt riggeredپin the first place, and didnبt just occur by coincidence. A portion of the energy released by an earthquake altered the state of stress and induced damage in regions that surround the earthquake source. The Figure2(b) shows that the rupture length is increasing with the rise in seismic energy during the preparation of the earthquake by generating changes in stress in the aftershock zone and near-fields. The triggering of new earthquakes is the result from the change in state of stress. The failure of the rocks between the two lithospheric plates causes a drastic slip as a conversion between potential and kinetic energy. This energy is often viewed in the form of seismic waves as a way of mathematically representing the release in energy.

This analysis carried out in the present study provides a clear information on the issue of earthquake genesis, showing that the seismicity rate got increased after the 2011 Sikkim Earthquake (M 6.9) as evident from Figure 2(a, b) with greater rupture length for a smaller release of strain for the region. In order to draw a conclusion for determination whether a larger earthquake will occur in the near future, we have used isolines and we found that the region 27.4 - 28.1ؒخN and 88-90.2ؒخE along the Tsangpo Suture along the Eastern Himalaya and the region 22.4-23.1ؒخN and 95-96ؒخE in the Arakan تYoma are the plausible zone for future earthquake vulnerability where seismic activity may be followed by Naga Hills region in the Indo-Myanmar border region are the likely seismogenic zones that generated lot of strain energy in the past two years as shown in Figure 3 (a, b).



(a)

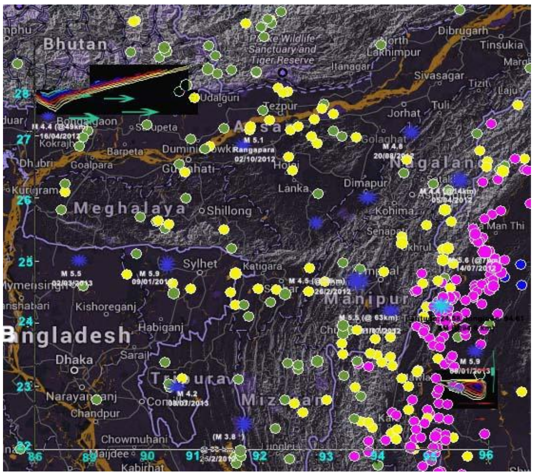
Figure 2. (a) Seismic release rate for energy affecting change in rupture length for the events in (2009-2011) in the Shillong Basin prior to the Sikkim Earthquake, 2011



(b)

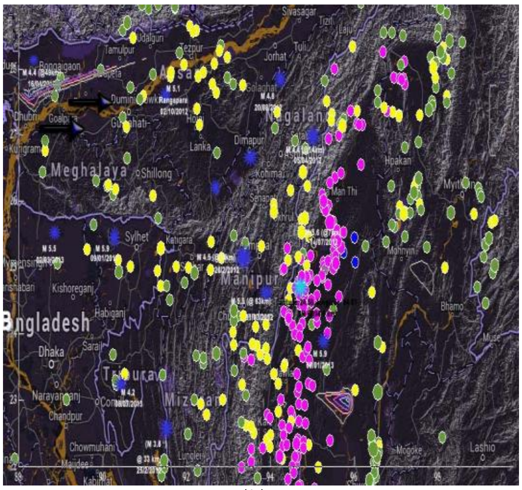
Figure 2. (b) Seismic release rate for energy affecting change in rupture length for the events in (2011-2014) in the Shillong Basin after the Sikkim Earthquake, 2011

It is intriguing to note that a new rupture is found to be opening up as shown in Figure 3(b) in the Shillong Plateau region and Brahmaputra Valley due to intense accumulation of strain energy and susceptible for release of strain as found based on the rupture length. Geological, geophysical, and geo-morphological trends and seismicity of Indo-Burma region (20ؒخ - 26ؒخN; 92ؒخت96 ؒخE) suggest existence of active subduction tectonics of the region. This area is a transition zone between the main Himalayan collision belt and the Indonesian arc where the Indian plate is currently subducting under Asia. The map shown by overlaying the isolines on top of the Earthquake map as in Figure 3(a-b) with data taken from the IRIS earthquake browser shows high strain energy released and a new rupture zone created at Central Myanmar Mollasse Basin along the Eastern Boundary thrust. This may be due to bending of the subducting Indian plate as well as external forces due to overriding Burmese plate in this zone. The seismic events of Indo تMyanmar region has deep focus due to subduction of the Indian Plate under the Myanmar Plate. The last big event in terms of size that occurred in the North-East region had been recorded on 11th November, 2012 was of M6.8 earthquake at a depth of 13.7 km located that had its epicenter at 23.01ؒخN and 95.89ؒخE in Myanmar and the latest event that occurred as on 16th August, 2014 was of M5.0 earthquake at a depth of 96.5 km with a latitude of 24.58ؒخN and 94.61ؒخE in the Indo-Myanmar border region. Based on this analysis we define the region of interest in the Shillong Plateau and Indo-Myanmar border for all 103 earthquakes M≥3.6 and shallow earthquake in nature that are found to have occurred till date through a time series plot. The time series plots calculated seismic moment for every an event that occurred from 11th November, 2012 to 16th August, 2014 for examining average moment release rate and strain energy release rate within a certain time frame. The time series expresses the date on the x-axis and the seismic moment on the y-axis. The plot that was generated shows the history of seismicity during the time span of the catalogue for identifying the distribution of seismic moment derived as an expression from moment magnitude and strain release energy is found as heterogeneous and that the source time function is quite complex. Since each event is a point without duration, there is no possibility to define a moment release rate for each individual event. To define the moment release rate, the moving time window is used to smooth out the time series and remove some of the noise related to the randomness of individual events. The seismic release rate an empirical variable U_r is calculated by the sum of the moments or strain energy release occurring within is time window divided by variable number of days in the window, ιLبwhich in our case is static and can be calculated based on Equation - 7.



(a)

Figure 3. (a) Identification of the Iso-strain energy (ergs) x 10^7release map of the study region with grid



(b)

Figure 3. (b)Identification of the rupture pattern iso-lines based on the strain release energy x10^7map with grid design

$$U_r = \frac{1}{L}\sum_{d}^{d+L} U_0 \qquad (7)$$

As we can calculate average of the moment and strain energy associated with the earthquakes within that time frame. The process is repeated for the next ﺑs tart dayپand is continued until the end of the time series plot. Then the averaging scheme restarts for a different time window size. The moment release rate and the strain energy release rate is plotted within the time series plot as a logarithmic value to show the average of the energy released from the earthquake source depending on the length of time as shown in Figure 4 and Figure 5 respectively. The moment rate variability over a period of two years has been found in the Figure 5 shown below. We identify the seismic rate to define the temporal variation for large earthquakes to occur in the close vicinity of the region. We identify the seismicity rate of all the Magnitude events in the region and we found on examination of seismicity rate drops along with the moment release rate especially during the period preceding the 29th January, M5.1 earthquake occurring at a depth of 61.5 km in 23.9ﺦN latitude and 93.96ﺦE longitude in Myanmar- India Border Region has undergone a tectonic mode shift with a drop followed by both an increase in moment rate and seismic strain energy release rate thus showing that a nucleation locking has taken place and a likely earthquake in the vicinity is underway in the near future. However the exact time period for the slip is impossible to define as the time period for the analysis of seismic moment is not same as that of the strain energy release rate. Based on this analysis we can say that although the total radiated energy cannot be measured, the average strain energy that causes a rupture is a very important aspect that needs to be treated in the future to find a relationship between seismic moment and magnitude, and the relationship between strain energy and seismic moment for that particular earthquake prone-region to identify the depth varying rupture properties as done in (Lay et al., 2012). The cumulative histogram is an important tool in this aspect to find the distribution of moment release rate during the two years from 2012-2014 as shown in Figure 5. In the present set of data we found that data are heavily skewed towards the larger moment release rates probably showing that the earthquake basins are clustered by nature and are not spatially clearly that the moment release rates distributed but rather occur along seismically concentrated zones. The moving window analysis time series can also be used for the temporal evolution of the state of stress distribution in time as shown in Figure 5 by analyzing the strain energy seismic energy E_s released by earthquakes applied to a time series leads to the extrapolation in the future by means of the correlations between known values for the past and those for the future.

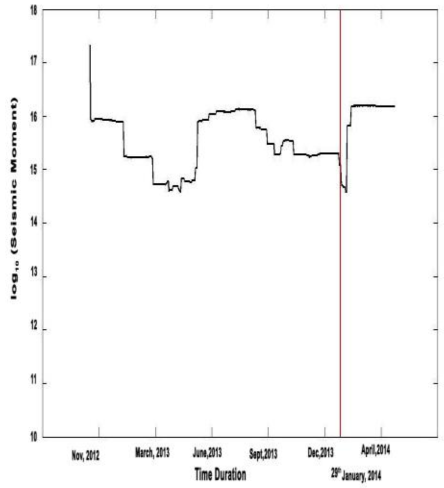


Figure 4. Seismic Moments and window moving averages in two year duration from November, 2012-August, 2014 for all events of M3.6 or greater in Shillong Basin and the Indo-Myanmar Region. The red line denotes the M5.1 event in Indo-Myanmar border region with highly variability observed in the average seismic moment

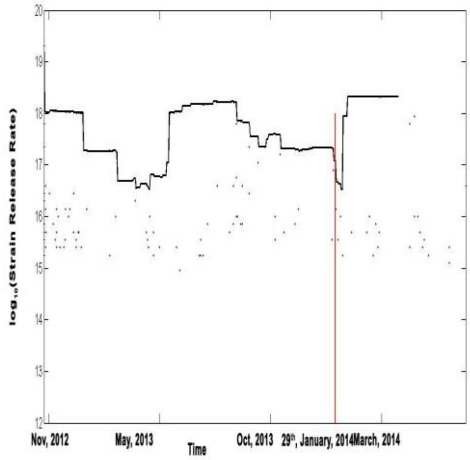


Figure 5. Strain energy release and window moving averages in two year duration from November, 2012-August, 2014 for all events of M3.6 or greater in Shillong Basin and the Indo-Myanmar Region. The M5.1 event in Indo-Myanmar border region with highly variability observed in the average strain energy relevance

However the exact time period for the slip is impossible to define as the time period for the analysis of seismic moment is not same as that of the strain energy release rate. The post- 5.1 January 29th, 2014 earthquake clearly shows that the moment release rate increases in small steps throughout and then increases by a large value every 50 days or so. After every 50 days, the moment release rate again increases progressively. This shows that the Shillong area is in all likelihood to be a highly pro-active seismic region. It has also been identified in Figure 3(b) that the neighborhood of the of 23.9°N latitude and 93.96°E longitude in Myanmar- India Border Region has suffered a rupture along different directions. So identification of the future seismogenic zone extends towards the Myanmar or the Naga Hills.

The flow diagram through an integrated earthquake model has been designed and has been shown in **Figure 6** as given in the figure provided below.

CONCLUSION

Firstly, it can be inferred from the study of strain release pattern of the six tectonic blocks of the study region that, Eastern side of the region consisting of the Naga Hills and Arakan – Yoma block is seismically more active than the other regions.

Secondly,the occurrence rate of intra-plate earthquake (Mw ≥ 4.2) with a shallow depth between (5 km -48 km) depth causing a wide-spread ground shaking, which has increased in recent time, 150 such occurrences has been noticed between 2012 and 2014 with the latest incident of M5.0 last recorded on 16th August, 2014 at the Manipur-Myanmar border at a depth of 96.5 kilometers

Thirdly,it has been observed that the strain energy bearing capacity of the rocks of the Arakan – Yoma region is high as compared to other regions. Moreover, in the Shillong Plateau amount of strain energy due is comparable with the estimated strain bearing capacity of the rocks of the region. Hence the probability of occurrence of earthquake in that region in the near future is greater than the other regions. It is also seen that there is some effect of release of energy by a tectonic block on nearby blocks when earthquakes of magnitude greater than 6.0mb occur.

Fourthly, from the iso-strain release map, the crustal structure of the study region and also areas of different seismic activity could be identified. The present study has great significance as a number of devastating earthquakes have occurred in this region. Again, knowledge of the size of the most probable earthquake occur in the region as shown in Figure 6 will help the structural and architectural engineers while designing buildings.

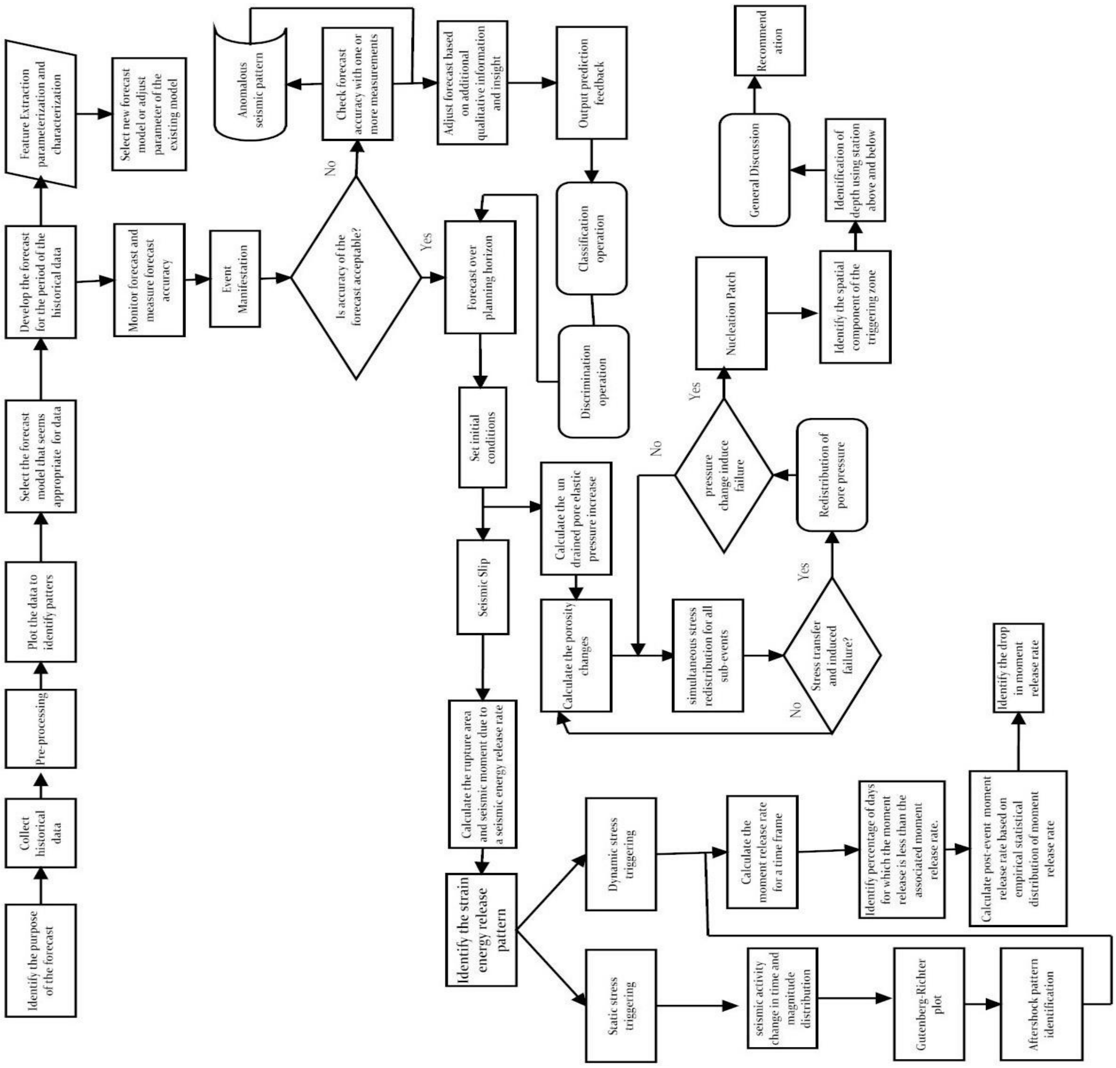


Figure 6: An Integrated model for earthquake genesis pattern analysis (Dutta, 2014)

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