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ARTICLE

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Abnormal disappearance of Duoqing Co lake between November 2015 and April 2016, due to far-field aseismic creeping of the southern Yadong-Gulu rift of Tibet, triggered by the 2015 Ms 8.1 Nepal earthquake

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ABSTRACT

Duoqing Co is a 60 km^2 outflow lake in the N-trending Pagri graben, located at the southern end of the Yadong-Gulu rift in Tibet. The water in this lake suddenly disappeared between November 2015 and April 2016, closely following the *Ms* 8.1 (*Mw* 7.8) Nepal earthquake in April 2015. Both, geomorphological and remote sensing data indicate the existence of blind faults striking NNE along the east boundary of Duoqing Co lake. There were also several nearly NE-trending extensional cracks preserved in the dried lakebed, apparently formed in response to creeping deformation of the underlying rock. Based on field studies and analysis of meteorological and remote sensing data, it is suggested that this phenomenon cannot be explained by evaporation linked to climate change nor can it be related to human activity. Instead, it is considered that the lake water drained through the extensional cracks formed in the lakebed as it responded to the far-field effects of the 2015 Nepal earthquake. It is proposed that a shift in regional tectonics occurred as a result of the Nepal earthquake, causing a sharp increase in stress accumulation along the seismically locked Bhutan–Sikkim zone on the Main Himalayan Thrust (MHT) fault, which was accommodated by the extension of the Pagri graben in the southern Yadong-Gulu rift. It is believed that the crust may have reached a critical stress-state that resulted in strain hardening and brittle failure throughout the region along the Bhutan–Sikkim segment of the MHT. If so, considering the high potential for tectonic activity along the segment of the MHT, it may be worth paying attention to deformational changes and potential geomorphological precursors that might appear in the seismically locked Bhutan–Sikkim gap to predict future earthquakes.

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Yadong-Gulu rift; nearly N-trending normal fault; the Bhutan–Sikkim earthquake gap; seismic hazard in the Himalaya

1. Introduction

Several large earthquakes, including the 2005 *Mw* 7.6 earthquake in Pakistan-administered Kashmir, the 2015 *Ms* 8.1 earthquake in Nepal and the *Mw* 7.5 Hindu Kush earthquake in Afghanistan, occurred successively along the MHT between 2005 and 2015, each resulting in heavy casualties. This sequence of large earthquakes could indicate that the world's most active continental collision belt has entered a new, more seismically active phase.

During field investigations along the Yadong-Gulu Rift in Tibet, it was observed that Duoqing Co, an about 60 km^2 outflow lake located in the Pagri graben in the southern part of the rift, had almost completely dried up. The rapid disappearance of the lake occurred within 6 months after the Nepal earthquake, which led to conjecture among researchers that some tectonic mechanism might be the reason behind it, rather than climate change or human activities. Available evidence was examined and three possible explanations for the disappearance of the lake were proposed: first, increased evaporation related to climate change, second, some change in the surface inflow or outflow within the local watershed, and third, lake drainage through subaqueous dilation cracks that formed in response to a shift in regional tectonics.

Historically, great earthquake events show a particularly obvious temporal and spatial correlation between the MHT and the southern Tibet rift zone. Some M ≥ 7.0 earthquakes usually occurred along the southern Tibet rift a few to a dozen years after an occurrence of a previous M ≥ 7.5 earthquake occurred along the MHT. The spatio-temporal correlation of great earthquake events implies a close genetic link between the two. However, after the 2005 Kashmir earthquake and the 2015 Nepal earthquake, there have been no M ≥ 7.0 earthquakes along the southern Tibet rift. Therefore, what caused the sudden drying up

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of Duoqing Co Lake – climate change, human activities or seismic activities? Furthermore, is this phenomenon a precursor to a large earthquake in the eastern part of the Himalaya or southern Tibet rifts? It is the aim of this paper to address the possible causes for the abnormally quick drying up of Duoqing Co, based on field geological investigations and combined with remote sensing and geomorphological data, from the perspective of the active tectonic system and seismological geology, and it will lay out the evidence for a potential connection between the abnormal quick drying up of Duoqing Co and future large earthquake hazards in the Himalayan orogenic belt.

2. Historical lake disappearances

There are numerous historical examples of other dramatic lake disappearances. For example, Lop Nor, formerly a salt lake in Northwestern China, was once an oasis with perennial lakes, which completely disappeared during the 20th century. Lop Nor is an example of a lake that disappeared completely after an upstream diversion of the river interrupting water influx and leading to a continuous drought (Qian 2004). A similar event occurred after a river was naturally diverted in Diexi of western Sichuan in 1933, when an M 7.5 earthquake caused a landslide that cut off the Minjiang River, forming a large natural dam which gradually formed a temporary lake. Five days after the earthquake, the hydraulic pressure exceeded the strength of the natural dam's walls, which failed, resulting in a tragic flood that inundated hundreds of square miles downstream and killed more than 20,000 people (Liu 2010). In theory, there are a variety of possible tectonic processes that could lead to lake disappearance, such as taphrogeny, and vertical or horizontal offset of streams along faults, or even drainage caused by uplift of the lakebed, although none of these phenomena have actually been observed so far in China. There are other lake disappearances that remain unexplained. For example, the Malay Lake near Tanzania in Africa periodically shrinks until it is almost completely dried up, then suddenly recovers, often even flooding the lakeshore. These variations in lake level seem to have no fixed pattern and the lake may recede for only 1 day to more than 10 days. Despite repeated investigations, these cycles of recession and recovery remains unexplained. A similar phenomenon occurs in Lake George, a freshwater lake near Canberra, Australia, which periodically disappears and reappears with an average period of about 12 years. These long lake cycles also remain mysterious.

In order to evaluate the different potential explanations for the rapid recession of Duoqing Co, a field investigation of the lakebed was conducted. Based on field investigations and combined with remote sensing and geomorphological data, aforementioned three possible causes for the disappearance of Duoqing Co were evaluated. Furthermore, the implications for this hypothesis in the broader context of the active tectonics system in the region were explored, and evidence for a potential connection between the disappearance of Duoqing Co and future large earthquakes in the Himalayan orogenic belt were considered.

3. Regional background of the Duoqing Co

Duoqing Co is located at 89°14′–89°29′E, 27°58′–28°36′N, at the junction of Yadong County and Kangmar County, near Xigaze. The Duoqing Co National Wetland Park covers approximately 320 km^2 (Liu *et al*. 2009). Duoqing Co is not a seasonal lake, although the lake has been slowly shrinking annually, since 2000 (Laba 2011). Duoqing Co is approximately rectangular, around 12 km long and 4–6 km wide, striking NE. In recent years, the surface area has been around 60 km^2 (Figures 1 and 5).

Duoqing Co lake is located in the Pagri-Duoqing Co basin on the northern slope of the Himalayas (Figure 1) surrounded by several glaciers with an elevation exceeding 6,000 m including the Kangshuoba glacier and several others on Chomolhari peak and Bubble peak, with the highest on Chomolhari peak at an elevation of 7,350 m (Figure 3(a)). The Pagri-Duoqing Co basin falls between 4,300 m and 4,400 m above sea level and its width varies between 1 km and 10 km. The topography surrounding it to the east and the south is extremely rugged, with mountainous glacial and river valleys at elevations of 5,800–6,000 m. To the west are more rugged mountains, with glacial valleys having an average elevation of 5,300–5,400 m (Figure 3(c)). There are several lakes within the basin – Duoqing Co lake in the north, and Gala Co Lake and Mabu Co Lake at its southern end. The significant relief between the basins and the surrounding mountains is typical of faulted basins in this area.

The Duoqing Co is located at the southern end of the Yadong-Gulu rift, filling one of several secondary faulted basins within the N–S-striking rift. The Yadong-Gulu rift is part of the northern edge of the convergent boundary formed by the subduction of the Indian plate under the Eurasian plate. Previous studies and remote sensing data show that the formation of the Pagri-Duoqing Co basin is controlled by the major boundary fault on the east side of the basin (Armijo *et al*. 1986; Wu *et al*. 2011; Wu et al., 2015; Figure 3). The eastern part of the Pagri-Duoqing Co basin is dominated by the Precambrian Yadong group, which mostly consists of plagioclase gneiss intruded by granite. The Tethys Himalaya sedimentary rocks that mostly consist of

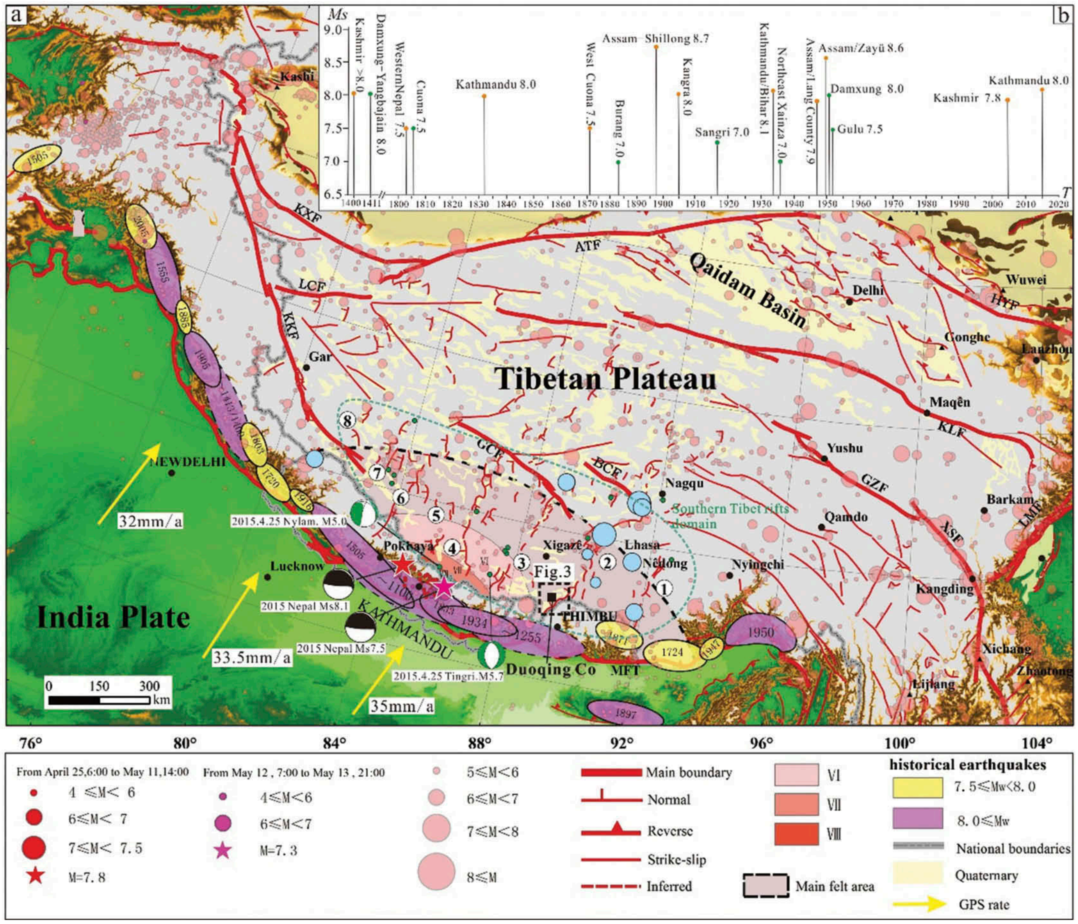

Figure 1. (a) Regional map of the Tibet Plateau showing active tectonic structures and the distribution of earthquakes, revised from Wu *et al*. (2016). (The Nepal earthquake data is from Bilham 2004; Avouac 2007; with GPS data from Bettinelli et al., 2006; The focal mechanism solution data from 【】】USGS, 2015; Institute of Geophysics CEA, 2016). The black focal mechanism solution represents the 2015 Nepal earthquake and a strong aftershock. The green focal mechanism solutions represent the activity of two moderately sized earthquakes trigged by the Nepal earthquake in Nylam and Tingri County, southern Tibet. The green circles show the locations of these moderately sized earthquakes (M ~ 5) in southern Tibet that occurred after the 2015 Nepal earthquake. The blue circles show the locations of historical moderate to large-sized earthquakes triggered by very large thrust fault earthquakes in the Himalayas before the 2015 Nepal earthquake. Rifts in south Tibet labeled 1–8: ① Cona-Oiga rift; ② Yadong-Gulu rift; ③ Dinggye-Xainza rift; ④ Gangga-TangraYumco rift; ⑤ Nyalam-Coqên rift; ⑥ Zhongba-Gêrzê rift; ⑦ Kunggyu Co-Yagra rift; ⑧ Burang-Gêgyai rift. Main active faults in the region: MFT-Main Frontal Thrust fault zone of Himalaya; KKF-Karakorum fault zone; GCF-Gyaring Co fault; BCF-Beng Co fault; GZF-Ganzi fault zone; XSF-Xianshuihe fault zone; KLF-Kunlunshan fault zone; LMF-Longmenshan fault zone; LCF-Longmu Co Fault; KXF-Kangxiwa fault zone; AFT-AltynTagh fault zone; HYF-Haiyuan fault zone. (b) Magnitude (Ms) vs. Time (T) plot showing historical seismic activity throughout the Himalaya and southern Tibet (showing earthquakes M > 7.0). The orange circles indicate earthquakes that occurred along the Himalayan orogenic belt while the green circles represent earthquakes that occurred on faults in the southern Tibetan rift zone.

black shale and limestone of the Lower Jurassic Luotong Ridang Formation, dominate the western part of the basin. The central part is dominated by loose sediments dating from the Pliocene (Figure 3(b)), followed by Pliocene fluvial and lacustrine fine sand layers interlayered with clay, Early Pleistocene fluvial gravel, Middle Pleistocene glacier-ice water gravel, and Late Pleistocene lacustrine sand and clay. The total thickness of the Late Cenozoic sediment layer is about 1,500 m (Cogan et al., 1998).

4. New observations

On June 28th, 2016, when field investigations were conducted at Duoqing Co, the lake, which had been full during the same period in the previous year, had become almost completely dry. Except for the northern and southern ends, it resembled an aeolian desert landscape (Figure 2(a,b)). Inquiries conducted at the nearby Duoqing and Qionggui villages regarding the abnormal disappearance of the lake revealed that the level of Duoqing Co had begun to decrease around November 2015 and reached a low

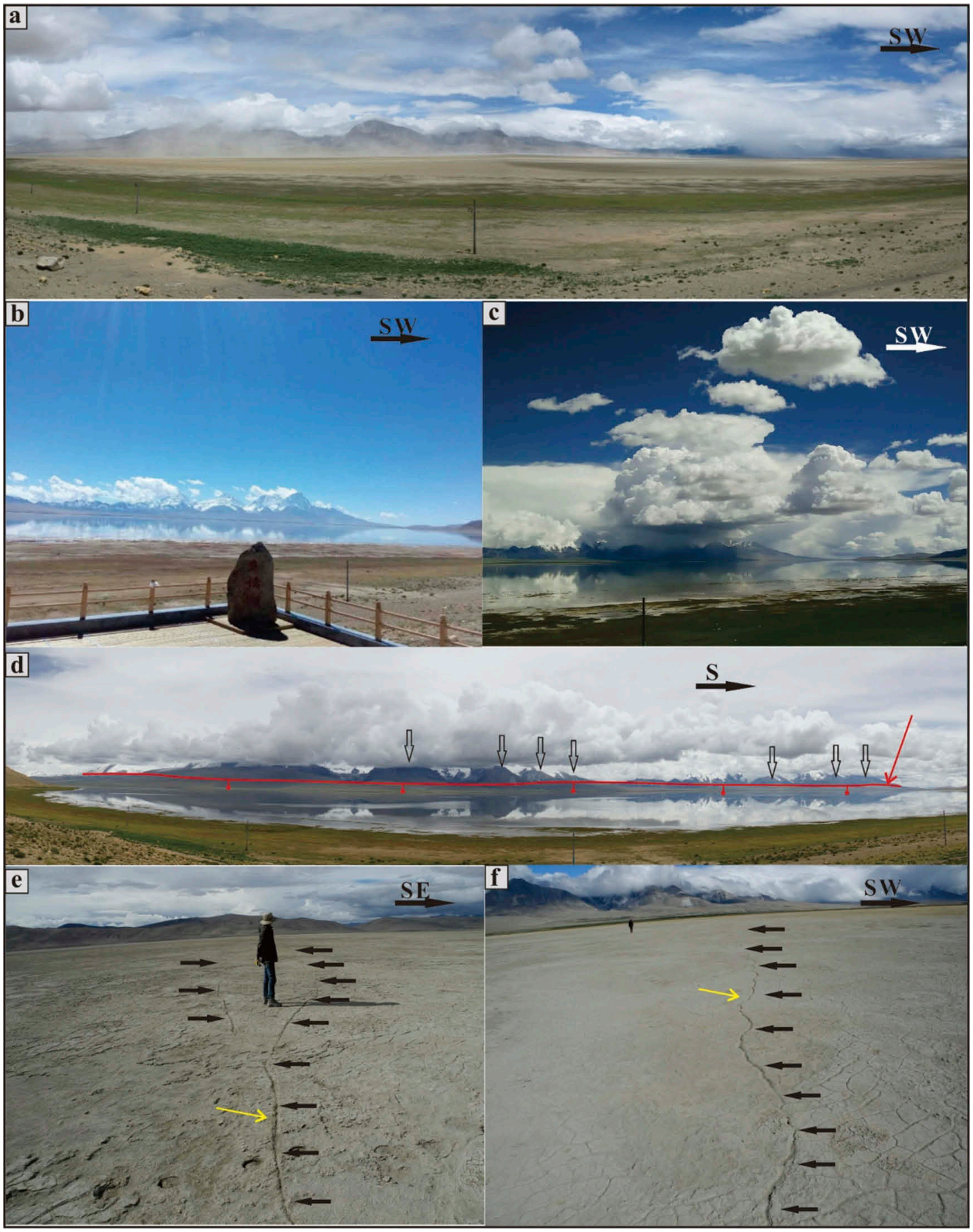

Figure 2. Pictures of Duoqing Co during different stages of recession. (a) A panorama of dried Duoqing Co in early June 2016. (b) Duoqing Co filled with water in October 2015. (c) Duoqing Co filled with water in mid-late August 2016. (d) Traces of the eastern normal fault and the significant fault facets of the fault controlling Duoqing Co's basin, the photo was taken in August 2014). (e–f) Extensional cracks in the dry lakebed of Duoqing Co.

around the Tibetan New Year, in March or April of 2016. The elderly residents of the nearby villages attested that this was the first time in its history that the lake level had fallen so low in such a short time.

The lake bottom is nearly flat, having an elevation ranging from 4,475 to 4,480 m. The lakebed deepens toward the southwest. On surveying the Duoqing Co lakebed, dead and desiccated seaweed were found, along with large areas covered by mollusk shells. No dead fish were found, although there were previously rich fish reserves in Duoqing Co. Field investigations revealed that the Duoqing Co basin is surrounded by

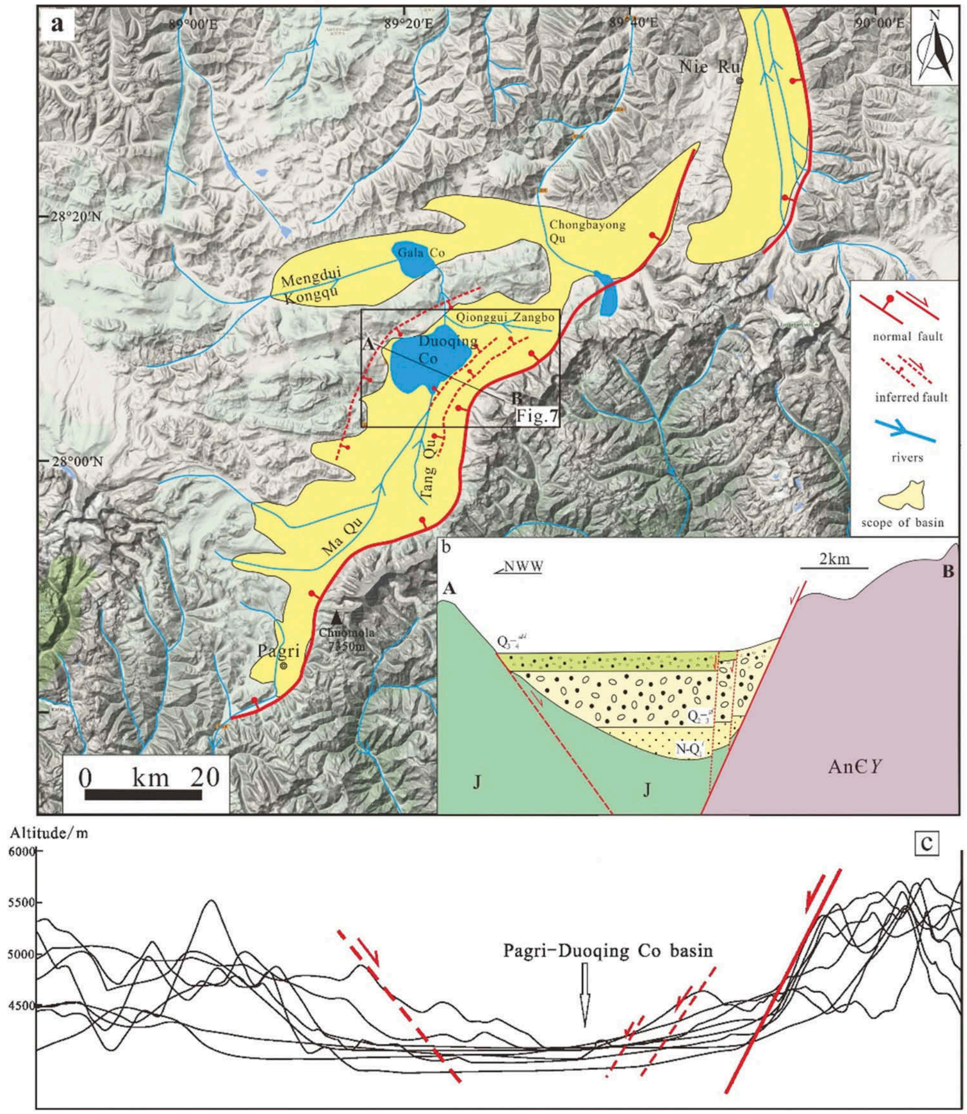

Figure 3. (a) Topography and the drainage structure of the Pagri-Duoqing Co basin. (b) Schematic cross sedimentary section of the Duoqing Co basin (this section is located along line A–B in Figure 3(a)). $Q_{3\text{-}4}^{l-al}$ is alluvium and lacustrine sediments of late Pleistocene to Holocene. $Q_{2\text{-}3}^{gl}$ is moraine and fluvio-glacial conglomerates of middle to late Pleistocene. N-Q_1^{l} is Neogene to early Pleistocene lacustrine. J is Jurassic; AnЄY is the pre-Cambrian Yadong group). (c) Topographic section of Pagri-Duoqing Co basin showing the locations of normal faults.

swamps and swampy meadows and wetlands, especially on the eastern side. The 400,000 m^3 Yalu reservoir was built in 2013 by the Kangmar County government on the Yalu River, which connects Duoqing Co and Gala Co. Artificial canals were constructed to guide additional water from the Qionggui Zangbo River into this reservoir.

One-meter deep trenches were dug in the Duoqing Co lakebed, and mostly gray fine sand and silty sand, free of plant materials were found near the bottom of these trenches. Above these layers was a silt clay layer around 10 cm in thickness, covered by a fine sandy layer containing waterweed roots and shells at the bottom. These strata are clearly Holocene-age lake facies (Figure 4(a)). Frequent NE-striking fissures were also discovered in the lakebed. These extensional fissures cut a 4 km by 2 km swath east–west across the lake. They tend to have a very consistent strike and are generally more than 500 m long. In terms of scale and structure, they are unmistakably different from the much smaller-scale hexagonal mud cracks formed as muddy sediment dries and contracts (Figure 4(b)). On-site excavation showed that these fissures had been filled by aeolian sand (Figure 4(c)), indicating that these extensional fissures probably formed during the lake's disappearance.

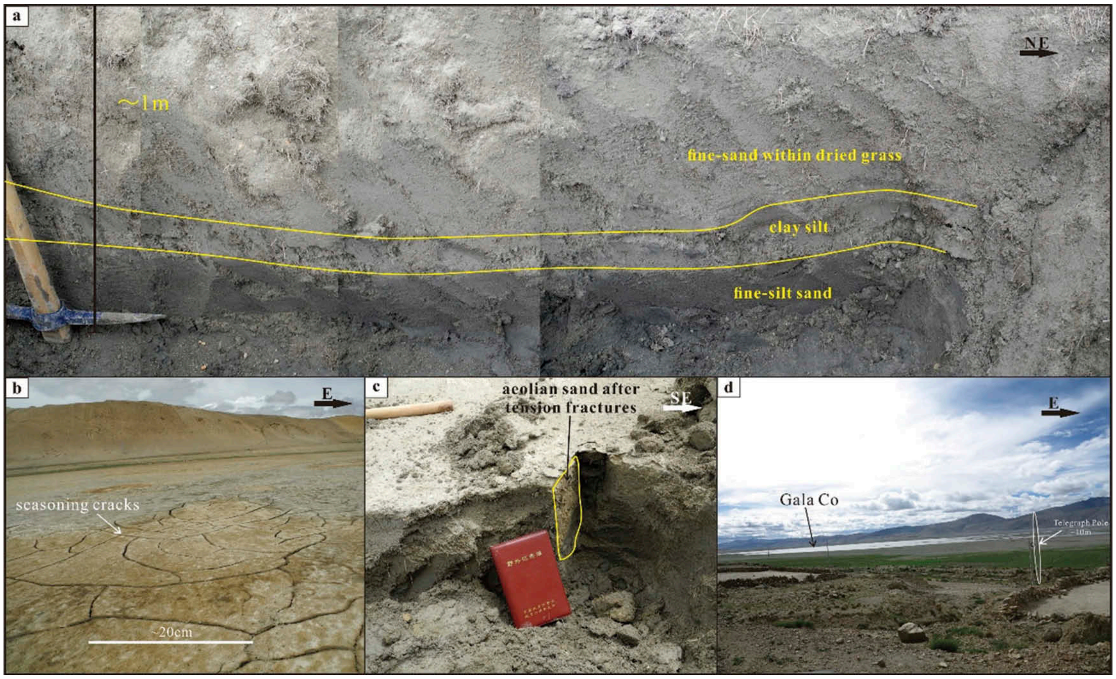

Figure 4. Duoqing Co and Gala Co. (a) deposition under the lake at a depth of 1 m. (b) hexagonal morphology of mud cracks on the dried lake. (c) NE-trending extensional cracks and sand transported by wind in the cracks on the dried lake. (d) Gala Co in late June 2016 (without obvious decrease compared to past years).

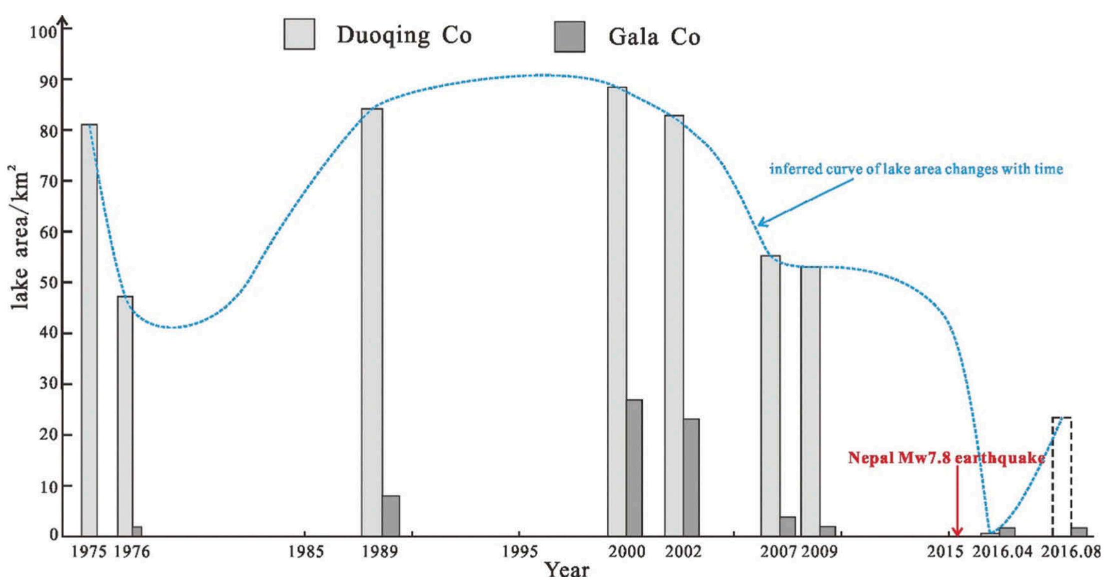

Figure 5. Diagram of the lake area of Duoqing Co and Gala Co versus time (adapted from Yang and Li 2013). The dashed line represents an estimate for lake area following the lake's partial recovery post August 2016.

5. Abnormal disappearance of Duoqing Co

Duoqing Co is located in a cold plateau, in a semi-dry climatic zone. The area suffers from a harsh climate with little rainfall and abundant sunshine. Duoqing Co and Gala Co together form a closed drainage basin, and are typically wetland lakes supplied by meteoric water and snowmelt from the southern Tibetan plateau. Two major rivers, the Ma Qu and the Qionggui Zangbo run into Duoqing Co, while the Menduigong Qu is the main river running into Gala Co (Figure 3(a)). As Duoqing Co is higher than Gala Co, the water from Duoqing Co flows into Gala Co through the Yalu River. In recent years, rising temperatures led to increased evaporation and decreased precipitation, resulting in glacial recession and decreased river flow. Many of the surrounding streams dried up completely or have become seasonal streams. The net result of increased evaporation and reduced influx has progressively shrunk Duoqing Co. Laba (2011) conducted a climatological study that measured the lake's surface area each year from 1975 to 2009 using remote sensing imagery, and established that Duoqing Co reaches its maximum level each year around November and approaches its minimum level around February or April. The lake covered an area of about 80 km^2 prior to 2002, except for a low in 1976. In 2000, the lake's surface area reached 90.3 km^2, which was followed by a dramatic shrinkage period between 2001 and 2005, reaching 56.8 km^2 by 2009. Remote sensing imagery from 2014 to 2016 shows the lake area fluctuating significantly before and after its disappearance in 2016 (Figure 6), however, in contrast to both the pattern of seasonal variability and the long term trend of lake recession, this sudden event occurred within just 5 months. Based on the unprecedented rate and magnitude of the decrease in the lake level in 2016, this sudden recession unquestionably appears to be an abnormal phenomenon.

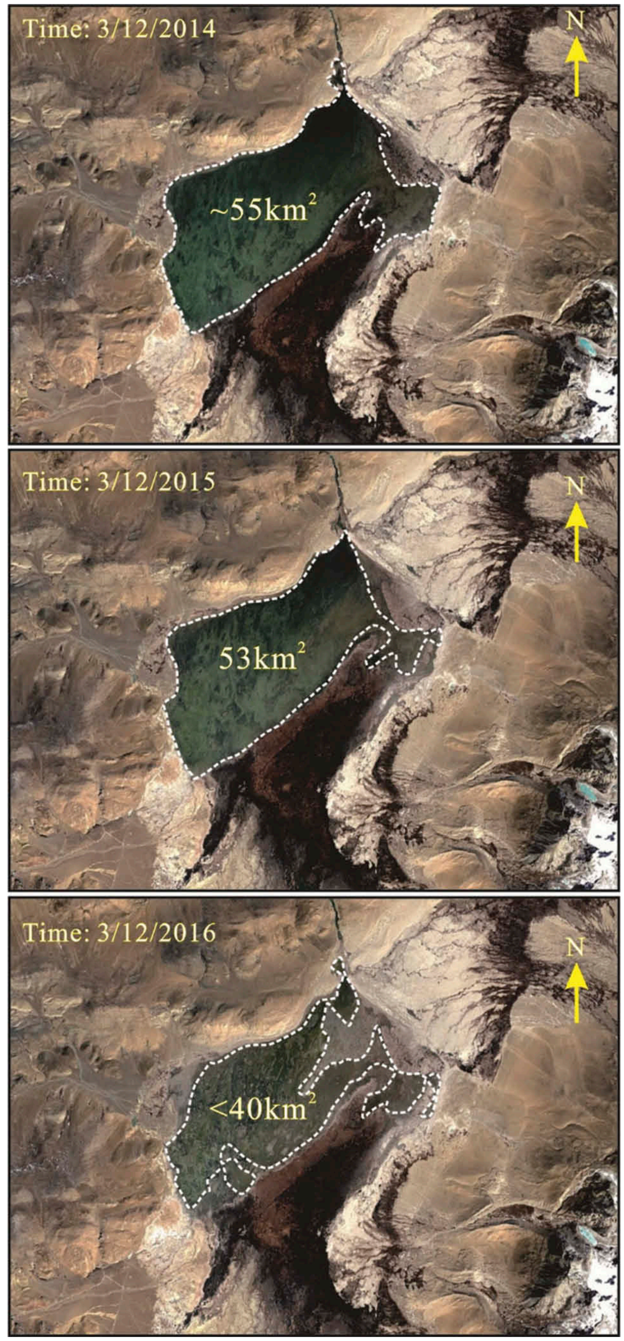

Figure 6. Satellite Imagery (Google Earth) showing changes in the extent of Duoqing Co from 2014 to 2016, indicating lake surface and position of the lakeshore (white dotted line).

5.1 Evolution process of the quick drying of Duoqing Co

Based on previous studies, it was concluded that the disappearance of Duoqing Co occurred in two distinct stages: first, a period of gradual shrinkage followed by a second shorter period of accelerated decline. Recently, Duoqing Co seems to have entered a third stage in which lake levels are recovering.

Stage I, the period where the lake's surface area shrank relatively slowly occurred between 2000 and 2015. Remote sensing data indicates that the Duoqing Co area started to shrink in 2000, from a high point of 90 km^2 until it covered an area of only 60 km^2 by 2009 (Figure 5). This decline occurred slowly enough to be explained by a reduction in the influx of meteoric water caused by a change in the regional climate toward warmer, drier conditions during this period (Laba 2011).

Stage II, the period of rapid decline in the lake's surface area occurred between November 2015 and April 2016. During this stage, Duoqing Co started to recede much more rapidly after November 2015, about 6 months after the 2015 Nepal earthquake. Within less than 6 months, the lakebed had become completely dry, exposing a dense network of fissures. These fissures usually extended for over 500 m, and have a consistent NE-trend, indicating that they are tension fractures and not desiccation cracks (Figure 2(d–g)). These interconnected dilation cracks seem to have been formed under significant extensional strain, and may have comprised a permeable network that rapidly drained the lake. Based on the geomorphological impact to the lakebed, the rate of extension during this stage seems to have been much greater than it was during the first stage, possibly indicating a change in the regional tectonic stresses on the lake.

Stage III, recovery of lake levels from July through August 2016.

Starting in August 2016, photos showed the water level of the lake had begun to recover (Figure 2(c)).

Although the shoreline of Duoqing Co tends to expand during the rainy season, the rainfall during late 2016 was similar to historic trends, hence, it seems unlikely that this recovery can be entirely attributed to two months of abundant rainfall. This is also supported by remote sensing images, which indicate that in December 2016, the lake's surface area was two-thirds the area in December 2014 (Figure 6). It is presumed that the extension fractures in the lakebed may have closed or clogged due to sediments, which enabled meteoric water to collect in the lakebed.

5.2 Relationship between abnormal dry period and regional climate

Next, whether the timing and pattern of the lake's disappearance was correlated with a commensurate change in regional precipitation was investigated. Based on remote sensing data, it is clear that there was a sudden fall in the lake's level from December 2015 to April 2016. A GPS field survey of the old shoreline revealed that the original lake elevation prior to this drop was 4,482 m, with a surface area around 60 km^2. It is estimated that the volume of water lost was in the range of 120–420 million m^3. The annual precipitation varied greatly during the 50-year interval between 1960 and 2010. However, averaged over the long term, annual precipitation has remained relatively constant during this interval (Figure 7). Between 2010 and 2015, there was much greater precipitation in southeastern China than in the northwest http://cmdp.ncc-cma.net/cn/index.htm. However, there has been little change in precipitation in the region surrounding Duoqing Co. For the past 50 years, rainfall has consistently remained within a range of 400–600 mm/a (Figure 7). The seasonal precipitation data between December 2015 and February 2017 was compared to the long-term average. Precipitation in the rainy season at Duoqing Co is much higher than it is in the dry season, however, average precipitation within the rainy or dry season during this period have low variability and are similar to the historic average. There is no clear correlation between precipitation data and the lake level. In addition, if climate had been the main cause of the 2016 recession of Duoqing Co, the adjacent lakes should have also shrunk. However, Lake Gala Co and Lake Mabu don't show any dramatic decrease in volume.

To calculate the time Duoqing Co took to dry up based natural conditions, the formula is expressed as:

$$T = Dep/(He - Ha - Hm) \quad (1)$$

$$Hm = Vm/S \quad (2)$$

T is the time taken for Duoqing Co to dry up. *Dep* is the depth of Duoqing Co during normal conditions that is 1–2 m. *He* and *Ha* are the annual evaporation and annual precipitation in Duoqing Co, respectively. *Hm* is the supply rate from melting glaciers around Duoqing Co, while, *Vm* is the volume of supplied meltwater to Duoqing Co and *S* is the area of Duoqing Co.

Based on remote sensing data, the meltwater runoff was 2.99×10^8m^3/a in the past 40 years around Nyenchen Tanglha glacier in Central Tibet (Fei *et al*. 2016). Utilizing Google Earth, it was estimated that the area of this glacier was approximately 4,000 km^2, while the glacier at Duoqing Co was estimated to be about 400 km^2. As the two regions share a similar climate, a similar melting rate of the glacier was considered for these two glacial regions. Under this circumstance, the estimated meltwater from the glacier that flowed into Duoqing Co was approximately 0.3×10^8m^3/a. Therefore, *Hm* is about 500 mm/a. Taking average *He* and *Ha* for the past 50 years from Figure 7, T was calculated to be greater than 1–2 years using Formula (1), which was significantly

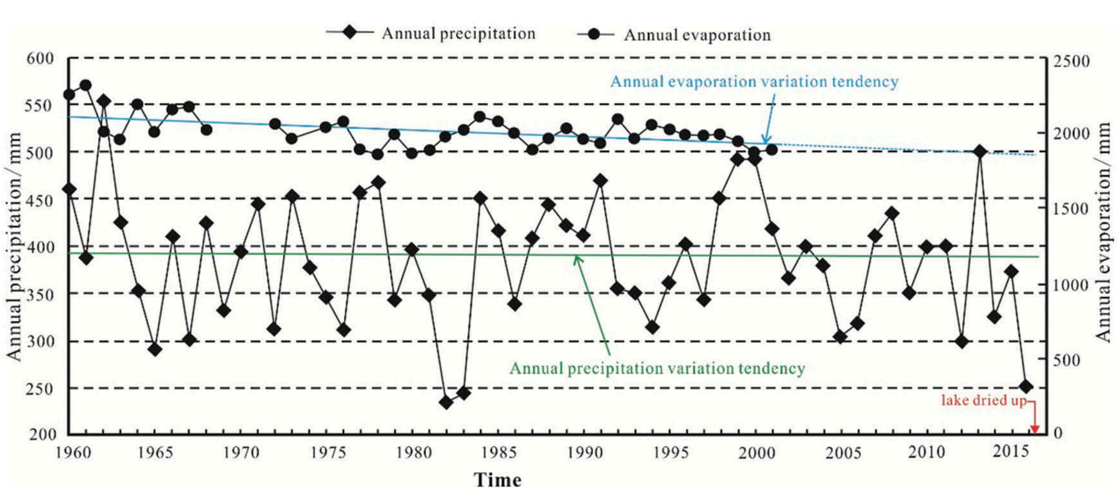

Figure 7. The change of annual precipitation and evaporation at Duoqing Co from 1960 to 2016 (adapted from Yang and Li 2013).

different from this drying up event (0.5 year). However, this estimate is achieved based on extreme conditions without taking into account ground water supply and any other precipitation data not obtained. Furthermore, remote sensing data suggests that the chance in glacier mass in the eastern Himalayas could reach 0.78–0.89 m/a (Gardner *et al*. 2013; Neckel *et al*. 2014). If all of the melt-water around Duoqing Co flowed into the lake, then, the lake area would increase every year.

6. Discussion

6.1 Tectonic origin of the abnormal drying up of Duoqing Co

As mentioned previously, it is considered that climate was probably not the main factor in the 2016 drying up of Duoqing Co. Instead, it is considered that the disappearance of Duoqing Co was most likely caused by rapid draining of water. The possible pathways this water could have followed include river channels, artificial hydrologic structures and permeable fractures. There is geological evidence that the Duoqing Co-Gala Co lake system has existed for tens of thousands of years (Liu *et al*. 2006, 2009; Kun *et al*. 2012). Duoqing Co and Gala Co form a closed system (Figure 3(a)) with Duoqing Co at a higher elevation, hence the first place to look for water disappearing from Duoqing Co would be in the Gala Co. However, field investigations did not indicate any noticeable rise in the level of Gala Co (Figure 4(d)). If water was draining from Duoqing Co, it did not flow into Gala Co and it seems unlikely that most of the lake water could have escaped through the existing outflow channel without affecting the downstream lake. Finally, there is no hydrologic infrastructure in the area that could have drained Duoqing Co. However, a network of dilation cracks observed on the dry lakebed suggests a third possibility – Duoqing Co most likely lost most of its lake water through extensional fractures that formed in a previously impermeable layer, potentially entering the Quaternary–Neogene sequence beneath the lake. This event would not have led to dead fish, as the fish could still swim into the Gala Co Lake or the Qialu reservoir.

These fractures most likely formed by extension across the lake in response to a sudden change in the regional tectonic stress field. The tension fractures, which cut a 4 km by 2 km swath east–west across the lake (Figure 2(d–g)), mainly strike NE, parallel to the major bounding faults of the Pagri-Duoqing Co basin (Figure 8). Remote sensing data shows the east shore boundary of Duoqing Co lake is linear with no obvious cliffs or fault scarps, and is approximately parallel to the major west-dipping fault bounding the eastern edge of the graben and the western bounding fault. Stepped normal faults parallel to the linear bounding faults are a common structure in grabens, hence, this linear, well-aligned eastern lakeshore might indicate the presence of a secondary normal fault running under the lake and wetlands (Figure 8). The tension fractures encountered during the study could be the surface expression of extension across a blind normal fault or a series of normal faults.

6.2 Genetic relationships between the extensional expansion of Duoqing Co and Nepal earthquake

The epicenter of the 2015 M 8.1 Nepal earthquake was around 400 km from Duoqing Co Lake, and its after-shocks were distributed along major NW–W striking fault zones, with the strongest aftershock (M 7.5) occurring 300 km away. The southern part of Duoqing Co is crossed by the Bhutan–Sikkim section of the eastern Himalaya, which happens to be a seismic gap in the Himalayan orogenic belt (Wu *et al*. 2016). The most recent great earthquake to occur here was an M 8 earthquake in 1255 CE, which elapsed time has clearly exceeded the about 400–680 years recurrence interval of earthquake along the Himalayan thrust fault zone (Bilham et al, 2001; Wu *et al*. 2016). This long gap between earthquakes could indicate that this section of the Himalayan thrust fault zone has accumulated more unreleased stress and has an increased potential for great earthquakes (Bilham et al, 2001).

Data from paleo-earthquake studies and the historical record of seismic activity in the area suggest that seismic recurrence follows a pattern, wherein adjacent sections on the MHT zone rupture in sequence (Wu *et al*. 2016; Zhao et al., 2015). When the stress that had accumulated in the Himalayan region in Nepal was released during the 2015 Nepal earthquake, it increased the stress on the seismically locked Bhutan–Sikkim zone, possibly causing enhanced viscoelastic deformation in the Pagri graben. The increased extension may have opened up porous pathways underneath the lake, explaining the rapid disappearance of Duoqing Co several months after the Nepal earthquake. This is consistent with the pattern of seismicity following the main earthquake. There were 23 M > 3 earthquakes prior to the Nepal earthquake and 60 after the earthquake in a comparatively similar period of time, with 78 M > 3 earthquakes by the end of 2016 (Figure 9; seismic static area shown in Figure 1 the dashed green circle). Several moderately sized aftershocks occurred along faults within the southern Tibet rift zone (Figures 1 and 9), far away from the epicenter of the Nepal earthquake and sometime after the main earthquake, suggesting that this earthquake had

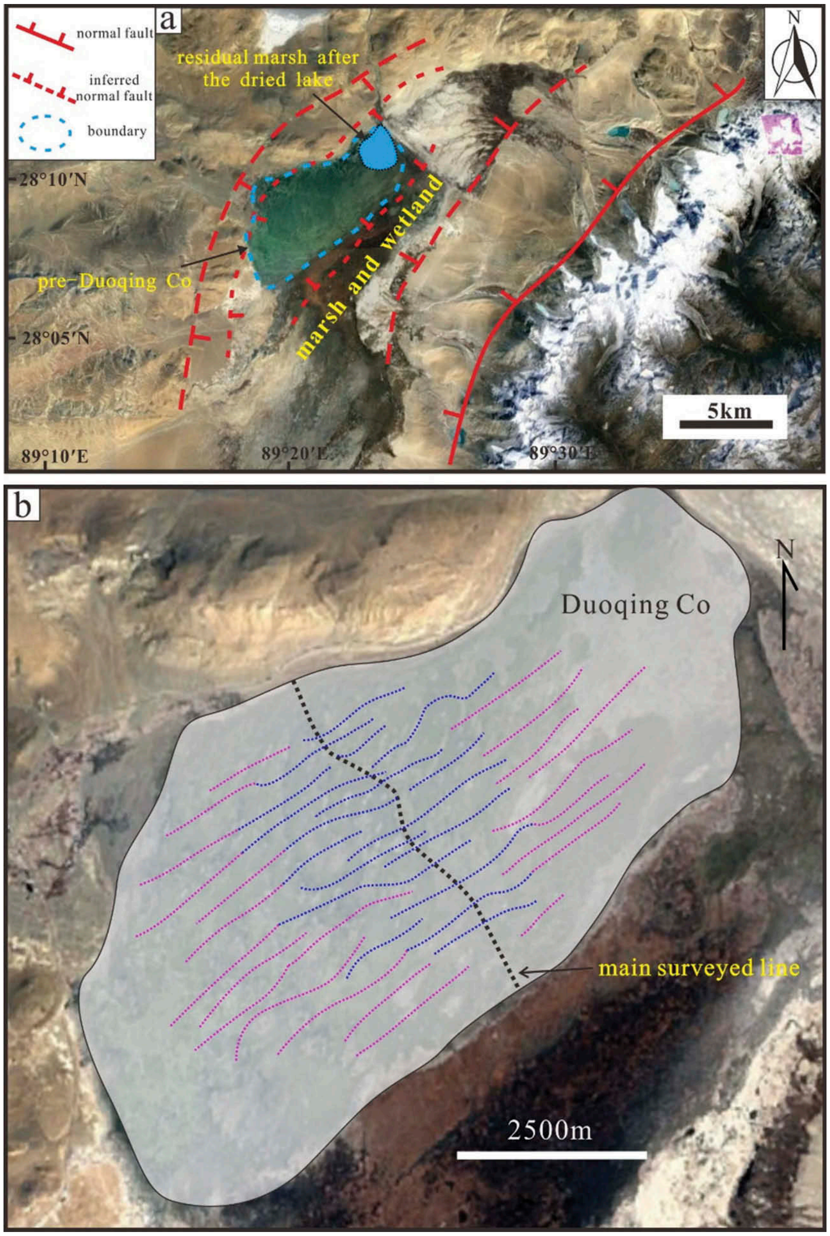

Figure 8. (a) Satellite image (Google Earth) of the region showing the locations of graben bounding normal faults and the inferred locations of blind normal faults under Duoqing Co and surrounding marshes. (b) The distribution of tensional cracks appearing on the lakebed of the dried-up Duoqing Co. The white shaded shows the area of Duoqing Co. The dark blue dashed lines show approximate distribution of the cracks observed in the field, while the purple dashed lines show the inferred cracks. The dark dashed thick line shows the rough location of the surveyed line in the field.

a significant seismic effect on active structures all across southern Tibet. The combined evidence suggests a high amount of stress was transferred to the southern Tibet rifts, potentially, over an extended period of time. This also has implications for increased regional seismicity. No evidence of M > 3 seismic activity was found near Duoqing Co https://earthquake.usgs.gov/; hence it is instead proposed that extensional strain could have been released by creeping deformation.

The data of the six GPS observation stations around Duoqing Co (three continuous observation stations: LHAS, XZRK and XZYD, three flow observation stations: J352, J353 and J356) (Figure 10(a)), showed that the vertical movement rate and the eastward movement rate of the crust both changed to different degrees before and after the Nepal earthquake in 2015 (Figure 10(b–g)). The eastward movement rate of these points located on the west side of the main boundary fault of the Duoqing Co graben had noticeable deceleration, which may indicate the acceleration of basin expansion. At the same time, a number of GPS stations have also indicated possible basin subsiding after the Nepal earthquake. In particular,

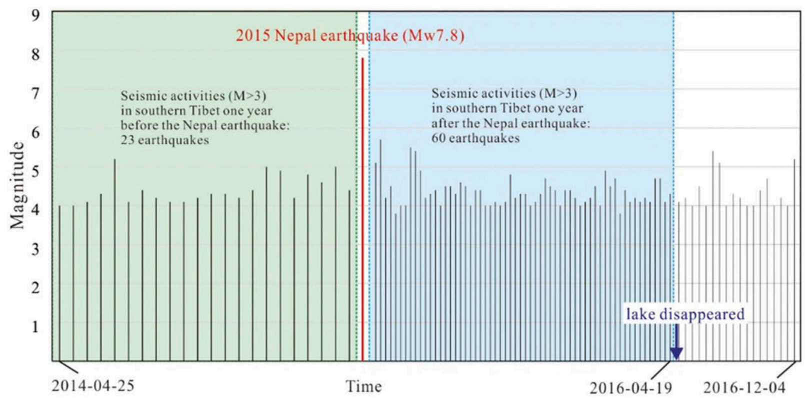

Figure 9. Magnitude (M) vs. Time (T) plot showing seismic activity in southern Tibet showing the years before (green highlight) and after (blue highlight) the 2015 Nepal earthquake (data from USGS https://earthquake.usgs.gov/).

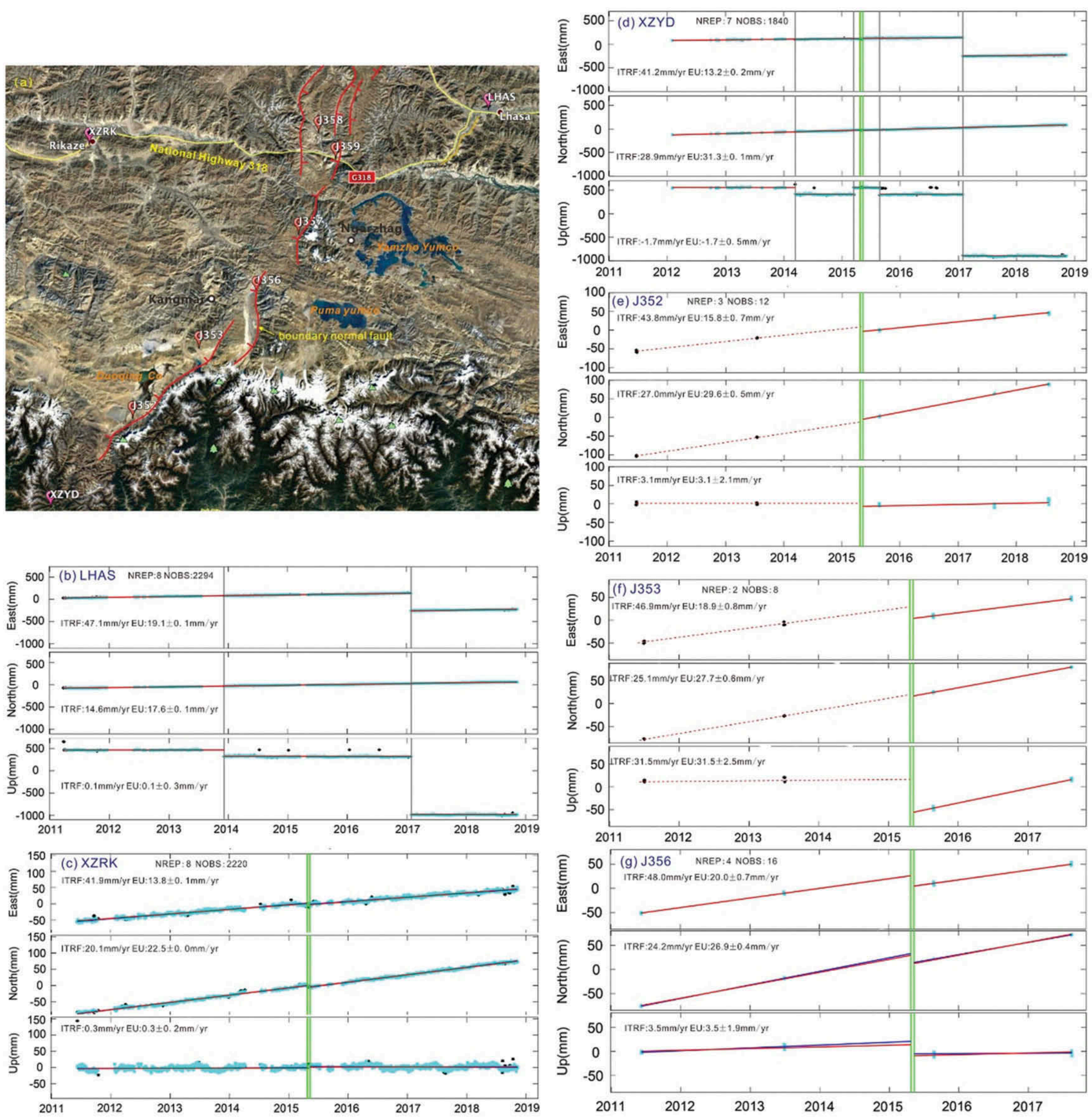

Figure 10. (a) The sites of six GPS observation stations around Duoqing Co. The (b)-(d) and (e)-(f) are rate profiles of three continuous observation stations: LHAS, XZRK and XZYD, and three flow observation stations: J352, J353 and J356 respectively. These rate profiles include the Eastward movement rate, Northward movement rate and vertical rate of the points acquired from these stations. ITRF: Relative rate to global, EU: Relative rate to Siberia, NREP: Number of observation periods (generally 2 years is a period), MOBS: Effective observations (days). Double green line: Nepal earthquake in 2015, Gray line: abnormal rate.

the vertical motion rates of 3 observation points (XZYD, 352 and 353) close to the Duoqing Co all changed significantly (Figure 10(d–f)). Although the limited data cannot be taken as direct evidence of creep deformation of the Duoqing Co graben, they can still suggest that the Nepal earthquake had a significant impact on the surface deformation around the Duoqing Co graben.)

Based on the aforementioned evidences, it is suggested that the water of Duoqing Co may have drained through the dilation cracks later observed on the lakebed, and that these were formed due to creeping extension of the units underlying the lakebed. The source of increased stress across the basin was the 2015 Nepal earthquake, which distributed increased extensional stress to rift bounding faults in southern Tibet, including the Pagri, where units within the upper crust immediately below Duoqing Co underwent viscous elastic deformation, and also led to brittle failure on shallow tension fractures in the thick sediments under the lake. It is believed that the process occurred in 3 stages (Figure 11). During stage 1, before the 2015 Nepal earthquake, the crust under Duoqing Co and nearby areas underwent extension under the influence of the MHT zone and E–W extension of Pagri graben (Figure 11(a)). During stage 2, the upper crust of Duoqing Co and adjacent areas were subject to increased stress focused on the region after the Nepal earthquake, which resulted in viscoelastic deformation and concurrent tensional fractures below the Duoqing Co Lake. There was increased permeability in the sedimentary strata under the lake due to dilation cracks, allowing the lake water to escape (Figure 11(b)). A large volume of water continued to leak over a relatively long period of time. At the same time, the lake fish travelled with the retreating water to the Qialu reservoir, Gala Co Lake or neighboring marsh wetlands downstream. Finally, during Stage 3, after the fractures closed or filled and lost connectivity to the porous Quaternary–Neogene sequence below the lakebed, the lake level rebounded during the subsequent rainy season (Figure 11(c)).

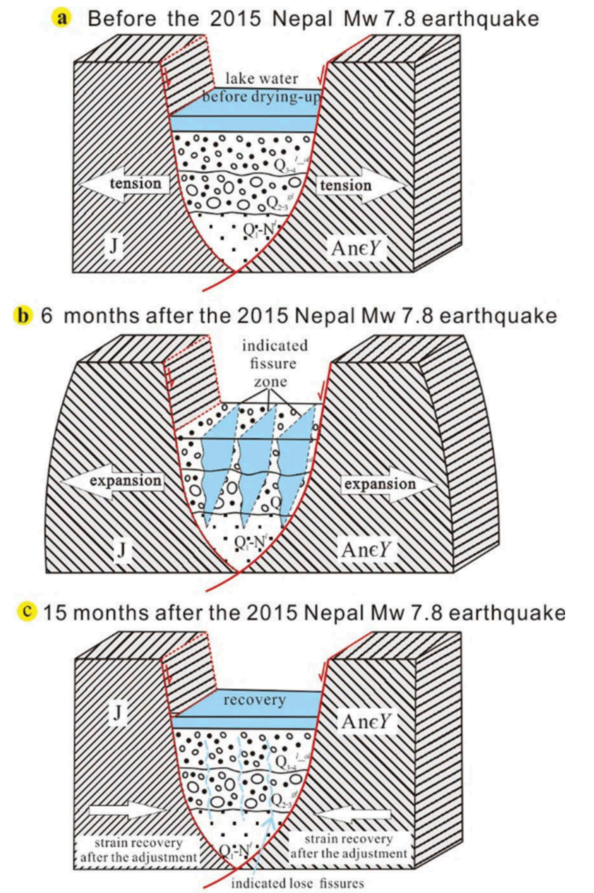

Figure 11. Conceptual model of the process of drainage and recovery of Duoqing Co in 2016. (a) Stage 1 – Extensional stress accumulates slowly and the strain rate is low. This reflects the previous stress state in the region, slow E–W extension of the rift zone as a response to N–S compression of the Himalayan orogenic belt. (b) Stage 2 – E–W extensional stress increases, leading to higher strain, aseismic creep beneath the lake and the concurrent formation of dilation cracks in the lakebed. This stage may have been triggered by a transfer of stress from central Nepal to the proximal Bhutan–Sikkim segment of the Main Himalayan tectonic belt after the 2015 Nepal earthquake. (c) Stage 3 – Lake recovery, probably signifying the closure of drainage pathways, signaling the end of a period of enhanced extension as well as the start of the rainy season in the Tibetan plateau.

6.3 Potential seismic hazard on MHT and southern Tibet rifts

This abnormal event at Duoqing Co is evidence of significant new stress across Pagri graben, and illustrates the potential for far field transfer of stress from the Main Frontal Thrust to rift bounding faults in southern Tibet, potentially raising the risk of local earthquakes following each large event in the MHT. Furthermore, seismologists studying the region, have now found clearer indications of a potential risk of a future earthquake in the Bhutan area. Paleo-seismological studies of Bhutan have uncovered several large historical and pre-historic earthquakes that occurred in Bhutan and its surrounding regions. The most recent earthquake took place in 1713 and had an estimated magnitude of earthquake in the range of 8.7–9.1. Significantly, this event is far less recent than any earthquakes in the other sections, hence Bhutan comprises a seismic gap in the Himalaya seismic Belt (Hetényi *et al.* 2016; Le Roux-Mallouf *et al.* 2016). Analysis off the stress-strain energy release curve for the MHT suggests that the MHT has reached a new more active phase of large earthquake activity following a quiet period of stress accumulation since 1950 (Wu *et al.* 2016; Zhao et al., 2015). The total energy accumulated during this quiescent period is

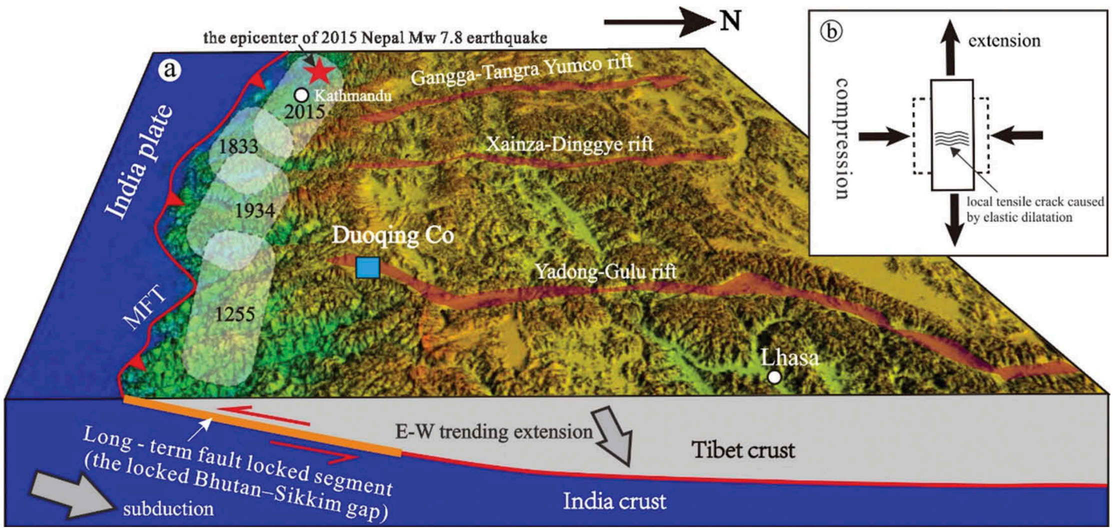

Figure 12. A schematic diagram to explain the possible dynamic connection between the elastic dilatation of the Duoqing Co graben of the south Tibet rift and the stress-strain enhancement along the locked Bhutan–Sikkim gap of MFT result from the 2015 Nepal Mw 7.8 earthquake. a: A block map showing the relation between the MFT and north-trending rifts of southern Tibet. b: A sketch map showing the dynamic mechanics between the compression and extension of elastic block. The dashed translucent rectangles with numbers show the latest rupture zones of large earthquakes (M ≥ 8) and corresponding occurrence time along the Himalaya. The red lines show the thrust of MFT and the transparent red shadows bands show the north-trending rift traces.

equivalent to several M > 8 earthquakes. Data of earlier strong earthquakes on the MHT, reveal an apparent trend of repeated waves of strong earthquakes migrating event by event from the western to the eastern side of the MHT over a 60–90 year interval. Recent seismic activity in the Himalayas included an M 7.5 earthquake in Pakistan in 2005, and an M 8.1 earthquake in Nepal in 2015, follow the west to east trend observed during past earthquake migrations. Extrapolating this into the future, the next large earthquake can be expected to occur somewhere in the eastern Himalaya. Potentially, the M_w 6.4 earthquake that occurred in Nyingchi on November 18th, 2017 https://earthquake.usgs.gov/ is a precursor to a larger earthquake, since significant stress likely remains on the fault. Although the exact structural model explaining this pattern of east–west seismic migration along the MHT remains unclear, it is at least supported by the current available evidence of the earthquake record. This indicates that Bhutan currently has a high potential for large earthquakes, which was previously overlooked due to a lack of paleoseismic data. As part of the Himalayan orogenic belt, it is possible that Bhutan may experience an M 7.0 earthquake at some point in the future (Le Roux-Mallouf *et al*. 2016).

An evidence of the close relationship between extension within these rifts and the subduction of the Indian plate (Figure 11) is that the total slip on these normal faults closely tracks the subduction rate. Another evidence is the pattern of seismic activity in the Himalayan Orogenic Belt; large earthquakes (M ~ 8) were followed by smaller earthquakes in southern Tibet, supporting a causal connection of the tectonic stress field between subduction and the consequent extension of normal faults in the southern Tibet rifts (Jing *et al*. 2015; Wu *et al*. 2016). For example, after the 2015 Nepal earthquake, a succession of M ~ 5 earthquakes occurred in the Nyalam-Coqên, TangraYumco-Gangga, and Xainza-Dinggye rifts in southern Tibet.

7. Conclusion

The strange and rapid disappearance of Duoqing Co lake cannot be explained by weather or climate. Based on the geological evidence, it is considered that the more likely explanation is increased tensional stress that caused creep extensional deformation of the sediment strata at the bottom of the Duoqing Co lake, opening a pathway for the lake to drain. Later, the fractures occurred re-closure after the elastic recovery of the upper crust, which allowed the water level to recover during the subsequent rainy season. Using evidence from past studies, it is inferred that the larger tectonic context of this recession event is the apparent causal relationship between shortening on the MHT and extension of rifts in southeastern Tibet. In this case, the Bhutan–Sikkim earthquake gap of the MHT now has increased stress transferred to it after the 2015 Nepal earthquake. There is a dynamic relationship among the large earthquakes in the Himalayan Orogenic Belt and the near N–S trending rift belt in southern Tibet and the apparent earthquake migration cycle in the Himalayan orogenic belt. According to this model, large earthquakes occurring in the main thrust zone could increase the likelihood of subsequent earthquakes in southern Tibet or other adjacent parts of China. In light of this trend, it is believed that more attention should be paid to the Sikkim–Bhutan seismic gap in the boundary between China and India. Considering the potential threat to relatively vulnerable nearby cities, the possibility of a large earthquake in this region should be reevaluated. Future investigations should focus on potential seismic hazards in near N–S trending rift of southern Tibet and the Bhutan–Sikkim earthquake gap of the MHT.

Highlights

(1) rapid dried up of Lake Duoqing Co located in the southern end of Yadong-Gulu rift
(2) a possible geological explanation of the abnormal drying-up of Lake Duoqing Co
(3) high seismic hazard risks of southeastern Tibet and Himalaya

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