Earthquake – Landslide - Flood nexus at the lower reaches of Yigong Tsangpo, Tibet: Remote control for catastrophic flood in Siang, Arunachal Pradesh and Upper Assam, India.

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Abstract

Unlike rain driven monsoonal floods in the upper reaches of Brahmaputra River, out of turn flood from breach of barrier landslide dam at the lower reaches of Yigong Tsangpo, upstream Siang River occurred in early June 2000. On 11 June 2000 catastrophic flood discharge passed through Pasighat where Siang debouches to the upper Assam plains in India. The landslide dam blocked the Yigong River on April 9, 2000 after a huge rock-debris avalanche slide down the Zemu creek to form a fan covering 2.5km of the Yigong River. The slide site has a protracted history of failure since 1900 when the Yigong Lake was first formed; recurrent block and breach of barrier dam followed by flood occurred several times and the lake-reservoir remained as a permanent feature. Seismotectonic analysis around the site indicates that preparatory phase activity within the slide debris was initiated in 1997 - 1998, which was triggered by earthquakes and the main avalanche of 9 April 2000 was also preceded by two earthquakes on the same day that might have been the immediate cause of triggering the landslide. The landslide dam site locates at the junction of two active strike slip faults accompanied with earthquake cluster that also include seismic swarm pulses during monsoon at regular interval, sufficient to destabilize the debris apron over steep rocky slopes. High stress in the region manifests through somewhat anomalous seismic activity including reservoir triggered swarms that have cascading effect through a complex interaction of earthquake, landslide and downstream flood.

1. Introduction:

Upper Assam is visited by damaging flood from River Brahmaputra with annual recurrence. The region experiences catastrophic flood almost once in ~4-5 years. Upstream of the town Dibrugarh three major rivers Siang, Dibang and Lohit join to form the mighty River Brahmaputra. The catchment area drained towards contributing to the River Siang up to its confluence with Dibang and Lohit is of the order of 2, 51,521 sq km of which 2, 36, 556 sq km area lies within Tibet. In comparison with Siang, the catchment areas of other two rivers are small; catchment area for Dibang is of the order of 12, 015 sq km up to its confluence with River Lohit, and the catchment area for River Lohit is of the order of 29, 487 sq km of which around 15, 034 sq km are estimated to be within Tibet, rest is from India. Thus, major contribution of flood discharge for River Brahmaputra up to Dibrugarh is primarily the River Siang. This river debouches to the plains of Upper Assam at Pasighat. Available data on high flood discharge at Pasighat indicate passage of high run-off in the years: 1950 (24, 514 cumec); 1954 (29, 372 cumec); 1962 (29, 643 cumec); 1981 (32, 813 cumec); 1984 (28, 113 cumec); 1987 (30, 171 cumec); 1991 (23, 280 cumec, at Rottung); 1994 (27, 412 cumec) etc.

Similar intensity discharges were also recorded in years 1988 and 1998; on 4 September 1998 the highest flood level recorded at Dibrugarh was 2.17m higher (at 106.41m) than the danger level (104.24m) [alternate record suggest highest flood level of 106.48m on 22 September 1998]. Is it only the hydro-meteorological setting in the catchment responsible for high floods through River Siang or there are other reasons?

Unlike the peak monsoonal floods resulting from heavy rainfall in the catchment, on June 11, 2000 extraordinary flood passed through Pasighat; available data indicate that the water level began to rise at 12:00 hrs on June 11 and peak discharge of ~44,200 cumec passed through Pasighat at 17:00 hrs; the maximum rise measured at Pasighat stage was 4.5m (Evans and Delaney, 2011). It is to be noted that this catastrophic flood discharge occurred prior to the usual annual monsoon (end June - October) discharge, and is due to a landslide dam breach on the River Yigong (also referred as Yi'ong, Yigrong) Zangbo (also referred as Tsangpo) that was initiated on 10 June, 21:00 hrs; at Pasighat Siang flowed 1.5 to 2.0m above danger level on 12 - 13 June 2000. Apart from extensive damage (bank erosion, submergence etc.) and some casualties recorded from upper Assam along the Brahmaputra plains, unconfirmed reports from the Siang catchment in Arunachal Pradesh indicated that 15 - 30 people died being washed away; 3000 - 5000 families heavily affected including rendered homeless and at least one bridge washed away. In the upper reaches of Siang River within Tibet, flood destroyed 5 highway bridges downstream from Tongmai (17 km downstream of the rockslide dam) and channel erosion destroyed a number of sections of the Sichuan - Tibet highway (Evans and Delaney, 2011).

Our prime objective in this communication is to present (i) succinct summary on nature of the rock-debris slide that occurred on 9 April 2000 in the lower reaches of Yigong River that dammed the river to form a huge lake and that subsequently breached on 10 June 2000 which generated catastrophic flood downstream in Siang River flowing through Arunachal Pradesh and (ii) seismicity pattern and seismotectonics of the region covering latitudes 29°- 31°N and longitudes 93.5°-96°E to probe into any possible causal relationship between earthquake and landslide. It may be noted that motive for this study initiated from the fact that two earthquakes occurred in the vicinity of the rock slide that blocked the Yigong River on 9 April 2000, the same day when the slide took place, and for the fact that the region is known for occurrence of anomalous earthquakes (Tatham et al., 1976) during 1968-69.

2. Landslide Dam and Lake:

The Yigong Tsangpo flows east-southeast for most of its length before trending slightly southwards from Lake Yigong for its final stretch before joining the Parlung Tsangpo near Tongmai to form the Po Tsangpo which flows southwest and then southeast to join the river Yarlung Tsangpo coming from south. The combined river flows southeast and then southwest across the Eastern Syntaxial bend of Himalaya to enter India at Gelling, where from it is known as Siang River. Distance from Yigong Lake to Pasighat at the Himalayan foothills is about 460 km (figure 1a).

On 9 April 2000 during the evening time a gigantic rock slide came down along the Zemu (Zhamu or Zamu) Creek, a small tributary of the Yigong River (figure 2c). The rock slide transformed into a super high- speed debris avalanche carrying deposits within the creek from previous slides, and blocked the Yigong River as a landslide dam (Xu et al., 2012). The debris fan at the base of the Zemu Creek constituting the landslide dam (figures 1b, c) was about 2.5 - 2.8 km in length along the thalweg of the Yigong River and was 90m high at its tallest edge (average 60-80 high); volume of debris material constituting the dam was of the order of 105 million m^3 (Evans and Delaney, 2011). The area of the lake and volume of water increased each day till it breached on 10 of June 2000, from 15 km^2 on 14 April (day 5 after blockade) to 37 km^2 on May 9 (day 30) and around 70 km^2 on 7 June (day 59); depth of water at the upstream toe of the dam was ~ 49m on that day (Zhou et al, 2001; Evans and Delaney, 2011). Though water started discharging through an excavated spill channel from June 8, water level kept on rising and by the evening of June 10 water column reached ~ 62m when the impounded water volume was about 3 billion m^3; soon the dam breached causing abrupt rise in water level downstream to about 41.77m at Tongmai Bridge, 17 km below the dam (Xu et al., 2012). A maximum instantaneous discharge of 1,20,000 cumec was reported from this site.

Available records indicate that rock - debris slide along the Zemu creek is a site of recurrent failure to block the Yigong River (figure 2). During July-August 1900, mass movement along the Zemu creek created a 60-80m high dam to block the Yigong River that initiated the barrier lake behind the dam. The impounded lake was of the order of 52 km^2 and while the dam breached after a month, it released enormous volume of water ~ 2.7 billion m^3 flooding downstream region. Since then debris flow of lesser magnitude was almost an annual feature at the site with occasional heavy influx through rock-debris avalanche forming fan deposit at the base of Zemu creek to block Yigong River. During 1940-1960 large scale slide occurred several times to repeatedly block the river thus forming a permanent barrier lake at the site (Xu et al., 2012; Evans and Delaney, 2011). In fact since the recorded 1900 landslide blockade, Yigong lake remained as a permanent reservoir (see figure 2) due constriction of the outlet through recurrent debris fall and during every monsoon it stored significant volume of water. Confirmation for the existence of natural lake along the Yigong Tsangpo comes from the travelogue of Nakamura (2006) who not only photographed the lake in October 2005 (figure 3b), but also narrates from the travel accounts of Bailey and Morshead who in 1913 recorded the origin of the lake and also *'crossed the lake by a ferry at the eastern end from the north bank to the south on 3 July then returned to Tangmai'*. Nakamura (2006) further states that Kingdom- Ward visited the site in 1935 and *'he was the first foreigner to complete the entire trek from Lake Yi'ong to Niwu'*. Since the formation of the lake - reservoir in the year 1900 in spite of several breaches during the next hundred years, it remained as a natural lake (figure 3) and even after the mega breach of 2000 the reservoir was not completely emptied and water level kept on rising during subsequent monsoon. Tibetan tour website (January 2013) states that the length of Yigong lake is 17km, average width is 1.3km and largest depth of water is 25m; further the area of the water surface is estimated to be of the order of 20 sq km but the lake region is ~13, 534 sq km. Dimension of the lake can also be assessed from recent publications (see figure 3a of Korup and Montgomery, 2008). Study of maps, imageries (figures 2 and 3) and available data indicate that annual fluctuation of water level in the lake could be to the tune of 5 to 10m and volume of water from 500 to 1000 Mm^3.

As discussed below we note convincing spatial association of recurrent seismic swarm with the lake - landslide and also temporal causal relationship between earthquake and the 2000 rock - debris avalanche.

3. Earthquake Cluster:

A seismotectonic map (figure 4) of the region (29°N - 31°N: 93.5° - 96°E) surrounding the landslide barrier dam (location: 30.20°N: 94.97°E - Xu et al, 2012; 30.18°N: 94.94°E - Evans and Delaney, 2011) shows the tectonic set up of the area (compiled after, Mukhopadhyay et al., 2011; Xu et al., 2012) with earthquake data for the period 1964 to 11.07.2011 from reviewed ISC Bulletin and elevation data after Smith and Sandwell (1997). Two major strike slip faults traverse the area and the landslide barrier dam happens to locate close to the intersection of the faults viz, the WNW- ESE right lateral Jiali fault following the Yigong-Parlung Rivers and the Yigong- Lulang strike slip fault which is almost perpendicular to the former. A NNE-SSW section (figure 5) across the earthquake cluster clearly shows that seismicity is associated with the activity of the steeply dipping Jiali fault.

The most striking feature in the map (figure 4) is the presence of a seismic cluster in close proximity to the landslide dam and the Yigong Lake. Detail appraisal of earthquake catalogue from the region reveals at least ten temporal clusters embedded within this spatial cluster and significantly all of them are seismic swarms, details of which are given (table 1) and discussed separately. Other than seismic swarms, the cluster (figure 4) also contains several independent events; a few such independent earthquakes that occurred since 1996 till and after the 9 April 2000, the day on which the rock avalanche blocked the Yigong River is listed (table 2).

It is significant to note that two shallow foci earthquake events of magnitudes (Ms) 4.9 occurred on 9 April 2000, a few hours before the rock - debris avalanche start moving along the Zemu creek. Further, available accounts (Xu et al., 2012) indicate that abnormal phenomena occurred along the Zemu creek by mid 1998 involving sound of collapse that continued till the final collapse and avalanche of April 9, 2000. Spatial and temporal association of earthquakes (table 2) with the landslide clearly indicates that recurrent earthquake in the vicinity ultimately triggered the mega landslide.

As has already been stated that the Yigong dam and the barrier lake first formed in 1900 and during the next hundred years several times fresh blockade and subsequent breach took place which in turn generated severe floods downstream including that passed through Arunachal Pradesh via Siang River. Paucity of temporal data on formation of landslide dam and their subsequent breach to generate out of turn floods along the Yigong - Siang River do not permit us to constrain causal relation with earthquakes for the pre - 2000 events; nevertheless intelligent perusal of the earthquake catalogue gives clue for earthquake - landslide - flood nexus during the 20th century. Our contention is that within a relatively small area surrounding the Yigong Lake small to medium magnitude earthquakes occur at regular interval both as solo and swarm that de-stabilizes the glaciated vulnerable slope to generate mass movement and eventually blocking the Yigong River. Reference is drawn to the earthquake of 21.11.1938 (Ms 6.0, h 35 km; location 30°N: 95°E) that could have triggered fresh landslide to block Yigong and subsequently flooding downstream in the 1940s (see Xu et al., 2012). Similarly within 24 - 30 July 1962, four earthquakes (magnitude ~ 4.0) occurred in the vicinity of the Yigong lake- dam site that might have triggered fresh landslide and subsequent breach to account for another spell of high discharge (see figure 2 of Phukan, 2005) through Siang River, recorded from Pasighat. Further, we have already mentioned on the incidence of high flood discharge in 1988 and on January 25 a moderate magnitude (mb 5.4, h 36 km) earthquake (30.16 N:94.87E) occurred close to the landslide blockade site, that possibly triggered a fresh earthquake-landslide-flood cycle.

4. Earthquake Swarm:

Irrespective of the phenomena of landslide dam breach and flood originating from a sepcific locality at the lower reaches of Yigong Tsangpo, the site drew attention of seismologists in early seventies due to the occurrence of an anomalous earthquake swarm during 1968 (see table 1; figure 6a) that behaved more like explosion rather than normal earthquake (see Tatham et al, 1976 and references therein; Blandford, 1977). Ms:mb discriminant function, which was considered as an effective tool for distinguishing natural earthquakes from underground explosions, categorized the 1968 swarm as explosions (red dots in figure 7) in spite of the fact that clear dilations were observed as initial P-wave motions for several events in the swarm. Similar to explosion, these earthquakes generate more high frequency radiation (more near field shaking) resulting higher mb values compared to Ms, which for natural earthquakes should be the opposite as long-period shear wave amplitude emitted by earthquake is ~ 6 times the compressional wave amplitude (Blandford, 1977). Similar to the 1968 swarm cluster located over the Yigong Lake, a number of swarms (see discussion below) occur at the same site. Ms vs mb plot for 38 events including those from Tatham et al (1976) for the 1968 swarm (figure 7) indicate that 15 belong to type I (clear earthquake population), 4 within type II (between explosion and earthquake) and the remaining belong to explosion type III. Magnitude ranges of earthquakes (figure 8a) indicate they belong to low magnitude swarm events and focal depth distribution (figure 8b) points to their shallow upper crustal origin considering the crustal thickness at the site around 70km. Nevertheless in spite of its anomalous nature, the swarm events were considered as natural earthquakes and it was concluded (Tatham et al, 1976) that the swarm events occur under conditions of both high apparent stress and high stress gradients and possibly associated with the end of a propagating crack; high stress gradients such as those associated with injection of magma into fissures, could also possibly be responsible for generation of swarm. Seven out of nine swarms for which b-value could be calculated using equation of Aki (1965) show low values (table 1) within the seismogenic source volume that correlate with increasing effective stress level prior to another burst of swarm or a major shock. Composite (142 events) b-value from swarm cluster and other independent events around the cluster gives a low value of 0.689 ± 0.057 that further attest to the very high stress level in the region.

Subsequent to the above stated studies on the 1968 (June- September) swarm a number of swarms originated from the same epicentral region which are listed (table 1) and separately plotted (figure 6). The next swarm of July - August 1977 (figure 6b) with 17 earthquakes was followed by a small swarm of 4 events (figure 6c) during June – August 1979 and a strong swarm of 19 earthquakes during August - September 1980 (figure 6d). It may be noted that all these swarm activities occurred within the monsoon period over a small source volume around the Yigong lake and could possibly trigger debris slide to block and breach, generating higher than normal discharge at Pasighat during 1980-1981. Swarm 5 (figure 6e) started in October 1981, continued till December 1981 (with 8 events) and reappeared in April - May 1982 with one event each. This was the first non-monsoon cluster swarm but locates in the opposite quadrant defined by the two strike slip faults. Two events from this swarm also registered slightly higher magnitudes 5.0 and 5.1. There is however no data to confirm or reject whether fresh slide took place during this period. The next swarm of July 1985 (figure 6f) with 8 earthquakes again a monsoonal swarm returns to the Yigong lake site. Swarm 7 (figure 6g) struck in two phases; 4 events during October 1986 and another 5 earthquakes in September 1987. One event from the 1987 cluster was of magnitude 5.0 and here we are inclined to consider fresh slide blocking of Yigong, its subsequent breach to account for higher flood discharge (> 30k cumec) through Pasighat in 1987. The next swarm of July 1991 with 11 events located over the Yigong Lake (figure 6h) triggered the same mischief resulting higher than normal monsoonal discharge through Pasighat. Subsequent swarm of July- November 1995 was a smaller swarm of 7 earthquakes (figure 6i) but the site was struck by independent events (see table 2) that culminated through the mega event of 2000. For the next ten years no swarm activity have been noted from the Yigong Lake site till the strong swarm reappeared at the same cluster location during July- December 2010 with 15 earthquakes. It is intriguing to note that nine out of ten swarm cluster (1981-1982 swarm in the opposite quadrant) located over the Yigong Lake since 1968 all struck during the monsoon period (see figure 8c) and this spatial correlation cannot be mere coincidental and overlooked. As already stated the Yigong Lake behaves like a permanent natural reservoir similar to man- made filling behind dams and during the monsoon it accumulates sufficient volume of water. During exceptional rainfall years in the upper reaches of Yigong Tsangpo, reservoir level increases sufficiently within a short span of time; water percolates through the Jiali fault resulting reservoir triggered earthquake swarm intermittently over the Yigong Lake during the monsoon. The infiltration of surface water within dilated seismogenic fault (Jiali fault) initiates an enhanced pore pressure front by fluid-diffusion mechanism. Generally, an increase in pore pressure front may cause the fault to slip and produce earthquakes (see Rajendran and Harish, 2000; Sibson, 2002 for details). Furthermore, the situation is aggravated by chemical weakening of fault zone by flow of aqueous fluid to enhance crystal plasticity and hydrolytic weakening of silicates (see Hickman et al., 1995).

We believe that in the region where stress is exceptionally high many of this high frequency radiating swarm earthquakes occurred since 1968 episode and triggered repeated landslides in this relatively small region. The landslides had repeatedly dam the Yigong Tsangpo and subsequent breach of which resulted downstream flash flood. Future monitoring of flood discharge upstream of Siyom- Siang junction within the Siang River and keeping note of earthquake incidence within the area under discussion will enable us to pinpoint the earthquake- landslide- flood natural nexus.

5. Discussion and Conclusion:

High rainfall (~ 10 cm during July-August) in the catchment areas of Siang, Dibang and Lohit Rivers within northeast Himalaya - Mishmi Hills and adjacent Tibet contributes to severe and sometimes catastrophic floods in Brahmaputra. With the largest catchment of Siang, major contribution to flood discharge in Brahmaputra in its upper reaches is through Siang and its Tibetan contributories like the Yigong Tsangpo. Extreme climate, complex tectonic set up and topographic architecture makes the region very fragile subject to failure even with subtle changes in endogenic and/ or exogenic conditions. Other than monsoonal floods the three tributaries of Brahmaputra, particularly the Siang River has witnessed different type of flood through catastrophic collapse of barrier dam that blocked the Yigong River several times during the period 1900 to 2000. Seismotectonic appraisal of the region clearly indicate the presence of active faults that frequently generates earthquake swarms and in turn triggers slope failure to block the mighty river. Subsequent sudden failure of such dam creates extreme flood downstream; such a situation on 11 - 13 June 2000 witnessed strong flood discharge in Siang at Pasighat and downstream. The region surrounding the Yigong lake and barrier dam is under high tectonic stress condition and is characterized by recurrent earthquake swarm activity. The natural reservoir-lake is a permanent feature that raises it water level during monsoon and there is positive indication for a monsoonal bias for the swarm activity. The role of fluids in triggering earthquakes are widely documented from man-made reservoirs (see among others Hariri et al 2010; Kumar et al 2012) and the same cause- effect relation can be attributed for the Yigong lake recurrent earthquake swarm. As Jiali fault (also known as Po Chu fault) is an active right lateral strike slip fault triggering both tectonic and reservoir triggered earthquake swarms it could generate large magnitude earthquake at the site under study in which case apart from strong seismic shaking super high discharge flash flood could also damage Arunachal Pradesh and upper Assam. We thus establish a complex earthquake – landslide - flood nexus in the region and suggest constant monitoring of both seismological and hydrological parameters within the Siang drainage basin in Arunachal Pradesh.

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Table 1

Characteristics of the 10 temporal earthquake swarm

Swarm No.	Duration of Swarm	Number of events	Magnitude (mb) range	Depth (Km) range	b-value (Likelihood Method)
1	28.06.1968 - 11.09.1968	20	4.0 - 4.9	0 - 70	0.59
2	21.07.1977 - 28.08.1977	17	4.3 - 4.9	10 - 62	0.99
3	26.06.1979 - 12.08.1979	4	4.6 - 4.8	27 - 54	-
4	07.08.1980 - 24.09.1980	19	4.2 - 4.9	15 - 57	0.94
5	03.10.1981 - 02.05.1982	10	4.0 - 5.1	7 - 47	0.89
6	18.07.1985 - 27.07.1985	8	4.2 - 4.8	6 - 35	1.12
7	10.10.1986 - 23.09.1987	9	3.8 - 5.0	4 - 33	0.61
8	18.07.1991 - 30.07.1991	11	4.3 - 4.9	6 - 34	1.37
9	04.07.1995 - 19.11.1995	7	3.7 - 4.8	1 - 33	0.69
10	27.07.2010 - 08.12.2010	15	3.5 - 4.8	10 - 48	0.65

Table 2

Earthquake Events within and around Seismic Cluster Prior to 2000 Landslide Dam

Source	Year	Mnth	Day	Hr	Mn	Sec	LAT	LONG	mb	Nsta	Ms	Nsta	Depth (Km)
ISC	1996	5	1	14	15	58.5	29.87	94.87	3.9	14			57
ISC	1996	10	27	1	54	12.6	30.10	94.99	4.3	28			53
ISC	1997	7	10	13	59	52.4	29.82	94.95	4.7	45	4.5	5	15
ISC	1998	8	29	19	52	27.5	30.30	94.74	3.7	9			22
ISC	2000	4	9	11	59	53.2	30.23	94.98	3.7	8	4.9	2	1
ISC	2000	4	9	12	0	8.8	30.19	95.00	4.1	15	4.9	1	18
ISC	2000	7	22	13	49	32.0	30.07	94.59	4.0	3			33
ISC	2001	3	16	4	38	16.4	30.32	94.80	4.8	39	4.3	3	7

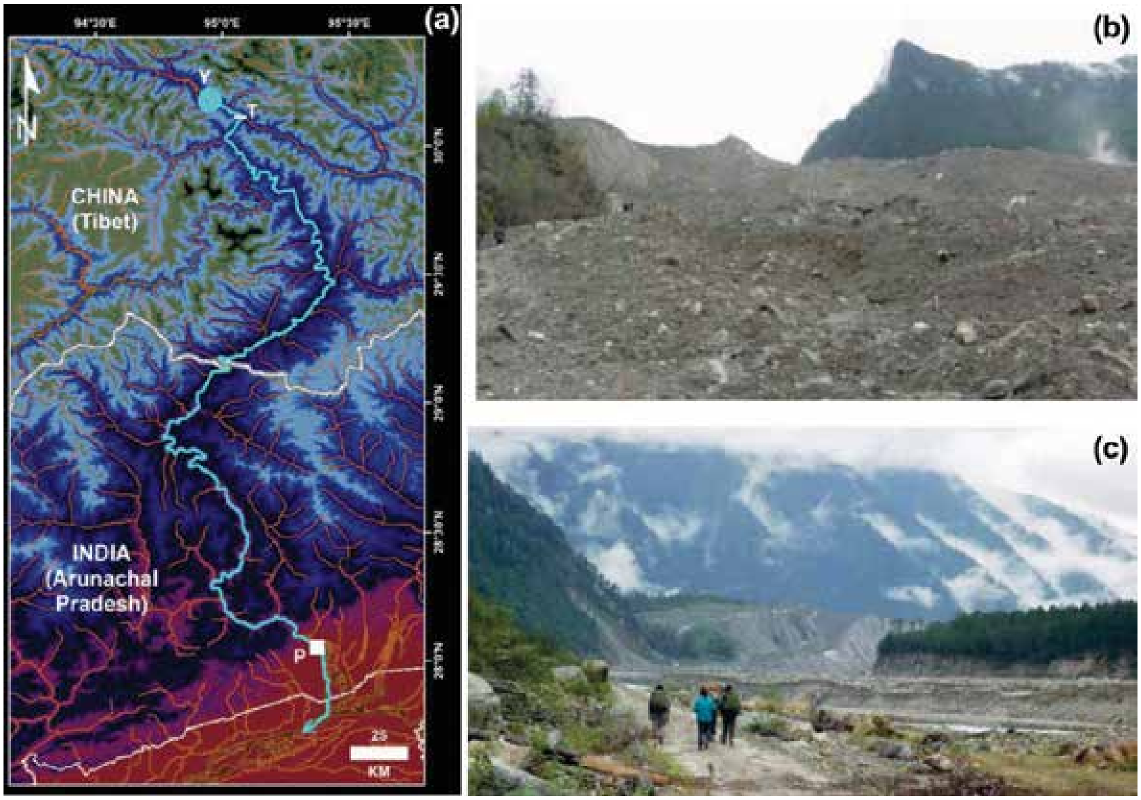


Figure 1 The Yigong Landslide Dam; a) The course of Yigong- Siang River that carried the 11 June 2000 flood discharge. Y- Yigong Landslide Dam; T- Tongmai Bridge; P- Pasighat (after Evans and Delaney, 2011); b) View of slide mass blocking the Yigong River; c) Remnant slide mass after collapse on 10 June 2000 (source: internet in *Avalanches and damming induced by earthquake and snowmelt*)

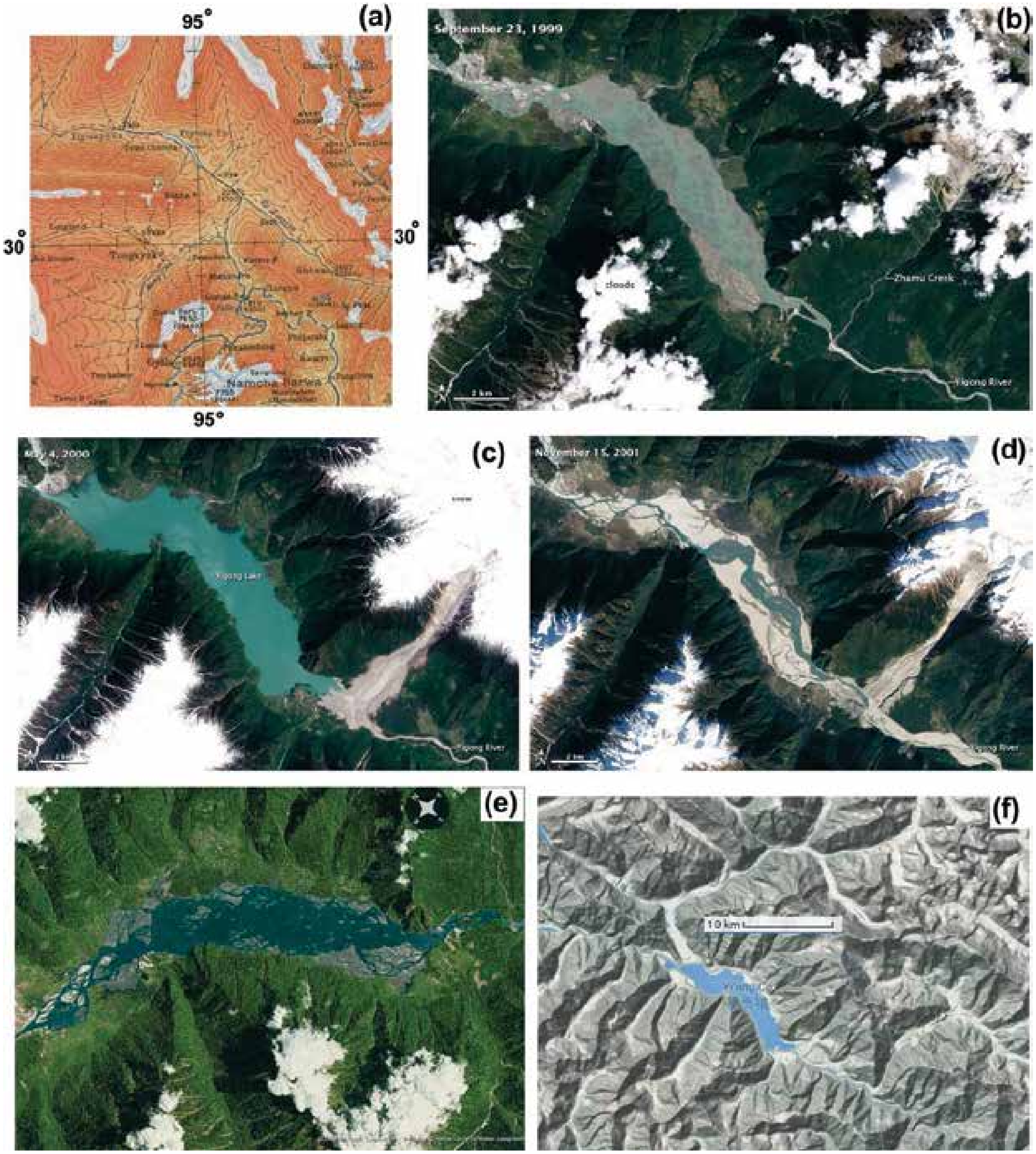


Figure 2 Map and Imagery of the Yigong Lake. a) About 15 km long Yigong Lake [Source:1: 1M Lhasa NH 46, AMS-2, 1945]; b - d) The Yigong Lake as on 23 September, 1999, 4May 2000 and 15 November 2001 respectively [Source: landsat.visibleearth.nasa.gov/view. Php/id=78293]; e) The Lake in 2009 [Source: Flash Earth]; The Yigong Lake in 2014 [Source: Map data ©2014 AutoNavi, Google]

Figure 3 Photographs showing the Yigong Lake. a) Cloud covered Lake in May 1983 (photo: Yang Yichou, source: internet); b) View of Lake north- eastwards from the south bank (after Tamotsu Nakamura, 2006); c) Yigong Lake (source: internet site *Tibet Tour,* January 2013); d) View of Lake from Google photo 2014.

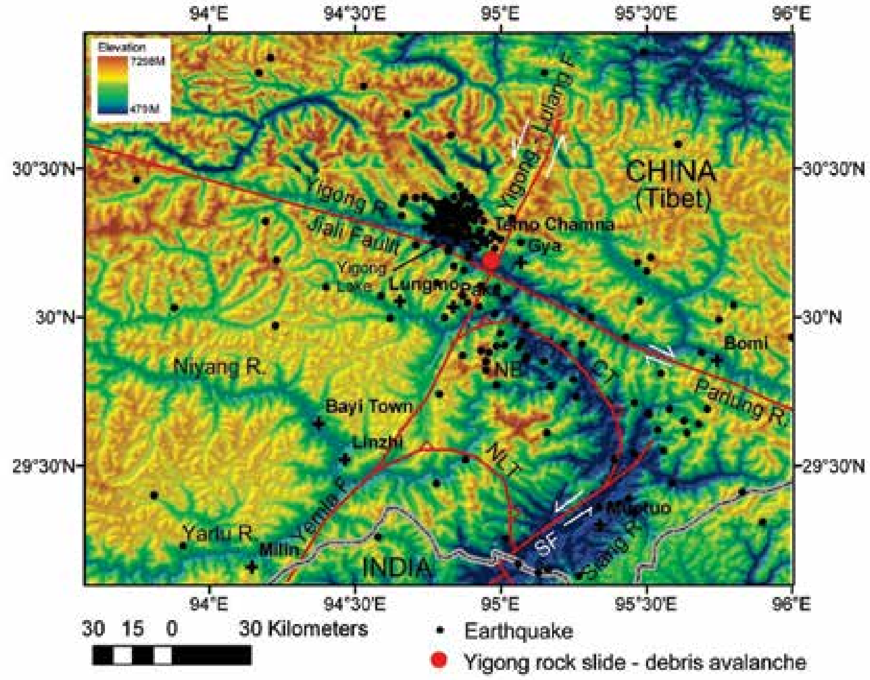


Figure 4 Seismotectonic Map of the eastern Himalaya Syntaxial zone (structural elements from Mukhopadhyay et al, 2011; Xu et al 2012); note the seismic cluster over the Yigong Lake close the intersection of Jiali and Yigong-Lulang Fault. CT – Canyon thrust; NLT – Namula thrust; SF – Siang Fracture; NB – Namcha Barwa. Elevation data is after Smith and Sandwell (1997).

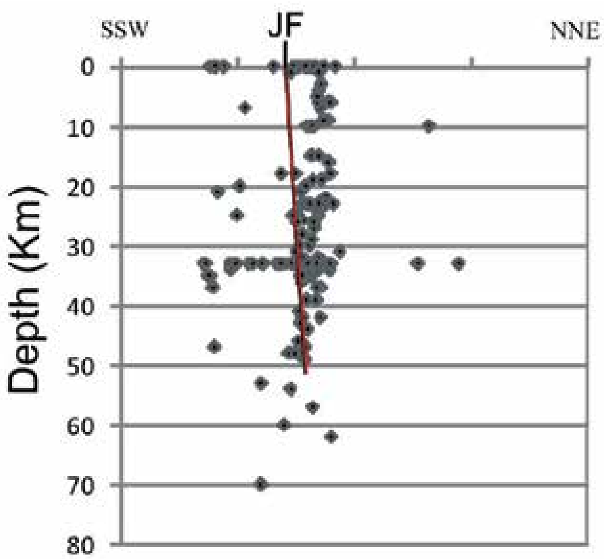
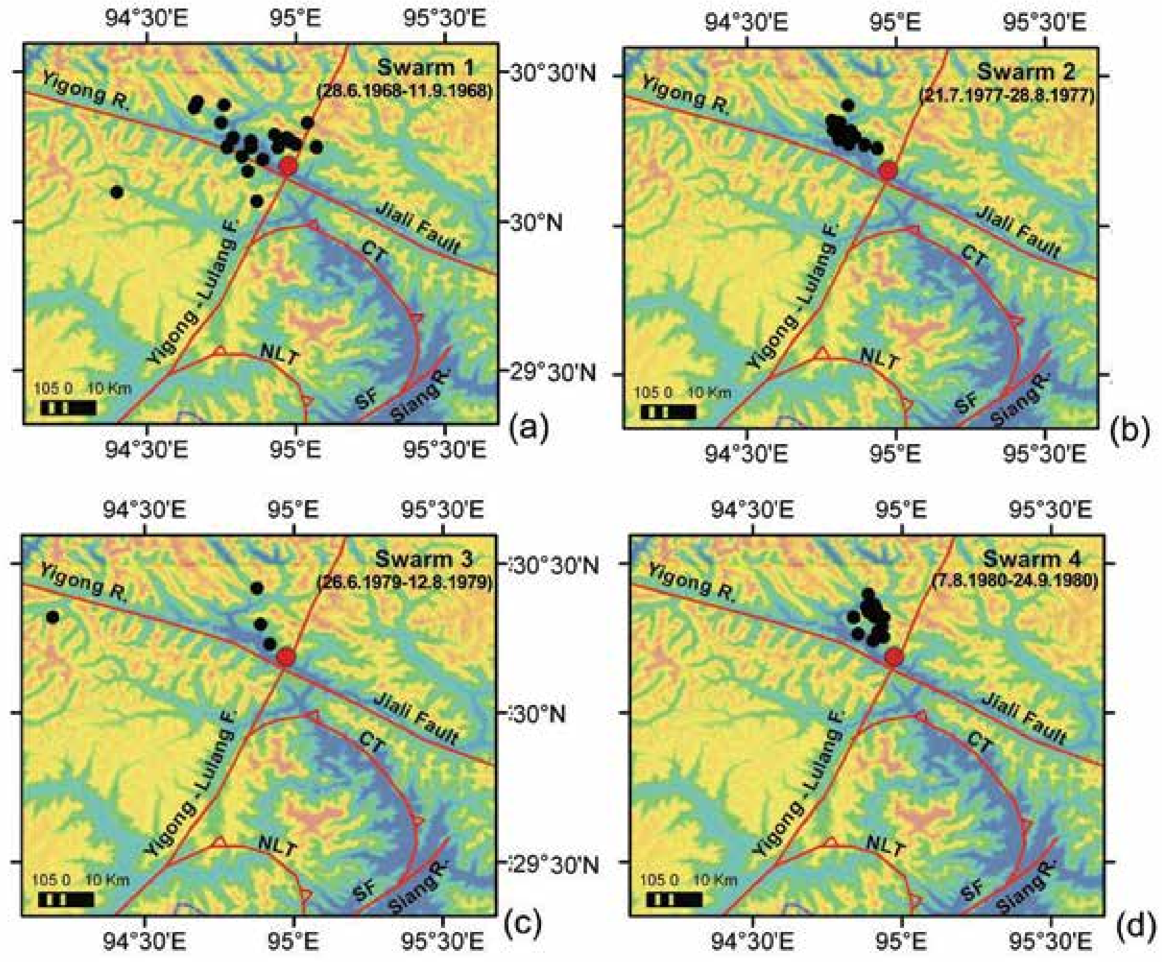


Figure 5 Section across the Jiali Fault- earthquake swarm cluster; note that swarm activity intimately associated with the fault



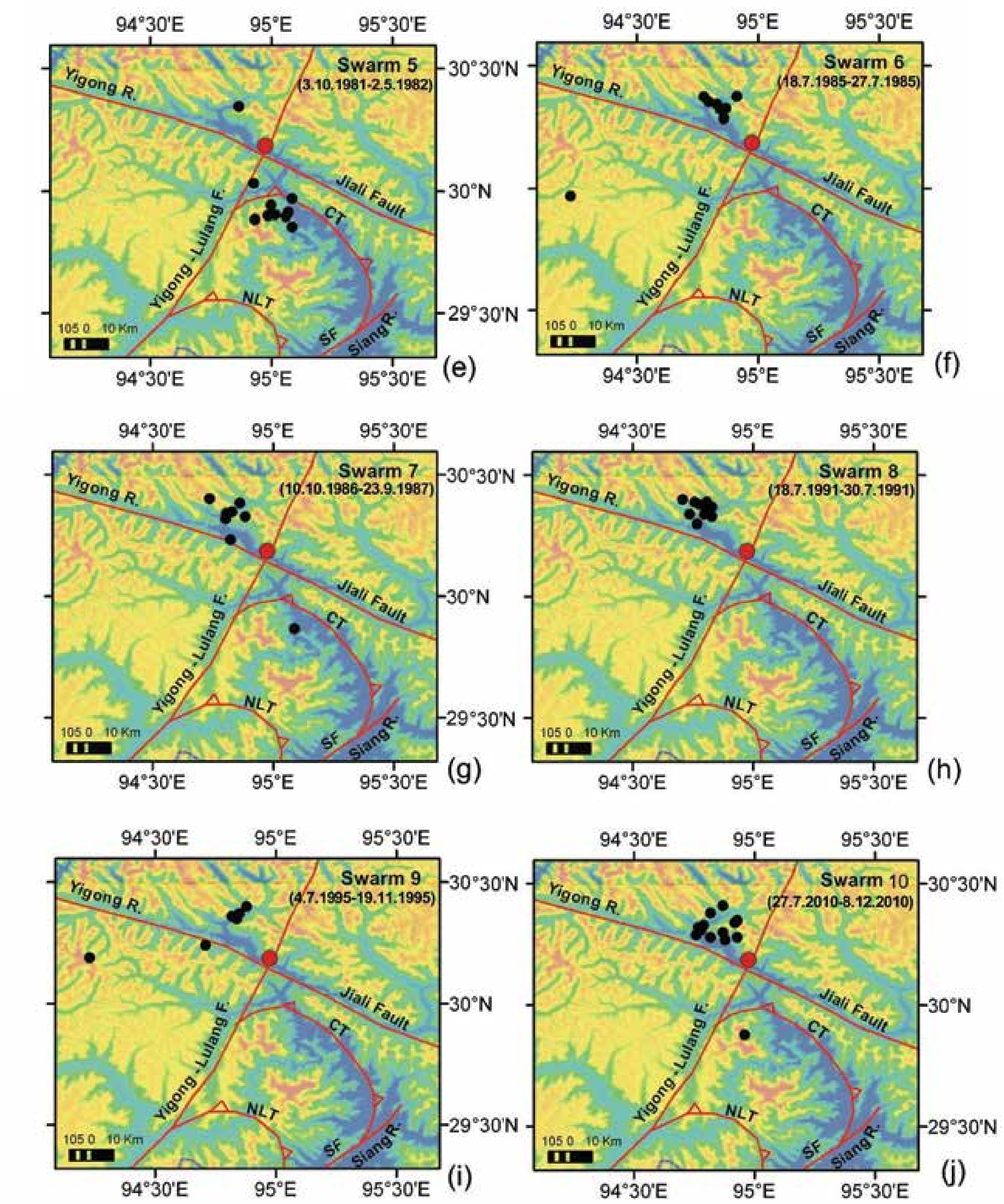


Figure 6 Seismotectonic Map of eastern Himalaya syntaxial belt showing temporal earthquake swarms. (a-f) shows the temporal swarm clusters 1 to 6 (table 1) whereas (g-j) shows disposition of temporal swarm clusters 7 to 10 (table 1). CT – Canyon thrust; NLT – Namula thrust; SF – Siang Fracture. Note red circle is the location of Yigong rock slide of April 9, 2000. Elevation data is after Smith and Sandwell (1997).

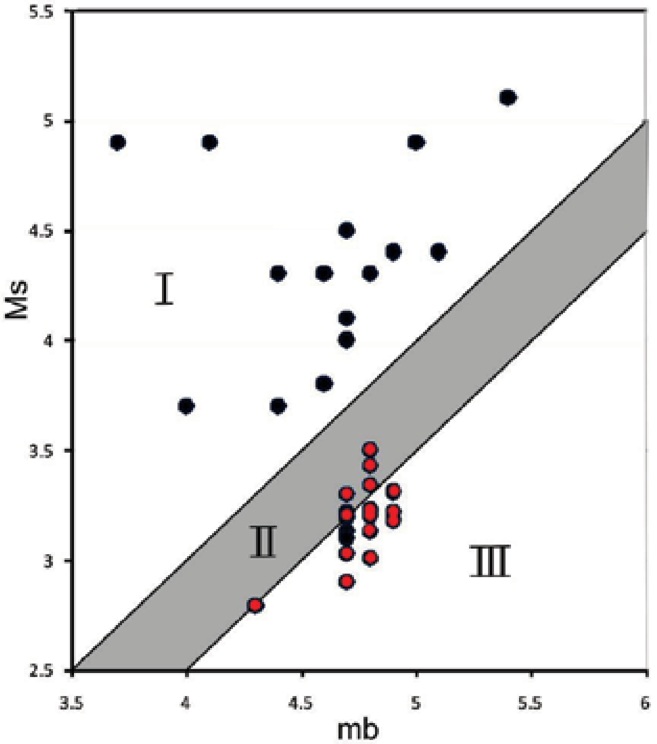


Figure 7 Ms-mb plot (after Tatham et al, 1976) for 38 earthquakes from swarm cluster that occurred between 1968 and 2010; red circles are from 1968 swam (swarm 1 of table 1).

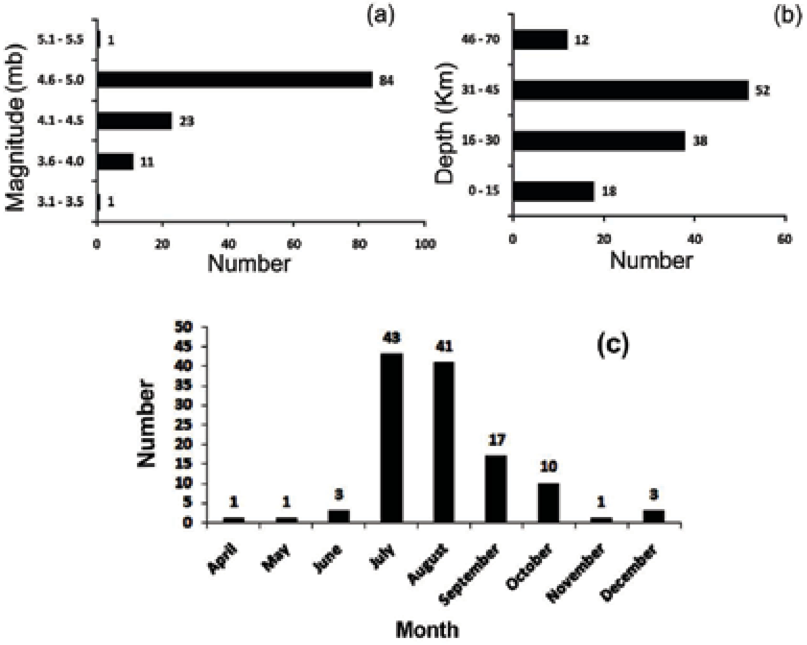


Figure 8 (a) Magnitude range of seismic events defining the cluster including swarm earthquakes; (b) focal depth distribution of seismic cluster events; (c) month wise distribution earthquake events from swarms (see table 1) indicating monsoonal linkage to swarm burst.