Geoscience Frontiers 6 (2015) 715–722

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Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research paper

Earthquake swarms near eastern Himalayan Syntaxis along Jiali Fault in Tibet: A seismotectonic appraisal

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ARTICLE INFO

Article history:
Received 13 October 2014
Received in revised form
13 December 2014
Accepted 27 December 2014
Available online 21 January 2015

Keywords:
Seismic swarm
Eastern Himalayan Syntaxis (EHS)
Jiali fault
Composite fault plane solution
Pore pressure
'r–t plot'

ABSTRACT

The seismotectonic characteristics of ten repeated earthquake swarm sequence within a seismic cluster along Jiali Fault in eastern Himalayan Syntaxis (EHS) have been analysed. The swarms are spatially disposed in and around Yigong Lake (a natural lake formed by blocking of Yigong River by landslide) and are characterized by low magnitude, crustal events with low to moderate b values. Ms : mb discriminant functions though indicate anomalous nature of the earthquakes within swarm but are considered as natural events that occurred under condition of high apparent stress and stress gradients. Composite fault plane solutions of selected swarms indicate strike–slip sense of shear on fault planes; solution parameters show low plunging compression and tensional axes along NW–SE and NE–SW respectively with causative fault plane oriented ENE–WSW, dipping steeply towards south or north. The fault plane is in excellent agreement with the disposition and tectonic movement registered by right lateral Jiali Fault. The process of pore pressure perturbation and resultant 'r–t plot' with modelled diffusivity ($D = 0.12$ m^2/s) relates the diffusion of pore pressure to seismic sequence in a fractured poro-elastic fluid saturated medium at average crustal depth of 15–20 km. The low diffusivity depicts a highly fractured inter-connected medium that is generated due to high stress activity near the eastern syntaxial bent of Himalaya. It is proposed that hydro fracturing with respect to periodic pore pressure variations is responsible for generation of swarms in the region. The fluid pressure generated due to shearing and infiltrations of surface water within dilated seismogenic fault (Jiali Fault) are causative factors.

1. Introduction

The Himalayan arc, a typical collisional feature in the Asian landscape extends from Pir Panjal, Nanga-Parbat in the west (western Himalayan Syntaxis) to Namcha Barwa in the east (eastern Himalayan Syntaxis). The arc forms a small circle between 77° and 89° with radius approximately 1623 km centered at 42.10°N, 90.72°E (Seeber and Gornitz, 1983; Bendick and Bilham, 2001). Himalayan arc to maintain its arcuate geometry needs arc parallel extensions in several places, in addition to layer perpendicular compressional stress due to plate convergence (Seeber and Pecher, 1998; Clark and Royden, 2000). The arc parallel extension zones form several grabens oriented perpendicular to the arc in the Tibet; whereas in between two extension zone (grabens) the tectonic zone experiences both layer parallel and layer perpendicular compression. In Tibetan Himalaya, these extensional grabens are sites of repeated seismicity mainly of earthquake swarms resulting from extensional stress; and thus showing fault plane solutions primarily normal with subordinate strike slip sense of movement. Association of sub-surface volcanic activity along these grabens is not ruled out due to mass flowage and crustal flow envisaged through modelling in shallow crustal level (Zhao and Morgan, 1987; Bird, 1991; Clark and Royden, 2000; Beaumont et al., 2001; Clark et al., 2005; Copley and McKenzie, 2007). In contrary, though tectonic swarm derived by compression is common in collisional tectonics, but in Himalaya, occurrence of such earthquake swarms in Higher Himalayan zone is relatively rare. One such rare site with occurrence of repeated earthquake swarm sequence of primarily tectonic origin has been detected from 1968 onwards along Jiali Fault (Figs. 1 and 2) in the vicinity of eastern Himalayan Syntaxis (EHS) around Namcha Barwa massif in Tibet. The tectonic importance of this swarm sequence increase manifold

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Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2014.12.009

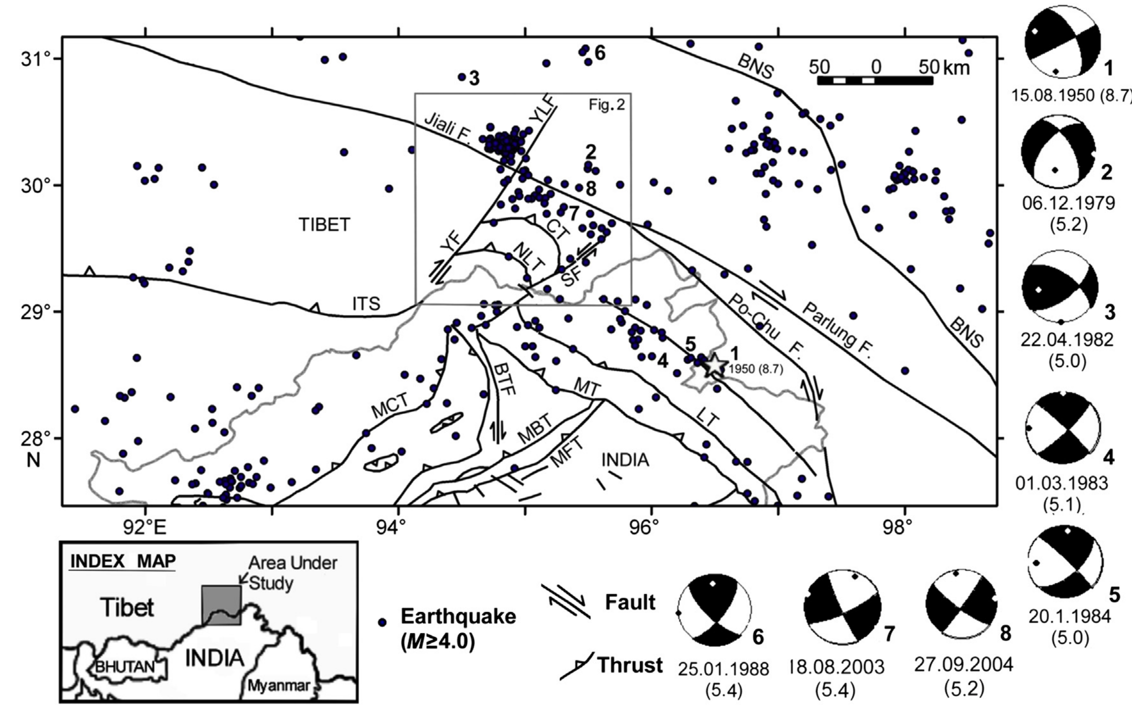

Figure 1. Seismotectonic map of area in and around the eastern Himalaya Syntaxis (compiled after Lee et al., 2003; Mukhopadhyay et al., 2011; Xu et al., 2012) with earthquake data ($M \geq 4$) for the period 1964 to 2011 of reviewed ISC Bulletin. Star indicates location of Great Assam Earthquake of 1950 with strike slip fault plane solution (after Ben-Menahem et al., 1974). Other fault plane solutions (from CMT data) are shown as Beach ball with corresponding numbers. BTF: Bame Tutin Fault; BNS: Bangong–Nujiang Suture; CT: Canyon Thrust; ITS: Indus–Tsangpo Suture Zone; LT: Lohit Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; MFT: Main Frontal Thrust; MT: Mishmi Thrust; NLT: Namula Thrust; SF: Siang Fracture; YF: Yemla Fault; YLF: Yigong–Lulang fault.

due to its location, around which the rigid clockwise rotation of the Tibetan Plateau has been established by geodetic surveys (Zhang et al., 2004; Ren and Shen, 2008; Cao et al., 2009; Mahesh et al., 2012) and thus deserve attention to unravel its tectonic character, the basic theme of this paper. The swarms further draw attention to seismologist for its anomalous character and its origin from prevailing active tectonism i.e. remarkable right lateral strike slip motion along Jiali, Po-chu and Parlung faults produced from plate interaction and rigid block rotation as stated above.

2. Earthquake cluster

A seismotectonic map (Fig. 1) of the eastern Himalayan Syntaxial region (27°–31°N, 92°–99°E) shows the tectonic set up of the area

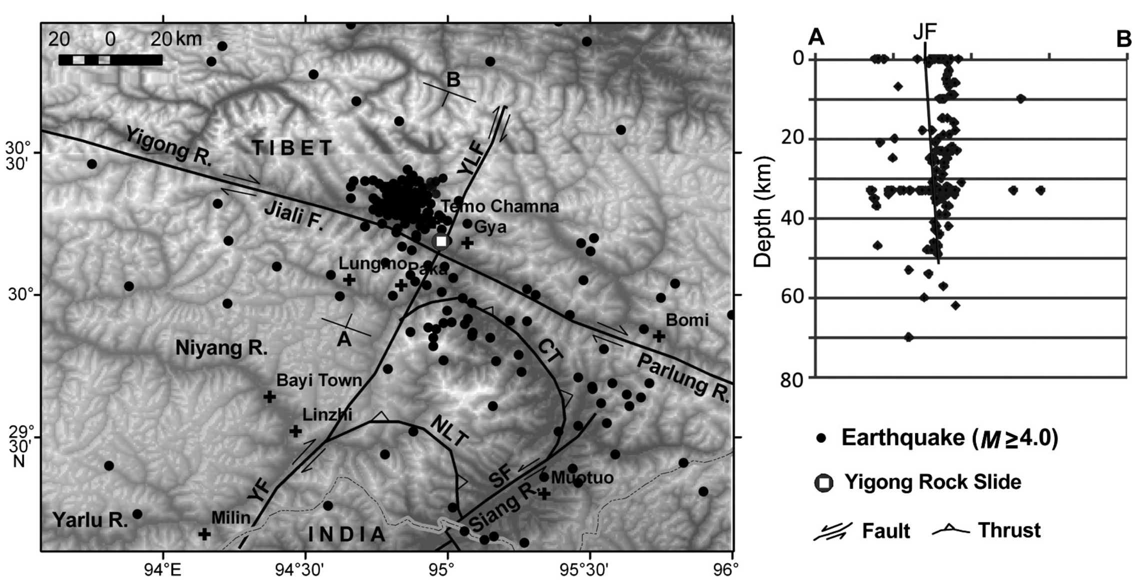

Figure 2. Further zoomed in to the study area (see inset in Fig. 1) in eastern Himalaya Syntaxis (EHS) around Namcha–Barwa Massif showing the earthquake clusters ($M \geq 4$) with 10 swarm sequence. Note the interaction of two major strike slip faults, the WNW–ESE right lateral Jiali Fault and the left lateral Yigong–Lulang strike slip fault, perpendicular to the former to form the cluster. *A–B* is the seismic section showing the activity of Jiali Fault as causative structure. Note white box is the location of Yigong rock slide of April 9, 2000.

Table 1
Characteristics of the 10 temporal earthquake swarm (for spatial locations refer Fig. 4).

Swarm No.	Duration of swarm	Number of events	Magnitude (mb) range	Depth (km) range	b-value (Maximum 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[a]	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[b]	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

[a] This cluster is unrelated to other nine swarms that are associated with the Yigong Lake.
[b] Four events occurred in October 1986 and another 5 during September 1987 to define the spatial swarm cluster.

(compiled after Lee et al., 2003; Mukhopadhyay et al., 2011; Xu et al., 2012) with earthquake data ($M \geq 4$) for the period 1964 to 2011 of reviewed ISC Bulletin. Local seismic network data are not available to the authors. Great Assam Earthquake (15th August 1950, M_W 8.7) with strike slip fault plane solution (Ben-Menahem et al., 1974; star and fault plane solution No. 1 in Fig. 1) occurs in this zone. The fault plane solutions in this zone complied from CMT data show by and large strike slip mechanism, see beach balls (1 to 9) in Fig. 1. Further zooming to the area of interest (Fig. 2) reveals earthquake cluster with periodic swarm sequence in the NW quadrant of intersection of two major strike slip faults that traverse the area; the WNW–ESE right lateral Jiali Fault following the Yigong–Parlung rivers and the left lateral Yigong–Lulang strike slip fault (Xu et al., 2012) which is almost perpendicular to the former. The seismic section (*A*–*B*) drawn across the cluster (Fig. 2) indicates sub-vertical Jiali Fault is the causative structure to generate the spatial cluster and swarms. The swarm clusters are located over 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 (Fig. 2) also contains several independent events.

3. Earthquake swarm

3.1. Anomalous earthquake or swarm?

The area drew attention of seismologists in early seventies due to the occurrence of an anomalous earthquake swarm during 1968 (see Table 1, Figs. 3, 4a and 5a) 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 (white dots in Fig. 3) 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 subsequently at the same site. Ms vs. mb plot for 38 events including those from Tatham et al. (1976) for the 1968 swarm (Fig. 3) indicates that 15 belong to type I (clear earthquake population), 4 within type II (between explosion and earthquake) and the remainings belong to explosion type III. Magnitude ranges of earthquakes (Fig. 6a) indicate they belong to low magnitude swarm events and focal depth distribution (Fig. 6b) show that majority of the earthquakes in the swarm originate from depths of less than 45 km, thus points to their mid to shallow crustal origin considering the crustal thickness at the site around 70 km. 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 earthquakes 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. The swarm of 1968, 1977 and 1980 was also studied by Gupta and Singh (1986) who observed that these intense and concentrated swarms occur in small rock volume within the preparation zone of 1950 earthquake; but did not offer any satisfactory explanation for the occurrence of such seismic swarms, except commenting that these are usually associated with movement of magma in the crust of volcanic terrain.

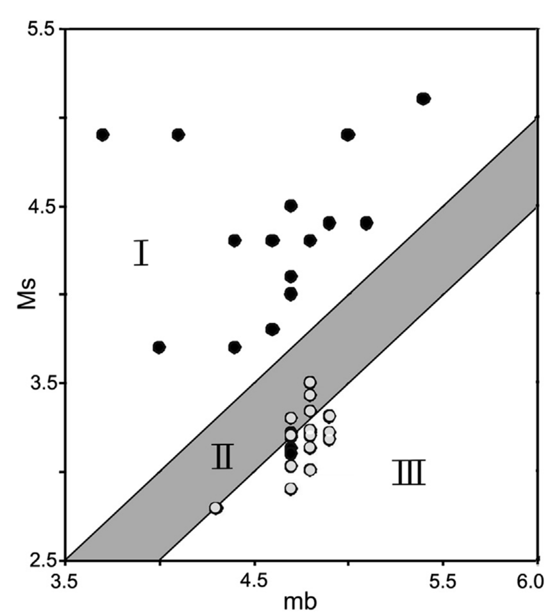

Figure 3. Ms–mb plot (after Tatham et al., 1976) for 38 earthquakes from swarm cluster that occurred between 1968 and 2010; grey circles are from 1968 swam (swarm 1 of Table 1). Type I–Clear earthquake population, Type II–Between explosion and earthquake, and Type III–Explosion type.

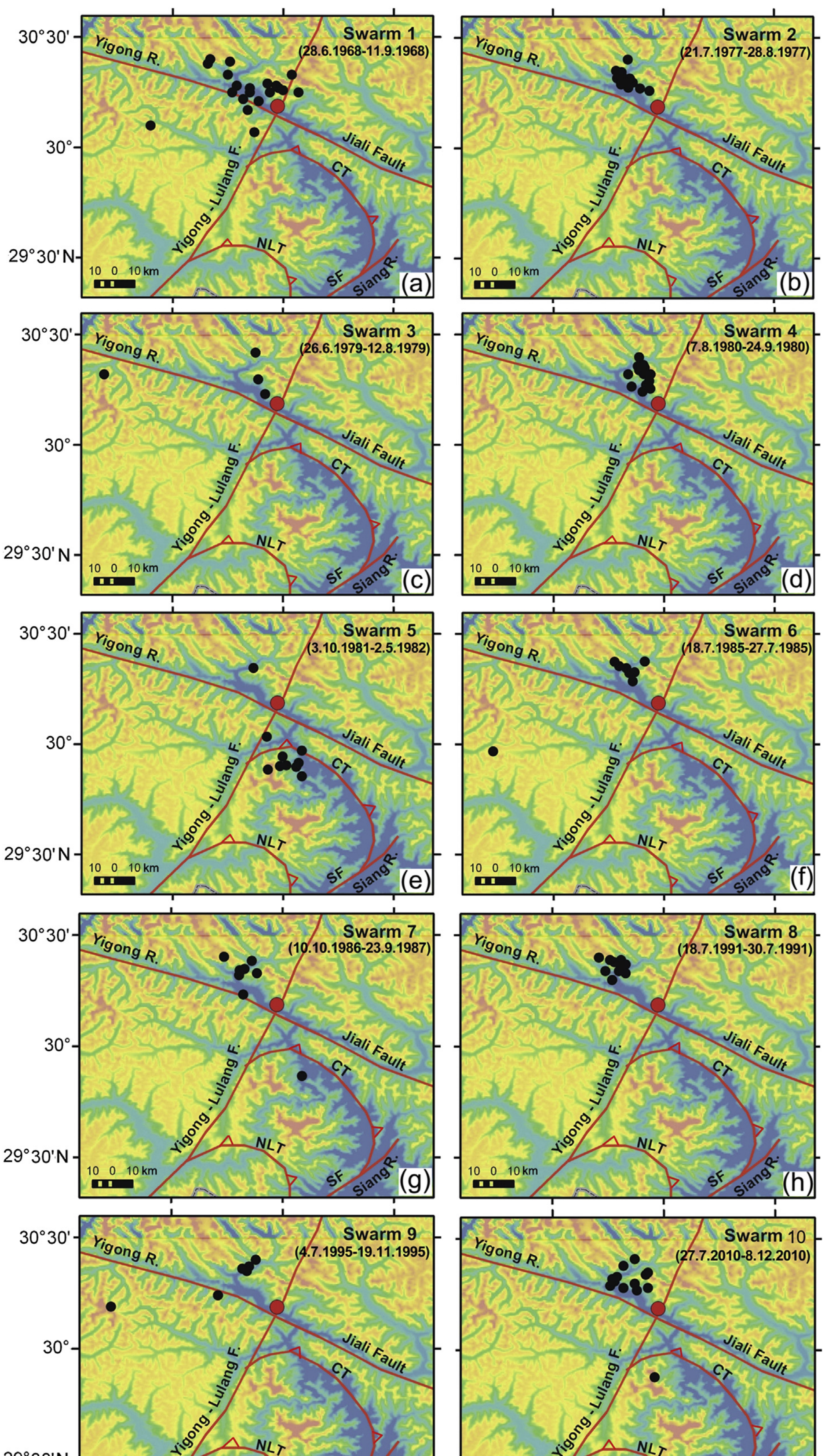

Figure 4. Seismotectonic map of eastern Himalaya syntaxial belt showing temporal earthquake swarms. (a–f) show the temporal swarm clusters 1 to 6 (Table 1) whereas (g–j) show disposition of temporal swarm clusters 7 to 10 (Table 1). CT–Canyon thrust; NLT–Namula thrust; SF – Siang Fracture; YL–Yigong Lake. Note red circle is the location of Yigong rock slide of April 9, 2000.

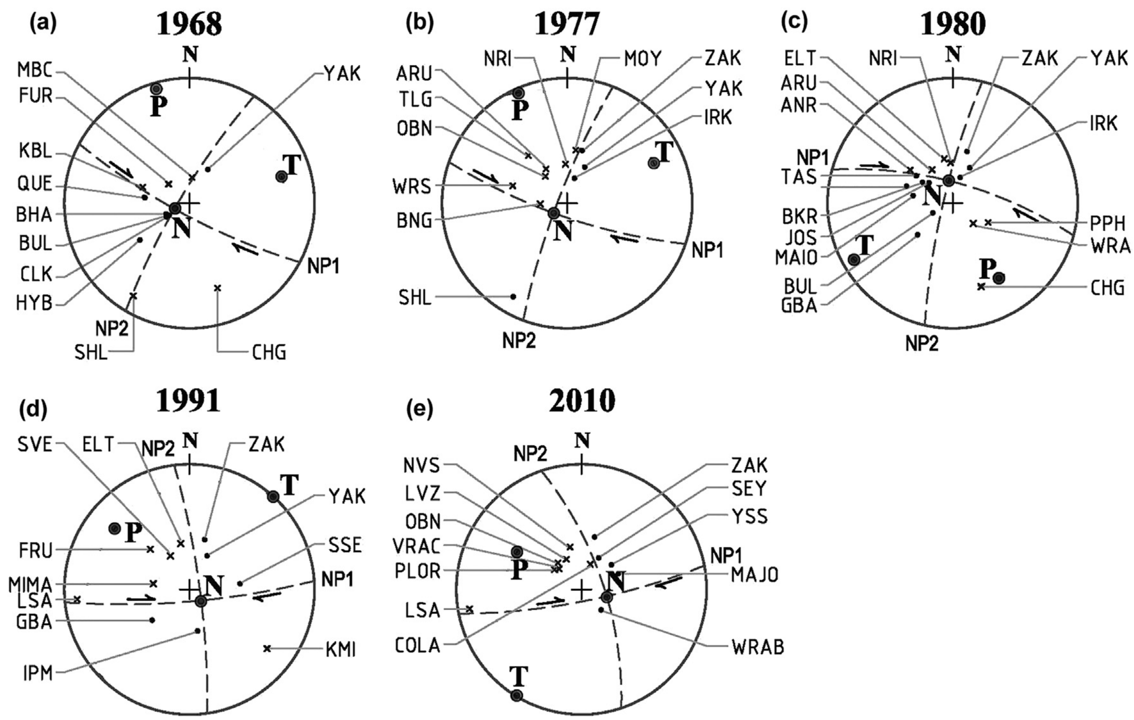

Figure 5. P wave first motion data and nodal planes plotted on equal area projection of lower focal hemisphere for 1968, 1977, 1980, 1991 and 2010 swarm sequences (5a to 5e, see Table 1 and Fig. 4). The black dots represent compression and black cross represent dilation (with station code). P is the axis for maximum compression and T is the axis of least compression. Note that steeply dipping nodal planes exhibit right lateral strike slip sense of motion. Strike and dip of the nodal planes and parameters for P, T and N (Neutral) axes are listed in Table 2. NP1—Nodal fault plane 1; NP2—Nodal fault plane 2. ISC Station locations are in abbreviated form.

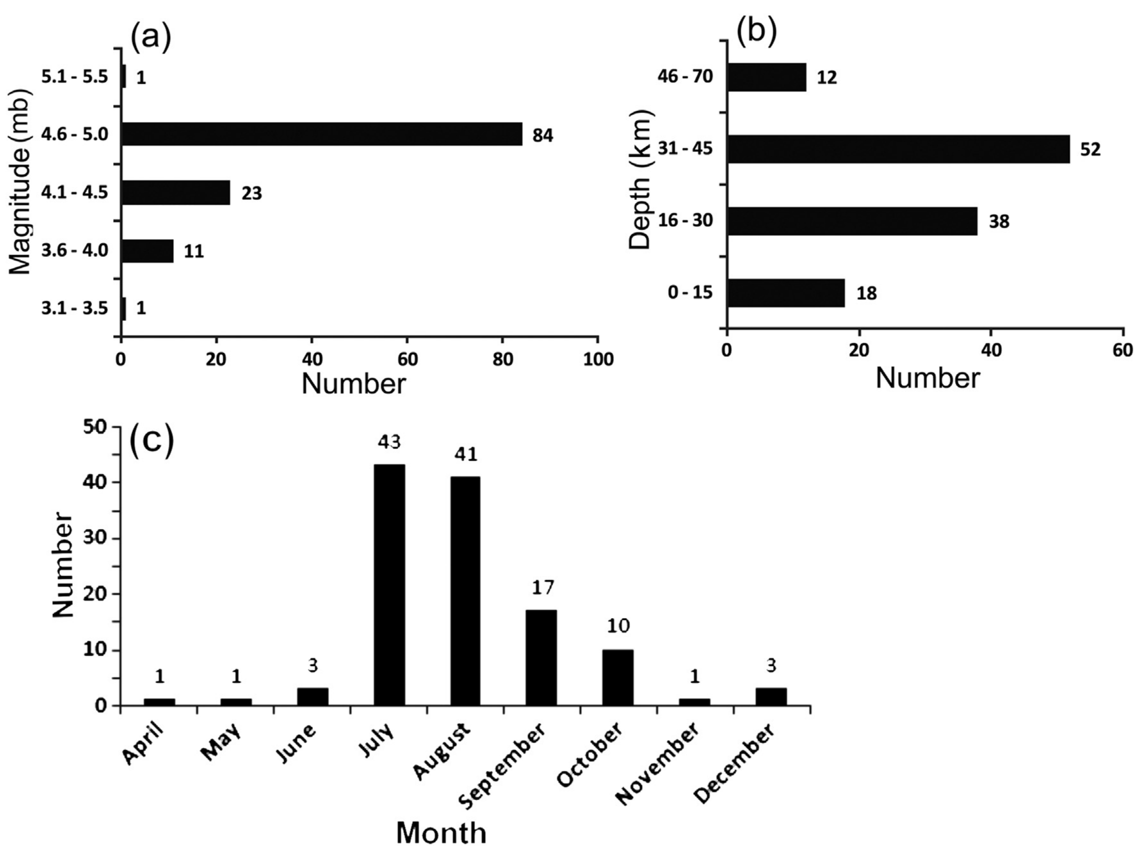

Figure 6. (a) Magnitude range of seismic events defining the cluster including swarm earthquakes; (b) focal depth distribution of seismic cluster events; (c) month wise distribution earthquake events from swarms (see Table 1) indicating monsoonal linkage to swarm burst.

Seven out of nine swarms for which b-value could be calculated using maximum likelihood equation of Aki (1965) show low or near normal 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, rather than magmatic source that usually generates higher b-values.

3.2. Spatial disposition of swarms

The first recognized swarm in the database occurs during June to September of 1968 with 20 events (Fig. 4a). The swarm is well studied as stated above. Subsequent to the above stated studies on the 1968 (June–September) swarm, a number of swarms originated from the same epicentral region which is listed (Table 1) and separately plotted (Fig. 4). The next swarm of July–August 1977 (Fig. 4b) with 17 earthquakes was followed by a small swarm of 4 events (Fig. 4c) during June–August 1979 and a strong swarm of 19 earthquakes during August–September 1980 (Fig. 4d). It may be noted that all these swarm activities occurred within the monsoon period. Swarm 5 (Fig. 4e) occurred in two phases; it 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 swarm cluster but locates in the opposite quadrant defined by the two strike slip faults, and not over the Yigong Lake on which all other swarms locate. Two events from this swarm also registered slightly higher magnitudes 5.0 and 5.1. The next swarm of July 1985 (Fig. 4f) with 8 earthquakes was again a monsoonal swarm; swarm 7 (Fig. 4g) 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. It may be noted both the clusters of swarm 7 occurred at the end of the monsoon. The next swarm of July 1991 with 11 events located over the Yigong River Lake (Fig. 4h). Subsequent swarm of July–November 1995 was a smaller swarm of 7 earthquakes (Fig. 4i). For the next ten years no swarm activity has been noted from the site till the strong swarm reappeared at the same cluster location during July–December 2010 with 15 earthquakes. It is intriguing to note that 9 out of 10 swarm cluster (1981–1982 swarm in the opposite quadrant) located over the Yigong River Lake since 1968 all struck during the monsoon period (see Fig. 6c) and this spatial correlation cannot be mere coincidental and overlooked. The same is studied in details in the next sections.

3.3. Composite fault plane solution of the swarm

In absence of CMT fault plane solutions of the swarm, composite focal mechanism solutions of selected swarm sequences that occurred during 1968, 1977, 1980, 1991 and 2010 have been determined using P-wave first motion data (both short and long period; source ISC Bulletin). The ISC station locations with dilation (black cross) and compression (black dot); P, T and N axes and orientations of two causative fault planes (NP1 and NP2) are marked in the composite beach ball diagrams (Fig. 5). The sense of shear is marked on nodal plane 1 (NP1); solution parameters are listed (Table 2) and results indicate that compression axis is low plunging along NW–SE direction; whereas the tensional axis is also low plunging along NE–SW direction and neutral axis is very steeply plunging indicating a tectonic condition for strike slip movement to occur along causative fault plane. The causative fault (nodal plane 1 of Fig. 5 and Table 2) is oriented ENE–WSW, dipping steeply towards south or north. It is intriguing to note that all solutions indicate right lateral strike–slip mechanisms sense of shear and have excellent agreement to the disposition and tectonic movement registered by Jiali Fault in the study area.

3.4. Whether pore pressure is responsible for swarm generation?

Worldwide, pore pressure diffusion as a triggering mechanism has been proposed for evolution of earthquake swarms (Parotidis et al., 2003; Hainzl, 2004). In the swarm sequence, event hypocentres migrate during the swarm evolution due to fluid migration. As a result of fluid intrusion, activity starts at depth and spreads upwards with time (t) for short or can withstand very long time interval. The relationship between the swarm sequence and its causative pore pressure perturbation is studied by a process called the 'r–t plot' what is based on the diffusion equation for a point pore pressure source in a homogeneous and isotropic fluid saturated poro-elastic medium having specific hydraulic properties. The extension of the rupture zone can be approximated by the theoretical curve, $r = \sqrt{4\pi Dt}$, describing the distance (r) of the pressure front from the fluid source with time (t) (Shapiro et al., 1997, 1999, 2002, 2003). The equation actually defines the enveloping parabola in the r–t plot with variable hydraulic diffusivity (D) values, where, seismicity points should lie below the modelled parabolic curve. 'D' is scalar, whose value depends on permeability (k), uniaxial specific storage coefficient (S) and viscosity of the fluid (μ) by the equation $D = k/(\mu S)$ (Kuempel, 1991; Wang, 2000). On the contrary, if the earthquake triggering occurs shortly after the pore pressure perturbations (Noir et al., 1997), we should observe a narrow cluster of seismicity along the line of the modelled parabola in the r–t plot with variable scalar D values. The D-value in the earth's crust usually ranges between 0.1 and 10 m^2/s (Shapiro et al., 1999) but can reach up to 90 m^2/s (Antonioli et al., 2005).

In the study area, entire earthquake points in the swarms are modelled with r–t plot taking the location of first earthquake of 26.08.1968 (latitude 30.29°N, longitude 94.93°E; M 4.8, focal depth 26 km) as starting point (point pore pressure source) of pore pressure perturbation. The assumption of prolong activity of pore pressure in the region may not be completely rigorous, but we accept this approximation well enough for our purpose as r–t plot

Table 2
The salient tectonic parameters derived from composite fault plane solutions of 1968, 1977, 1980, 1991 and 2010 swarm sequence (see Fig. 5).

Year and duration of swarm	P axis		N axis		T axis		Nodal plane 1		Nodal plane 2	
	Plunge	Dir^n	Plunge	Dir^n	Plunge	Dir^n	Strike	Dip	Strike	Dip
1968 (28.06.1968–11.09.1968)	3°	342°	75°	284°	16°	72°	117°	80°	198°	78°
1977 (21.07.1977–28.08.1977)	2°	335°	73°	235°	17°	65°	108°	78°	200°	80°
1980 (07.08.1980–24.09.1980)	20°	149°	70°	344°	6°	240°	284°	72°	192°	80°
1991 (18.07.1991–30.07.1991)	15°	308°	75°	125°	2°	37°	78°	80°	350°	80°
2010 (27.07.2010–08.12.2010)	29°	303°	66°	105°	0°	33°/213°	80°	80°	342°	70°

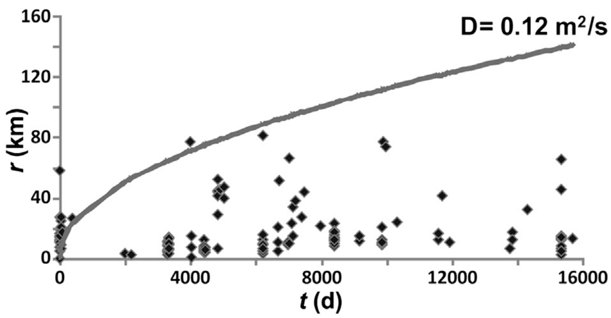

Figure 7. The r–t plot of the swarm sequence with modelled parabolic envelope of diffusivity ($D = 0.12$ m^2/s).

illustrate the same. In spite of constraints of low data density, the modelled diffusivity value D is low, 0.12 m^2/s (Fig. 7). A very high pore pressure activity with low diffusivity along a narrow zone of Jiali Fault within average crustal depths from 15 to 20 km can be inferred for repeated generation of swarms. The low diffusivity depicts a highly fractured interconnected medium that is generated due to high stress activity near the eastern syntaxial bent of Himalaya. As the hydraulic diffusivity 'D' mainly changes the spatio-temporal migration of activity, for smaller 'D', as in the present case, indicates that the intervals between swarms will be longer. It also indicates that overall duration of the pore pressure activity will be for a longer time and its sudden increase will generate swarm activity. The pore-pressure is active for last 45 years in the present case and will continue further as Yigong Lake acts as a natural reservoir to supply fluid regularly to maintain the pore pressure front. Thus, the hydraulic diffusivity along the Jiali Fault influences the speed of the evolution of seismic activity (see Hainzl, 2004 for more explanation). As proposed by Telesca et al. (2012) in reservoir-triggered seismicity observed at Acu, Brazil, we also conclude that the processes of formation of fractures in the anisotropic and heterogeneous rockmass, along with pore pressure diffusion driven processes, are hypothesized as physical mechanisms for swarm generation in the study area.

3.5. *Model for the swarm generation*

Swarm-like sequence could also be created by fluid flow from localized high pressure compartments when fractures are controlled by increasing permeability (Yamashita, 1999). The spatio-temporal variation of rupture activity is modelled assuming that the fluid migrates along a narrow porous fault zone in a semi-infinite elastic medium. As faults slip, pores are created and the Coulomb failure criterion introduces mechanical coupling between faults slip and pore fluid. The fluid flows from a localized high-pressure fluid compartment in the fault with the onset of earthquake rupture. The duration of the earthquake sequence is assumed to be considerably shorter than the recurrence period of characteristic events on the fault and rupture process is significantly dependent on the rate of pore creation. If the rate is large enough, a foreshock–mainshock sequence is never observed; the rupture sequences generate earthquake swarms. The model shows that a foreshock–mainshock sequence is only observed if the critical slip distance for pore creation is infinite, i.e. no pores are created by any slip in the model and the whole fault is moving. As a continuation, another model proposed by Tzschichholz and Wangen (1999) introduces hydraulic fracturing of a porous material in presence of high fluid pressure. It argues that crack start to move after the onset of fluid injection. This process decreases the strength and the hydraulic pressure within the material; crack propagation comes to an end after some time when a critical cohesion and hydraulic pressure is reached. The fluctuation in fluid injection induces more cracks initially but frequency of crack propagation becomes larger as the time goes by. This spatio-temporal fracture behaviour generated by the micro-mechanical hydraulic fracturing induces the swarm sequence. The micromechanical approach of Tzschichholz and Wangen (1999) also complements the results of Yamashita (1999). Both these models do not introduce the range of magnitude distribution within the clustered events.

Within this premise, we propose a model for generation of repeated swarm in the study area. The model combines hydro fracturing (Tzschichholz and Wangen, 1999) with respect to periodic pore pressure variations (Yamashita, 1999) to generate the earthquake swarms in the region. Moreover, as already stated the Yigong Lake behaves like a semi-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 as proposed above. 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.

4. Discussion and conclusion

The region surrounding the zone of swarm generation is under high tectonic stress condition with formation of antiformal domal structure (Namcha Barwa antiform), which is a structural and topographic expression of arc-parallel shortening at a rate of ~12 mm/yr that compensates for arc-parallel extension in southern Tibet (Seeber and Pecher, 1998). The zone has dynamic interaction guided by local erosion by Tsangpo/Siang River; rock uplift and thermal weakening of lithosphere and deformation (Finnegan et al., 2008). Tomographic surveys (Ren and Shen, 2008) have indicated low P and S wave velocity patches within the uplifted rocks of this syntaxis. These patches may be correlated with mass flowage of mobile rocks and creation of small magmatic pockets by possible decompressional melting. The thickening of the crust is also noteworthy (see sections in Mukhopadhyay et al., 2011) and the exhumation is caused by erosion along the Siang River with crustal scale folding at a rate of ~10 mm/yr (Burg et al., 1998). Such zone with extreme horizontal and vertical movement is an ideal candidate for stress accumulation and release and thus characterized by recurrent earthquake swarm activity. Our study indicates that tectonic interaction and right lateral strike slip movement along sub-vertical Jiali Fault is responsible to generate the periodic swarms (see Fig. 5). The swarms are tectonic in nature as indicated by the low or near normal b-value data. Thus, the swarms are the product of right lateral strike slip motion along Jiali Fault in coherence with the overall rapid clockwise flow around the syntaxis. It is also worth mentioning that occurrence of recurrent earthquake swarm along with some isolated events over the Yigong Lake trigger landslides that blocks the river to cause downstream flood after breach of the landslide dam; the June 11, 2000 flood through Siang River was devastating (Dasgupta and Mukhopadhyay, 2014).

The hydraulic diffusivity along the Jiali Fault influences the speed of the evolution of seismic activity (swarms) in the area. The processes of formation of fractures in the anisotropic and heterogeneous rockmass, along with pore pressure diffusion driven processes, are hypothesized as physical mechanisms for swarm generation in the study area. The natural reservoir–Yigong Lake (see Fig. 4 for location) along the Yigong River 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 infiltration of surface water within dilated seismogenic fault (Jiali Fault) initiates an enhanced pore pressure front by fluid-diffusion mechanism. In addition to this, the pore fluid activity has been enhanced by the high fluid content in the mid crust indicated by magneto-telluric data that imaged two major zones/channels of high electrical conductivity at a depth of 20–40 km in eastern Tibet. The fluid could have been derived from prograde metamorphism in a thickened crust or from under-plating. One of the conductors terminates near the Canyon thrust indicating a shear zone (Bai et al., 2010). This shearing in the eastern part of the Himalayas may be required to maintain regions with interconnected fluid, lower the crustal strength and permit rapid deformation and mass flowage. Thus, the fluid pressure generated due to shearing and infiltrations of surface water within dilated seismogenic fault (Jiali Fault) are causative factors to generate the periodic swarm sequences.

Acknowledgement

Authors thankfully acknowledge with gratitude the interest shown by the editors, especially Dr. Sanghoon Kwon, Associate Editor. Constructive comments and interest shown by learned reviewers including Dr. Harsh K Gupta have considerably improved the quality of presentation and scientific content of the paper.

References

Aki, K., 1965. Maximum likelihood estimate of *b* in the formula logN = a-bM and its confidence limits. Bulletin of the Earthquake Research Institute, Tokyo University 43, 237–239.

Antonioli, A., Piccinini, D., Chiaraluce, L., Cocco, M., 2005. Fluid flow and seismicity pattern: evidence from the 1997 Umbria-Marche (central Italy) seismic sequence. Geophysical Research Letters 32, L10311.

Bai, D., Unsworth, M.J., Meju, M.A., Ma, X., Teng, J., Kong, X., Sun, Y., Sun, J., Wang, L., Jiang, C., Zhao, C., Xiao, P., Liu, M., 2010. Crustal deformation of the eastern Tibetan plateau revealed by magnetotelluric imaging. Nature Geoscience 3, 358–362.

Ben-Menahem, A., Aboodi, E., Schild, R., 1974. The source of the great Assam earthquake – an interplate wedge motion. Physics of the Earth and Planetary Interiors 9, 265–289.

Bendick, R., Bilham, R., 2001. How perfect is the Himalayan arc? Geology 29, 791–794.

Beaumont, C., Jamieson, R.A., Nguyen, M.H., Lee, B., 2001. Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation. Nature 141, 738–742.

Bird, P., 1991. Lateral extrusion of lower crust from under high topography, in the isostatic limit. Journal of Geophysical Research 96, 10275–10286.

Blandford, R., 1977. Discrimination between earthquakes and underground explosions. The Annual Review of Earth and Planetary Sciences 5, 111–122.

Burg, J.P., Nievergelt, P., Oberli, F., Seward, D., Davy, P., Maurin, J.C., Diao, Z., Meier, M., 1998. The Namche Barwa syntaxis: evidence for exhumation related to compressional crustal folding. Journal of Asian Earth Sciences 16 (2–3), 239–252.

Cao, J.L., Shi, Y.L., Zhang, H., Wang, H., 2009. Numerical simulation of GPS observed clockwise rotation around the eastern Himalayan syntax in the Tibetan Plateau. Chinese Science Bulletin 54 (8), 1398–1410. http://dx.doi.org/10.1007/s11434-008-0588-7.

Copley, A., McKenzie, D., 2007. Models of crustal flow in the India–Asia collision zone. Geophysical Journal International 169, 683–698.

Clark, M.K., Bush, J.M.W., Royden, L.H., 2005. Dynamic topography produced by lower crustal flowagainst rheological strength heterogeneities bordering the Tibetan Plateau. Geophysical Journal International 162, 575–590.

Clark, M.K., Royden, L.H., 2000. Topographic ooze: building the eastern margin of Tibet by lower crustal flow. Geology 28, 703–706.

Dasgupta, S., Mukhopadhyay, B., 2014. 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. Journal of Engineering Geology (A bi-annual journal of ISEG) 39, 177–190.

Finnegan, N.J., Hallet, B., Montgomery, D.R., Zeitler, P.K., Stone, J.O., Anders, A.M., Yuping, L., 2008. Coupling of rock uplift and river incision in the Namcha–Barwa–Gyala Peri massif, Tibet. GSA Bulletin 120, 142–155.

Gupta, H.K., Singh, H.N., 1986. Seismicity of northeast India region: Part II: earthquake swarms precursory to moderate magnitude to great earthquakes. The Journal of the Geological Society of India 28, 367–406.

Hainzl, S., 2004. Seismicity patterns of earthquake swarms due to fluid intrusion and stress triggering. Geophysical Journal International 159, 1090–1096. http://dx.doi.org/10.1111/j.1365-246X.2004.02463.x.

Hickman, S., Sibson, R., Bruhn, R., 1995. Introduction to special section: mechanical involvement of fluid in faulting. Journal of Geophysical Research 100, 12831–12840.

Kuempel, H., 1991. Poroelasticity: parameters reviewed. Geophysical Journal of International 105, 783–799.

Lee, H.-Y., Chung, S.-L., Wang, J.-R., Wen, D.-J., Lo, C.-H., Yang, T.F., Zhang, Y., Xie, Y., Lee, T.-Y., Wu, G., Ji, J., 2003. Miocene Jiali faulting and its implications for Tibetan tectonic evolution. Earth and Planetary Science Letters 205, 185–194.

Mahesh, P., Catherine, J.K., Gahalaut, V.K., Kundu, B., Ambikapathy, A., Bansal, A., Premkishore, L., Narsaiah, M., Ghavri, S., Chadha, R.K., Choudhary, P., Singh, D.K., Singh, S.K., Kumar, S., Nagarajan, B., Bhatt, B.C., Tiwari, R.P., Kumar, A., Kumar, A., Bhu, H., Kalita, S., 2012. Rigid Indian plate: constraints from GPS measurements. Gondwana Research 22, 1068–1072.

Mukhopadhyay, B., Acharyya, A., Bhattacharyya, D., Dasgupta, S., Pande, P., 2011. Seismotectonics at the terminal ends of the Himalayan Arc. Geomatics. Natural Hazards and Risk 2 (2), 159–181.

Noir, J., Jacques, E., Bekri, S., Alder, P.M., Tapponier, P., King, G.C.P., 1997. Fluid flow triggered migration of events in the 1989 Dobi earthquake sequence of Central Afar. Geophysical Research Letters 24, 2335–2338.

Parotidis, M., Rothert, E., Shapiro, S.A., 2003. Pore-pressure diffusion: a possible triggering mechanism for the earthquake swarm 2000 in Vogtland/NW-Bohemia, Central Europe. Geophysical Research Letter 30, 2075.

Rajendran, K., Harish, C.M., 2000. Mechanism of triggered seismicity at Koyna: an evaluation based on relocated earthquakes. Current Science 79 (3), 358–363.

Ren, Y., Shen, Y., 2008. Finite frequency tomography in South eastern Tibet: evidence for the causal relationship between mantle lithosphere delamination and north–south trending rifts. Journal of Geophysical Research 113, B10316.

Seeber, L., Pecher, A., 1998. Strain partitioning along the Himalayan arc and nanga parbat antiform. Geology 26 (9), 791–794.

Seeber, L., Gornitz, V., 1983. River profiles along the Himalayan arc as indicators of active tectonics. Tectonophysics 92, 335–467.

Shapiro, S.A., Audigane, P., Royer, J.J., 1999. Large scale in situ permeability tensor of rocks from induced microseismicity. Geophysical Journal of International 137, 207–213.

Shapiro, S.A., Huenges, E., Borm, G., 1997. Estimating the crust permeability from fluidinjection- induced seismic emission at the KTB site. Geophysical Journal of International 131, F15–F18.

Shapiro, S.A., Rothert, E., Rath, V., Rindschwentner, J., 2002. Characterization of fluid transport properties of reservoirs using induced microseismicity. Geophysics 67, 212–220.

Shapiro, S.A., Patzig, R., Rothert, E., Rindschwentner, J., 2003. Triggering of seismicity by pore pressure perturbations: permeability related signatures of the phenomenon. Pure and Applied Geophysics 160, 1051–1066.

Sibson, R.H., 2002. Geology of the crustal earthquake sources. In: Lee, W.H.K., Kanamori, H., Jennings, P.C., Kisslinger, C. (Eds.), International handbook of earthquake and Engineering Seismology, vol. 81A. Academic Press, Amsterdam, pp. 455–473.

Tatham, R.H., Forsyth, D.W., Sykes, L.R., 1976. The occurrence of anomalous seismic events in eastern Tibet. Geophysical Journal of the Royal Astronomical Society 45, 451–481.

Telesca, L., Nascimento, A.F., Bezerra, F.H.R., Ferreira, J.M., 2012. Analyzing the temporal fluctuations of the reservoir-triggered seismicity observed at Acu (Brazil). Natural Hazards and Earth System Sciences 12, 805–811. http://dx.doi.org/10.5194/nhess-12-805-2012.

Tzschichholz, F., Wangen, M., 1999. Modellization of Hydraulic Fracturing of Porous Materials. WIT Press, Southampton, UK, pp. 227–261.

Wang, H., 2000. Theory of Linear Poroelasticity. Princeton University Press, Princeton, NJ.

Xu, Q., Shang, Y., Asch, T.V., Wang, S., Zhang, Z., Dong, X., 2012. Observation from the large, rapid Yigong rock slide- debris avalanche, southeast Tibet. Canadian Geotechnical Journal 49, 589–606.

Yamashita, T., 1999. Pore creation due to fault slip in a fluid permeated fault zone and its effect on seismicity: generation mechanism of earthquake swarm. Geophysical Journal of International 132, 674–686.

Zhang, P., Shen, Z., Wang, M., Gan, W., Bü Rgmann, R., Molnar, P., Wang, Q., Niu, Z., Sun, J., Wu, J., Hanrong, S., Xinzhao, Y., 2004. Continuous deformation of the Tibetan Plateau from global positioning system data. Geology 32, 809–812. http://dx.doi.org/10.1130/G20554.1.

Zhao, W.-L., Morgan, W.J., 1987. Injection of Indian crust into Tibetan lower crust: a two-dimensional finite element model study. Tectonics 6, 489–504.