[Overview the questionnaire]

<1Hazard>

The Himalayan orogeny accommodates about 15-20 mm/yr of shortening, and represents a major earthquake hazard for the densely populated Gangetic Plain and the populations living within the mountains themselves. The Main Frontal Thrust (MFT) is the frontal thrust of this fold and thrust belt, and is believed to accommodate most or all of the shortening occurring within the range. Therefore, understanding the past activity of this fault is a primary goal towards assessing seismic hazard in this region. Flights of fluvial terraces record this history, demonstrating long-term tectonic uplift. However, studies of these terraces typically assume that terrace formation is due solely to tectonic uplift, neglecting other formation mechanisms (such as climate).

Estimating faults’ activities is one of the primary works for assessing tectonic movement and seismic hazards in given area.

In neo-tectonic studies, fluvial terraces are thought to be scopes into tectonic uplift histories in the temporal scale of 103-105 yr (ref.).

With an assumption that driving of terraces formation other than tectonic movement are in equilibrium, tectonic uplift rates could ideally be extracted from flights of terraces (Mackin, 1948; ref…).

However, several challenges need to be overcome before we get a reliable “tectonic” “rate” from fluvial terraces. How to distinguish the driving forces (climatic and tctonic) and how to calculate the rate (alluvial cover and the sadler effects).

[Debating cases:全球、地方]

* However, globally there is a debate **in alluvial fan literature on the tectonics vs climate question** (Viseras et al., 2003; Harvey et al., 2005; Leeder, 2011).
* Previous studies in this area have supported two contrasting views for the genesis of terraces, either related to tectonic activity (Singh et al., 2001) or climatic amelioration (Khan and Dubey, 1981).之前就有構造or氣候主導生成terraces的討論
* The proximal foreland throughout the Himalayan foreland is considered tectonically active and many of the Quaternary fan and terraces of the **frontal Himalaya have primarily been attributed to the ongoing tectonic movements** (Singh et al., 2001; Chakrabarti Goswami et al., 2013).

<1. driving of terraces formations>

Several possible driving:

Fluvial terraces are possibly formed due to **intrinsic driving**, such as migration of river meander migrations (Finnegan and Dietrich, 2011; Finnegan et al., 2014), river captures (Stokes et al., 2002), bedrock structure variations (Wohl, 2008), or internal dynamic resulting from competing of vertical and lateral erosions (Limaye and Lamb, 2016; Malatesta et al., 2017); also could be formed by the processes of aggradation/lateral plantation followed by vertical incision/abandonment (e.g., Gilbert,1877; Mackin, 1937; Bull, 1979; Pazzaglia and Brandon, 2001; Wegmann and Pazzaglia, 2002, 2009), as the results of complex interplays between sediment flux, water discharge (e.g., Bull, 1991; Hancock and Anderson, 2002; Gasparini et al., 2006), and base level changes (e.g., Maddy et al., 2001; Tofelde et al., 2019,…). **Extrinsic driving** for fluctuating those factors could originate from tectonic movements (e.g., uplifting or subsidence), climatic variations (e.g., glacial-interglacial cycle, deglaciation rebounds, Holocene monsoonal dynamics, or stochastic extreme weather events), or human perturbations (e.g., deforestation) (human - Bridgeland, 2000; Collins et al., 2016; climatic - Schumm and Parker, 1973; Pazzaglia et al., 1998; Tebbens et al., 2000; Starkel, 2003; Pratt et al., 2004; Pan et al., 2007; Bridgland and Westaway, 2008; Wobus et al., 2010; Viveen et al., 2013 ; Jones et al., 2014; tectonic-ref; general review -Romans et al., 2016) .

Ref can be a support of many sentences, should they repeat?.

While some cases claim that terraces formation are dominated by tectonic movement, and thus terraces, which used with clear definition, could be considered as proxy of rock uplifts in tectonically active region, more studies show that it could be problematic to equate fluvial terraces incision rate with tectonic uplift rate. Or emphasize the climatic effects on terrace formations (e.g., Harvey, 2005; Bookhagen et al., 2006; Jones et al., 2014).

Thus, …we must have discretion in terraces that had witnessed climatic fluctuations crossing the late Quaternary (late Pleistocene to Holocene).

全球案例

Cases show ages of terraces genesis correlating to known climatic fluctuations (overwhelmed by), distributing widely **in tectonically active area**, such as Washiongton state (Wegmann et al., 2002), north California (Pazzaglia et al., 1998; Hancock et al., 1999; Fuller et al., 2009), the Casacadia fore arc (Pazzaglia and Brandon, 2001), the north-western Europe (Bridgland and Westway, 2008), central Europe (Starkel, 2003), central Asia, northern margin of Tibetan plateau (Hetzel et al., 2002), Tian Shan (Molnar et al., 1994; Poisson and Avouac, 2004), western Taiwan (Hsieh and Knuepfer, 2001; Le Beon et al., 2014). ; Pan et al., 2007---100ka scale的氣候控制; Jones et al., 2014

Some cases give an estimation of incision rate contributed by non-tectonic driving up to 2 mm/yr (Starkel, 2003); 7±2 mm/yr; that is, the excess in river incision can be 37±42 m to 92±51 m and 30~75% of the terrace heights . (Le Beon et al., 2014).

-

Le Beon et al. (2014) mention that several factors could cause this excess in incision: the unknown deeper structures responsible for regional uplift, sedimentation rate in the footwall, incision-sedimentation transition propagating from the downstream, or adjustment of river geometry. Che-Lung-Pu fault, with relatively fast slip rate ~17.7±2.2 mm/yr, cannot explain all the terrace relief/ height.

--

4.Likely, in the front of Himalaya or the Ganga river system, climatic influence is also presented.

(Kar et al., 2014幫整理:)

In the foreland of Himalaya, cases showing climate played a role on sediment process variation in Ganga river system during Quaternary were also reported (Goodbred, 2003; Srivastava et al., 2003; Gibling et al., 2005; Suresh et al., 2007; Tandon et al., 2008; Sinha et al., 2010). Thus, the climatic influence on terrace genesis, which highly related to sedimentary process, must be taken into account when reversing terraces’ driving.

controlled by climatic forcing (Pratt et al., 2002; Bookhagen et al., 2006)

Roy et al. (2012) reports that in the western frontal Himalaya, the alluvial events correspond to southwestern Indian monsoon and marine isotopes in both exposures from the valley margin and core records from the Ganga plain, and suggested the Ganga river has experienced strong variations in its profile (alluvial bed elevation/base level) over the last 100 ka.

This case reinforce the climatic effect in this region.

Kar et al. (2014) demonstrates the fan-terrace system in the Darjeeling Himalaya, presenting minor, tectonic-origin warps on Quaternary deposits, was first-orderly driven by climatically (monsoonal variations) commanding sedimentary process.

Ray et al. (2010) shows that the sections, covering ~200 km in the downstream reaches of the Alaknanda-Ganga River, present a varying ratio of bedrock and terrace sediments, relating to their distance from the active fault (the relative role of climate or tectonic might be evaluated through this ratio). Fill/cut-and-fill terraces far from tectonic influences, fully controlled by climatic, record the climate-driven differential incision, which fault-proximal terraces in downstream reach, mixing tectonic and climatic signals, should have experienced likewise but responded with (a few thousand years) time difference.

It is so evident that we shouldn’t neglect the importance of the climatic induced sedimentary process on terrace genesis all along the Himalaya from valley (bedrock channel, between MCT and MFT) to foreland (filled alluvial plain)

More works done in the western Himalaya decipher the interplay of tectonics and climate in the aggradation-incision of the fan–terrace system (Singh et al., 2001; Malik and Nakata, 2003; Suresh et al., 2007; Sinha et al., 2010; Singh and Tandon, 2010) and Eastern Himalaya (Kar et al., 2014). List down and map out the case along the Himalayan front.

The previous studies, delay responses of several thousand years from upstream to downstream reach …

[Our case]

we find that the relative base level in the Bardibas area in central Nepal has fluctuated by at least 100 m over the last 40 ka, implying that the tectonic signal cannot be extracted directly from fluvial terraces.

The purpose of this research is to quantify/delineate the uncertainties caused by non-tectonic driving when using terrace uplift rate as a representative of tectonic rate.

Here, we contribute a case in the fold and thrust belt of central Himalaya, which filling up the gap of known cases in the other frontal part.

With an advantage of locating in relay zone, Bardibas area has fan-terraces systems experienced varying degree of tectonic activities, gradually diminished along strike, within a relatively short distance (~10km). This provides us a control of the signals archived in the alluvial fans, contributed by non-tectonic driving, since it is tenable to assume that those adjacent rivers parallel to each other have gone through the common climatic condition.

Holding 10 boreholes and several (how many) samples on terraces along rivers in the reaches switched between the Patu and Bardibas faults, two strands of MFT relaying on another to be the frontal part of the MFT, we integrate those data to estimate how the alluvial bed elevations have evolved through time and then expect to acquire a climatically caused incision rate. Together with the tectonic rate, deduced from surface morphology (flights of terraces) combined with subsurface structural geometry drawn based on the seismic reflection images, we are able to estimate the vertical rate of terrace uplift due to tectonic and non-tectonic factors.

<9排除intrinsic factors, glacial driving(ref.), 冰沒有到這裡且catchment不相連-不會影響到sediment供輸, and human impacts>

<主要是沉積河段<2，sediment dominant；seismic image and borehole shows incision into at least 50m in depth，所以更應該考量alluvial bed elevation changes’ history>

<8within 10km could see variation of uplift rate due to sit in a overlaying zone,但不能排除Ratu river catchment size比較大stream power 及sediment response 不同，但所經歷的氣候應屬一致，可透過borehole來比較；以及不同河段time lag的問題>

<What we have>

Joint morphological and structural analysis can derive a slip rate independent from base level changes/ alluvial bed elevations, which is not an absolute reference frame over time.

Tilted/rotated terraces, like growth strata, will accumulate and record the dip angle, through this.

Not to mention that discrepancy between incision rate and uplift rate could occur when water and alluvial fill changes (Pratt et al., 2004).

Cases above reinforce However

Ages of terraces formation or abandonment cluster in transitions of monsoonal strength ( ), or show an enhanced incision rate since the LGM ( ).

Furthermore, even though we could exclude driving other than tectonic movements, incision rates might not straightly reflect tectonic uplift rates, for alluvial veneer mantled terraces would prevent bedrock incision or cause mismatches between incision and rock uplift rates (Lave and Avouac, 2001; Pratt et al., 2004; Lague et al., 2010; Yanties et al., 2011; Collins et al., 2016); incision ability, which depends on sediment loads (Gilbert 1877; Sklar and Dietrich, 2001), might not be steady through time, regardless of other factors being in equilibrium; in addition, time interval of sampling/measurement also affect interpretation for incision rate (commonly referred as the Sadler effect: Sadler, 1981; Schumer and Jerolmack, 2009; Finnegan et al., [2014](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JF003797); Gallen et al., [2015](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JF003797)).

-

Incision variations across the different fault slip rate (Wu et al., 2020; Ray et al., 2010)

Generally faster in Quaternary. Thus L and A 2000 might have wrong deduction even they give a strict definition of strath terraces.