# Vers le suivi spatio-temporel du transport sédimentaire, des pentes aux rivières, par l'analyse du bruit sismique haute-fréquence

Arnaud BURTIN

University of Cambridge

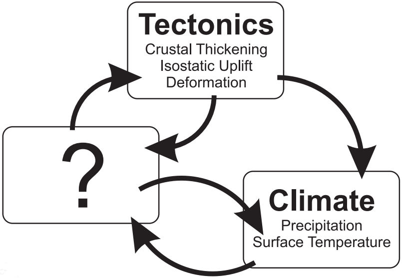
15 Février 2011

1. Landscape Evolution
   - Erosion Processes
   - Monitoring Sediment Transport
2. River Seismic Noise
   - Monitoring Bed Load Transport
   - Location of Sediment Transport
3. Hillslope Processes
   - Debris Flow Monitoring
4. Dedicated Experiments
   - Taiwan

# Shaping the Earth's surface

The landscape is driven by:

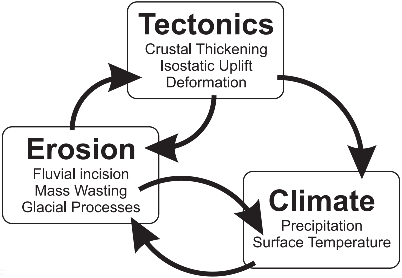
- Tectonics
- Climate
- Erosion



# Shaping the Earth's surface

The landscape is driven by:

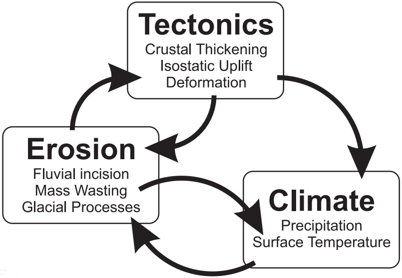
- Tectonics
- Climate
- Erosion



# Shaping the Earth's surface

The landscape is driven by:

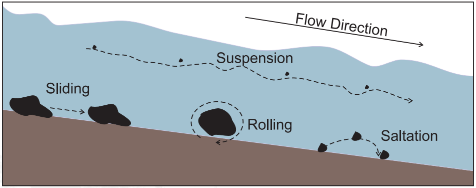
- Tectonics
- Climate
- Erosion




**Rivers play an important role in mass transport and erosion**

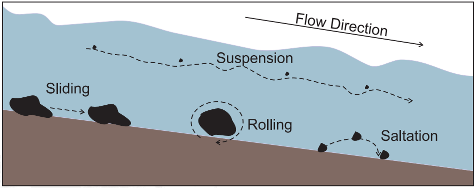
# Sediment transport & fluvial incision

- Dissolved elements, linked to chemical erosion
- Suspended load, no connection with the river bed
- Bed load, sediments mobilized in the vicinity of the river bed



# Sediment transport & fluvial incision

- Dissolved elements, linked to chemical erosion
- Suspended load, no connection with the river bed
- Bed load, sediments mobilized in the vicinity of the river bed




**Bed load transport through abrasion drives river incision**

# *In-situ* techniques

## Sediment traps

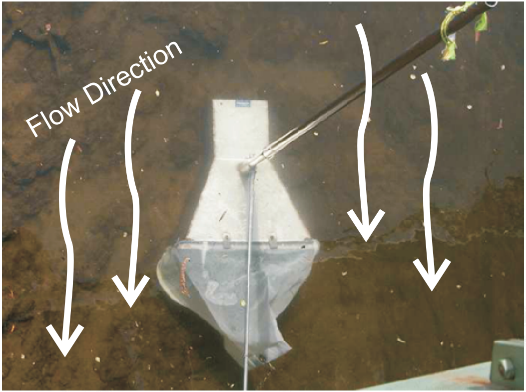
# *In-situ* techniques

## Sediment traps

- Ponctual measurements, integrated over a time period
- Invasive constructions disturbing the hydrology of a river
- Specific requirements to install such monitoring devices
- Not designed for all rivers

# *In-situ* techniques

## Helley-Smith sampler




# *In-situ* techniques

## Helley-Smith sampler

- Ponctual measurements, integrated over a time period
- The only method that provides a direct measurement of sediment transport
- Bed load estimates dependent of the river hydrology

# *In-situ* techniques

## Helley-Smith sampler

# *In-situ* techniques

## Acoustic sensors: hydrophones

# *In-situ* techniques

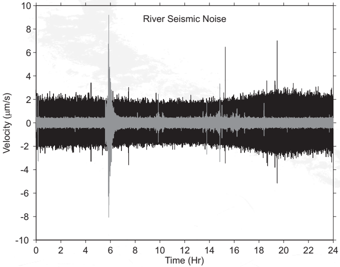
## Acoustic sensors: hydrophones

- Continuous monitoring, spatial extent allowed
- Bed load estimates dependent of the river hydrology
- Calibration is required to translate signal into sediment load

# A way of exploration. . .

## Background seismic noise

- Many sources of seismic noise have a natural origin (ocean, wind, rivers. . . ).




# A way of exploration. . .

## Background seismic noise

Seismic sensors installed along rivers to continuously study sediment transport and their spatial variations

- Spectral analysis of the continuous seismic signal recorded by stations:
  Characterize and Quantify ?
- Explore the ability of locating sediment transport and extreme events:
  Erosion Processes
- Study the feasibility in various hydrologic contexts:
  Himalaya, French Alps

# A way of exploration...

## Background seismic noise

Seismic sensors installed along rivers to continuously study sediment transport and their spatial variations

- Spectral analysis of the continuous seismic signal recorded by stations:
  Characterize and Quantify ?
- Explore the ability of locating sediment transport and extreme events:
  Erosion Processes
- Study the feasibility in various hydrologic contexts:
  Himalaya, French Alps

# A way of exploration...

## Background seismic noise

Seismic sensors installed along rivers to continuously study sediment transport and their spatial variations

- Spectral analysis of the continuous seismic signal recorded by stations:
  Characterize and Quantify ?
- Explore the ability of locating sediment transport and extreme events:
  Erosion Processes
- Study the feasibility in various hydrologic contexts:
  Himalaya, French Alps

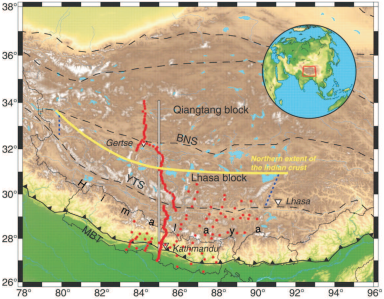
# How to sample?

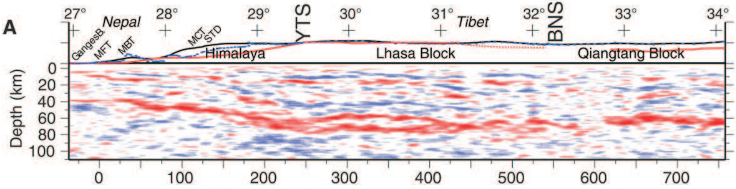
# How to estimate?

# The Hi-CLIMB experiment

Nábělek *et al.* (2009)

- Temporary seismological network from 2002 to 2005
- Almost 250 sites from Nepal to the Tibetan Plateau, dedicated to imaging the lithospheric structures of the India–Asia collision zone
- Broadband stations installed over 2 phases (Phase 1 located in the Himalayas)

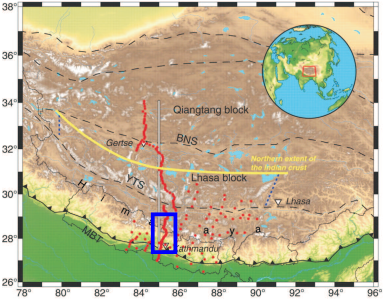


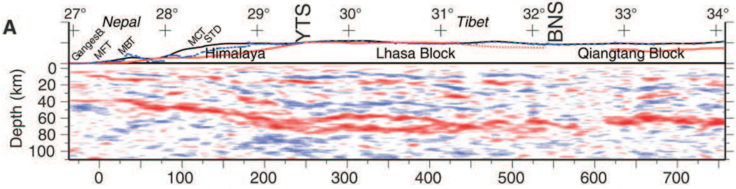



# The Hi-CLIMB experiment

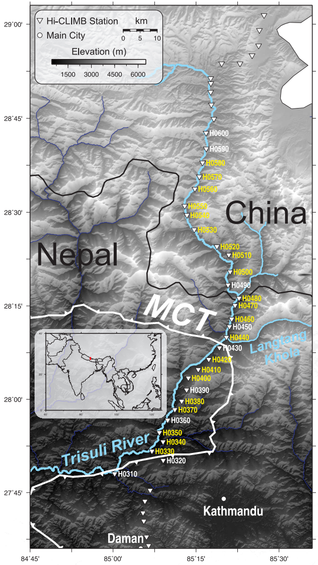
Nábělek *et al.* (2009)

- Temporary seismological network from 2002 to 2005
- Almost 250 sites from Nepal to the Tibetan Plateau, dedicated to imaging the lithospheric structures of the India–Asia collision zone
- Broadband stations installed over 2 phases (Phase 1 located in the Himalayas)



# Phase 1 of the Hi-CLIMB array

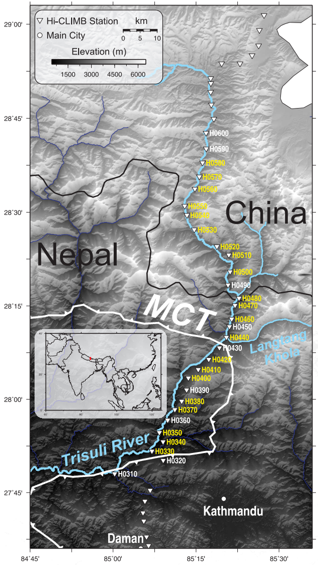



- Many stations are along a trans-Himalayan river: the Trisuli
- Inter-stations distances of 3-5 km (spatial variations)
- Year 2003 in full acquisition for most stations (temporal variations)
- The Hi-CLIMB network: a seismic observatory of the Trisuli River

# Phase 1 of the Hi-CLIMB array

- Many stations are along a trans-Himalayan river: the Trisuli
- Inter-stations distances of 3-5 km (spatial variations)
- Year 2003 in full acquisition for most stations (temporal variations)
- The Hi-CLIMB network: a seismic observatory of the Trisuli River

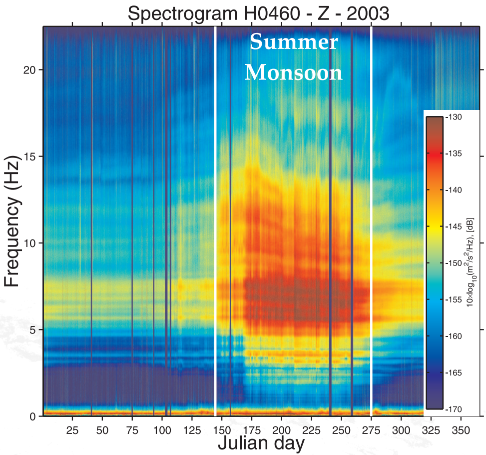
# Phase 1 of the Hi-CLIMB array




- Many stations are along a trans-Himalayan river: the Trisuli
- Inter-stations distances of 3-5 km (spatial variations)
- Year 2003 in full acquisition for most stations (temporal variations)
- The Hi-CLIMB network: a seismic observatory of the Trisuli River

# Seismic signal and spectral analysis

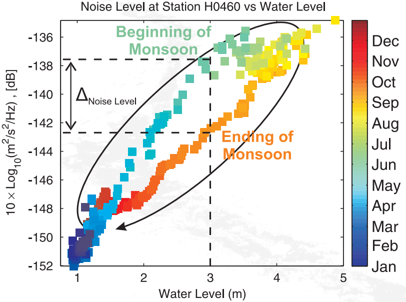
- Increase of seismic energy in a high-frequency band ($>$ 1 Hz) during the monsoon season
- Spectral characteristics observed for most stations located along the Trisuli River



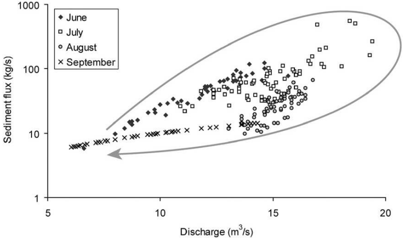
# Origin of high-frequency seismic noise

Burtin *et al.* (2008)

Seismic Noise [3-15 Hz]




Sediment Flux



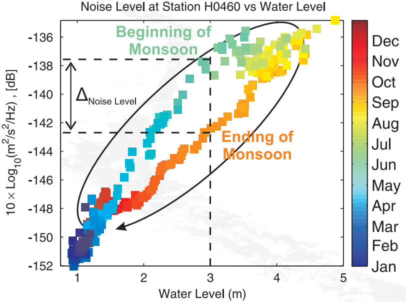

Gabet *et al.* (2008)

**Seismic noise analysis to monitor river sediment transport**

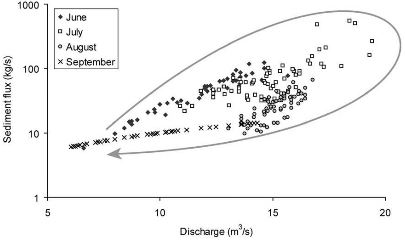
# Origin of high-frequency seismic noise

Burtin *et al.* (2008)

Seismic Noise [3-15 Hz]




Sediment Flux




Gabet *et al.* (2008)

**Seismic noise analysis to monitor river sediment transport**

**How to locate the sediment transport?**

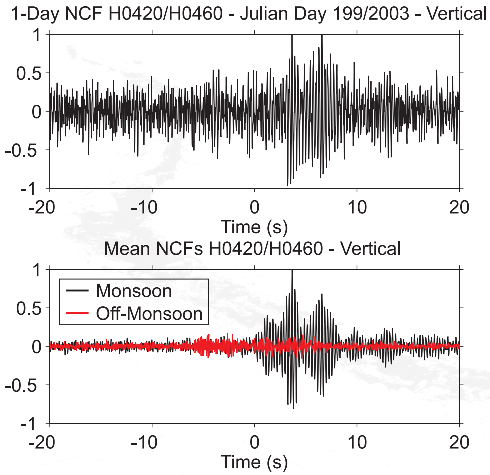
1. Landscape Evolution
   - Erosion Processes
   - Monitoring Sediment Transport

2. River Seismic Noise
   - Monitoring Bed Load Transport
   - Location of Sediment Transport

3. Hillslope Processes
   - Debris Flow Monitoring

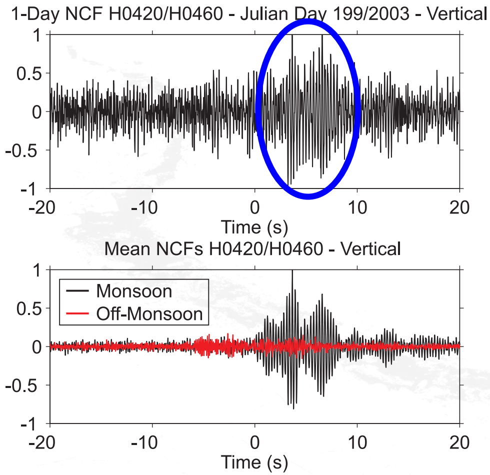
4. Dedicated Experiments
   - Taiwan

# Coherence in the seismic noise




- Vertical seismograms
- 1-d-long recordings
- 1-20 Hz frequency band (river seismic noise)
- 1-bit normalisation

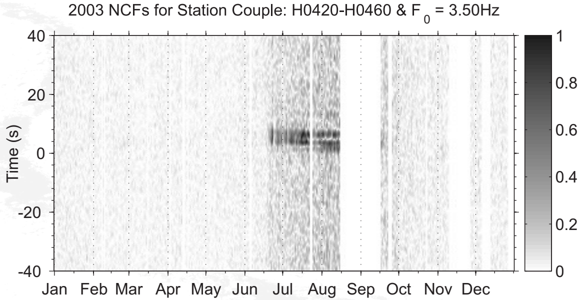
# Coherence in the seismic noise




- Vertical seismograms
- 1-d-long recordings
- 1-20 Hz frequency band (river seismic noise)
- 1-bit normalisation

# Time stability of the coherence

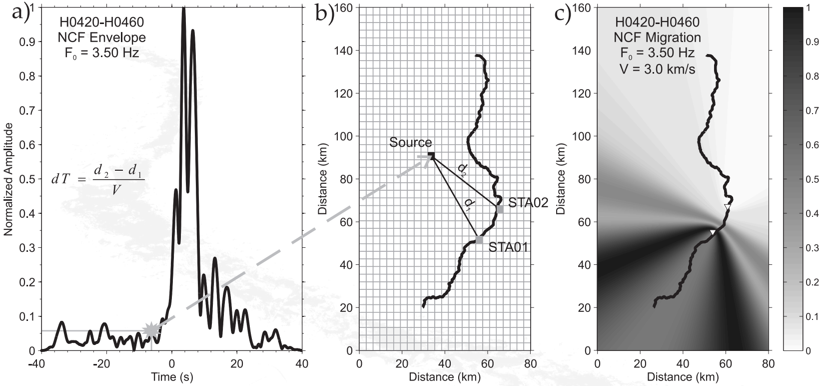
- High-frequency seismic noise is coherent during long time periods




- Envelopes of noise correlation function (Gaussian filter: $\sigma_f = 0.25$ Hz)
- Selection process to only keep coherence coming from river sources

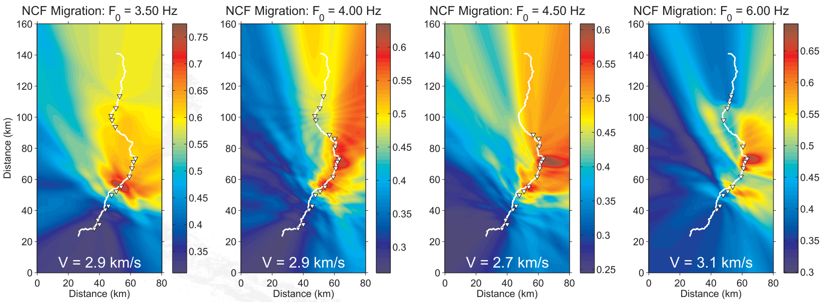
# Location of river seismic noise

## Migration of the coherence envelopes




- Proceed to the migration at various frequencies and apparent velocities
- Search for the best coherence to retrieve the source location and apparent velocity

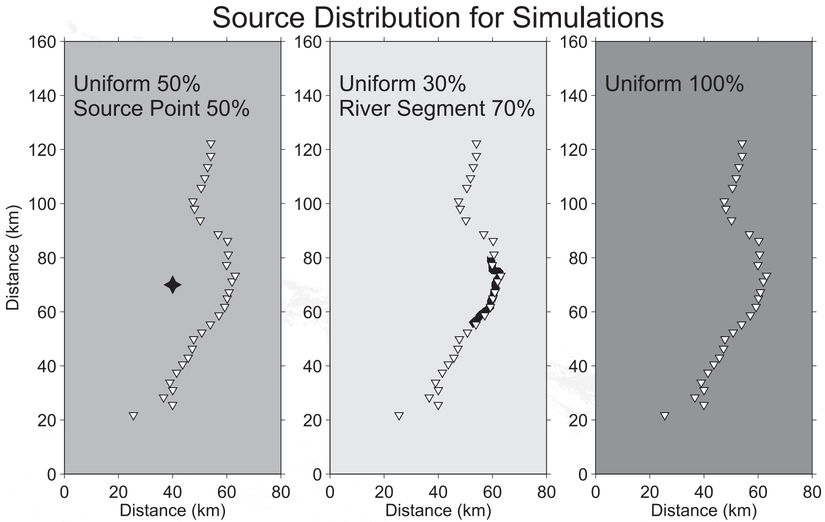
# Results: Coherence maps




- Regions of large coherence merge along the Trisuli River
- Two main spots are observed near H0410 and H0480
- Best apparent velocity is constant and equal to 3 km/s

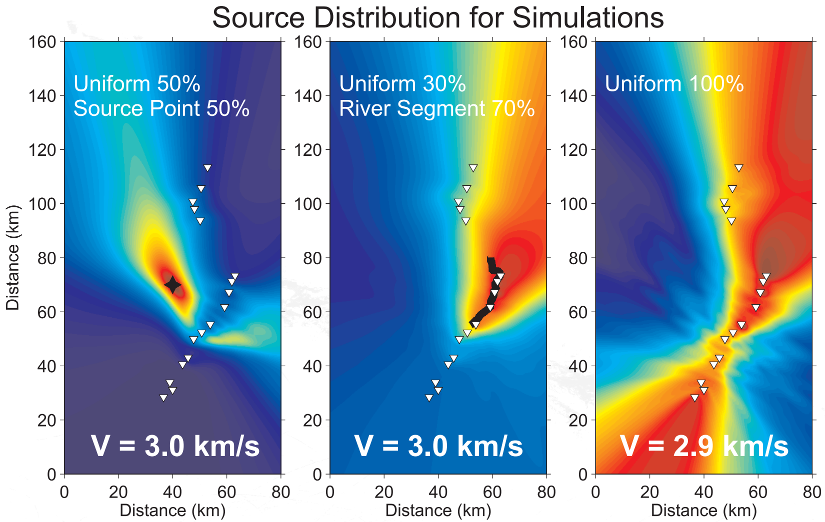
# Simulations of seismic noise

## Source distribution tests (3.5 Hz)



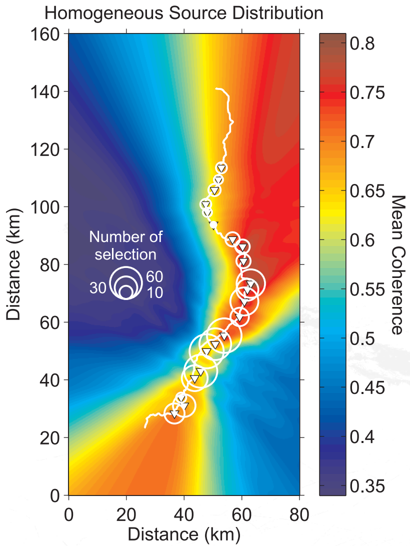
# Simulations of seismic noise

## Source distribution tests (3.5 Hz)



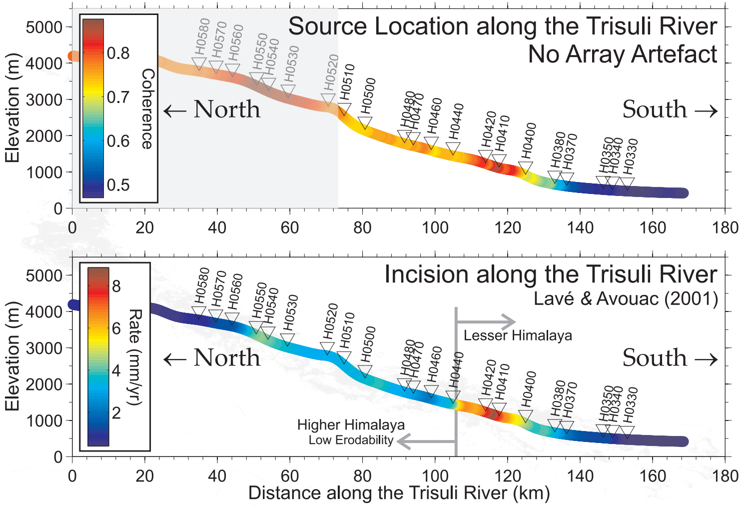
# Location results

## Array artefact

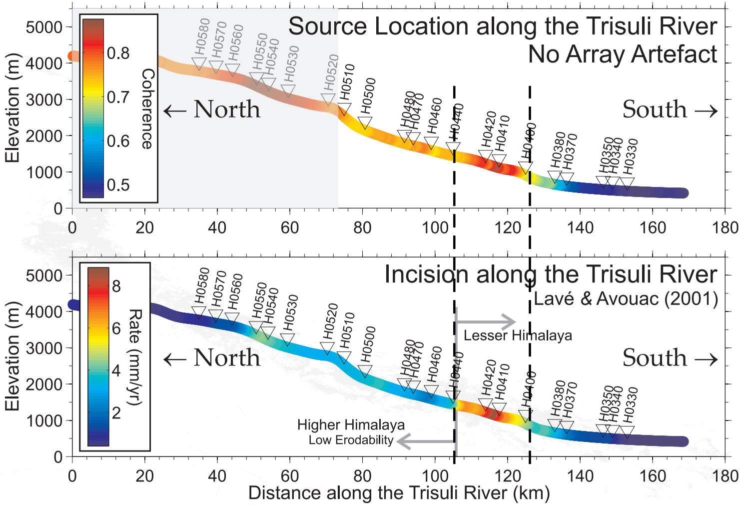



- Artefact from the geometry of the Hi-CLIMB array
- Correct the coherence maps from these perturbations

# Coherence along the Trisuli – River incision rates

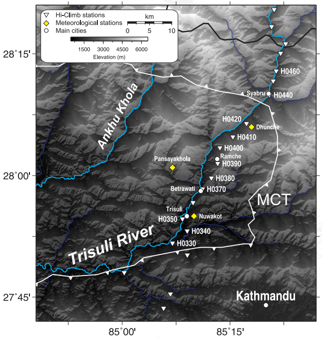


# Coherence along the Trisuli – River incision rates

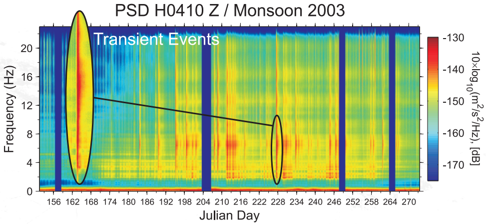


# Transient events at the front of the Himalayas

## Bursts of high-frequency seismic energy

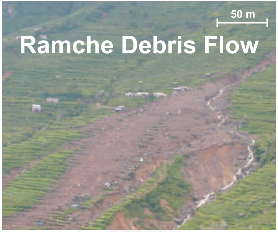


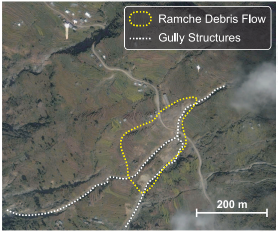

- Broad high-frequency band excited during the events (> 2 Hz)
- Observed at the front of the High-Range (H0370–H0410)
- Last several hours to days
- Many occurrences during the monsoon season



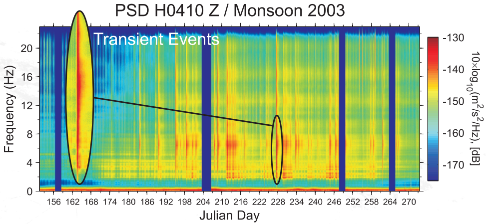
# Transient events at the front of the Himalayas

## Bursts of high-frequency seismic energy



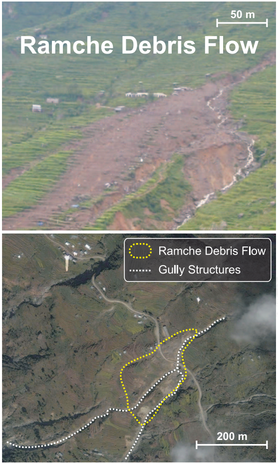




- Broad high-frequency band excited during the events ($> 2$ Hz)
- Observed at the front of the High-Range (H0370–H0410)
- Last several hours to days
- Many occurrences during the monsoon season

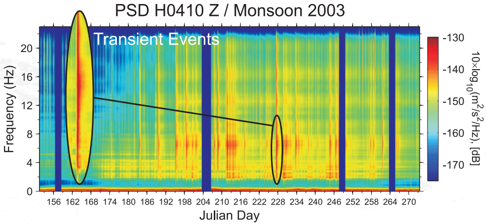


# Transient events at the front of the Himalayas

## Bursts of high-frequency seismic energy




- Broad high-frequency band excited during the events ($> 2$ Hz)
- Observed at the front of the High-Range (H0370–H0410)
- Last several hours to days
- Many occurrences during the monsoon season

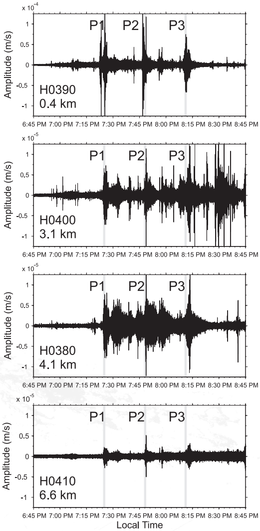



**Link between transient events and debris flows ?**

# Ramche Debris Flow

## Seismic signal

- The Ramche Debris Flow (RDF) is observed at many Hi-CLIMB stations
- Seismograms show great complexities
- Three main events are noticed (P1, P2 and P3)
- The events last $\sim$ 2-min and are separated from each others by $\sim$ 30-min

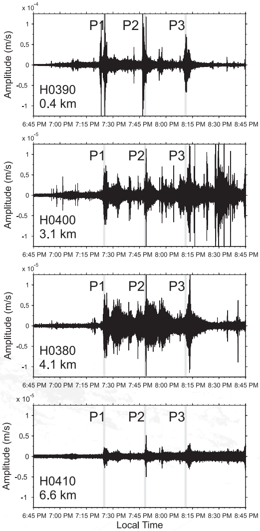


# Ramche Debris Flow

## Seismic signal

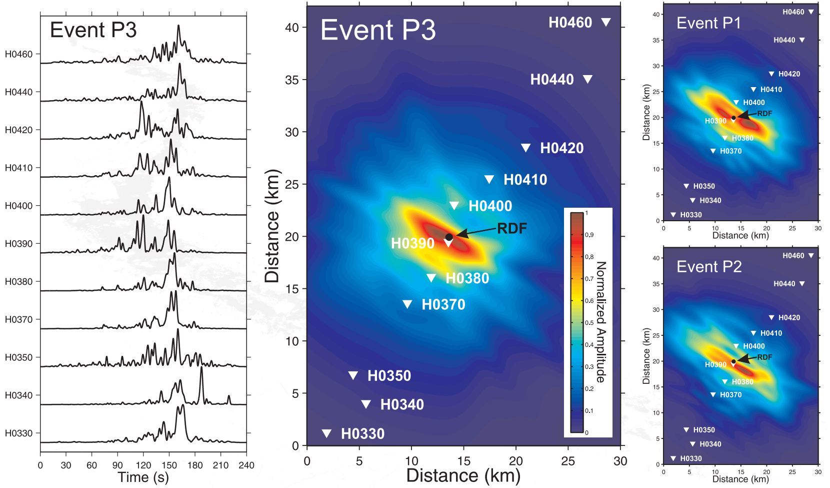
- The Ramche Debris Flow (RDF) is observed at many Hi-CLIMB stations
- Seismograms show great complexities
- Three main events are noticed (P1, P2 and P3)
- The events last $\sim$ 2-min and are separated from each others by $\sim$ 30-min

**Proceed to the location of these events**



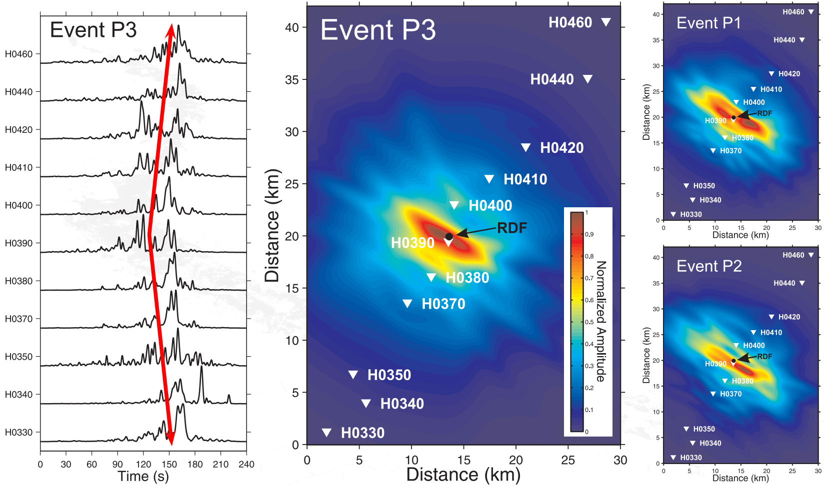
# Location process

## Correlation of seismic envelopes and probability density method



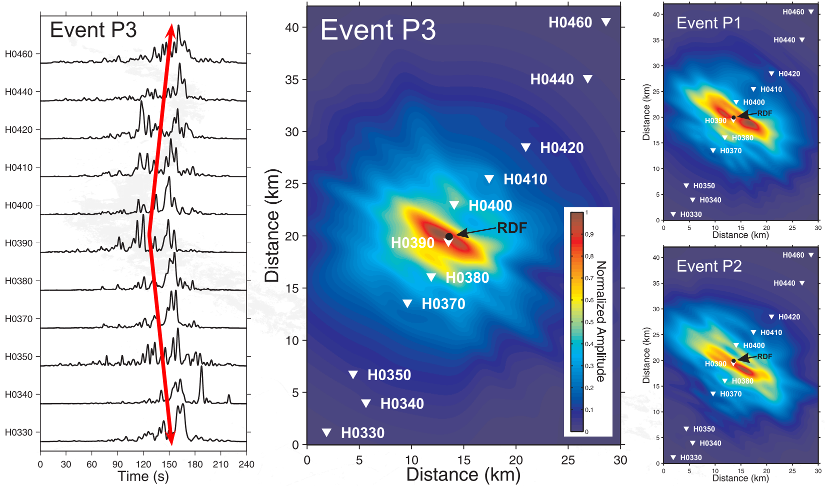
# Location process

## Correlation of seismic envelopes and probability density method



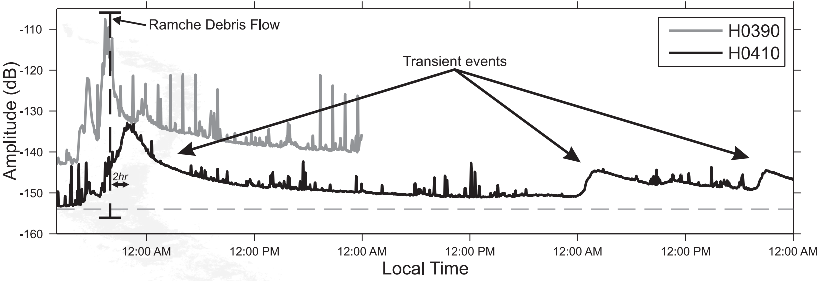
# Location process

## Correlation of seismic envelopes and probability density method



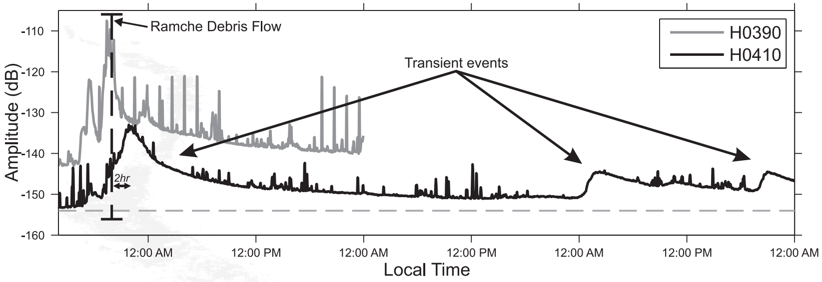

Potential for the detection and location of such mass movements

# Transient event characteristics



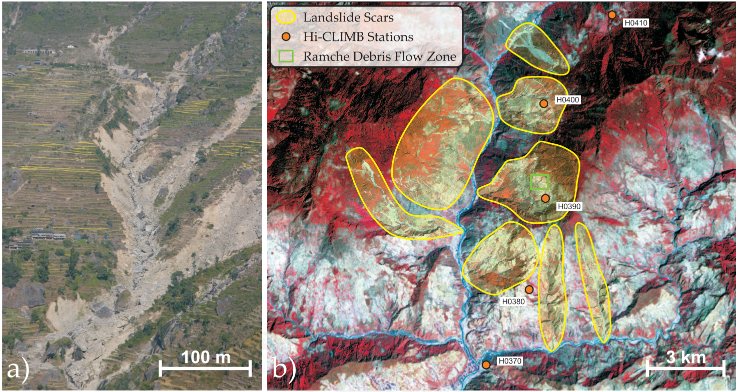

- Peaks of noise level are delayed with 2-hr (H0390–H0410 7km)
- Similar mechanisms for the generation of high-frequency seismic energy
- Different locations for the source origin

# Transient event characteristics




- Peaks of noise level are delayed with 2-hr (H0390–H0410 7km)
- Similar mechanisms for the generation of high-frequency seismic energy
- Different locations for the source origin

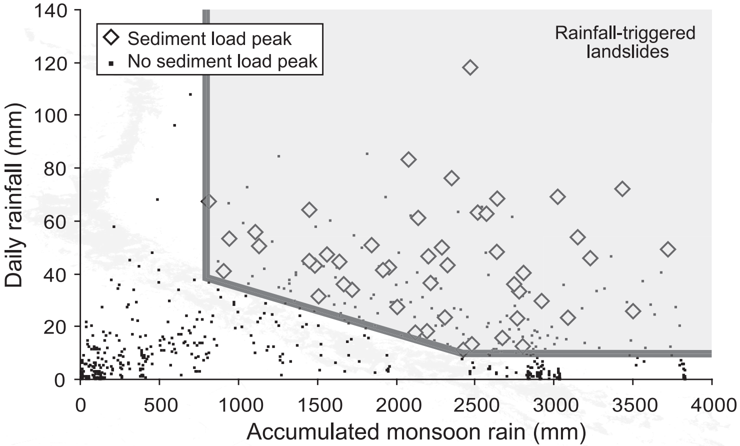
# Spatial distribution of transients




- Hi-CLIMB stations located at the front of the High-Range are close to major landslide scars and large gully structures
- Do transients denote debris removal and/or sediment transport in gullies ?

# Temporal variations

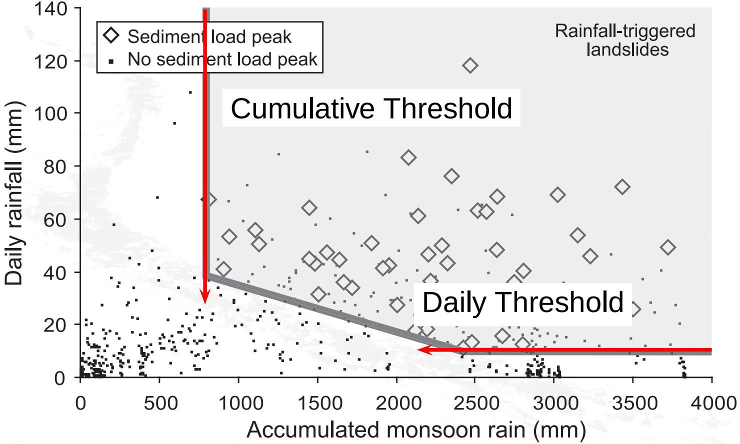
## Transient event occurrences – River sediment load – Landslide monitoring




Precipitation from Gabet *et al.* (2004)

# Temporal variations

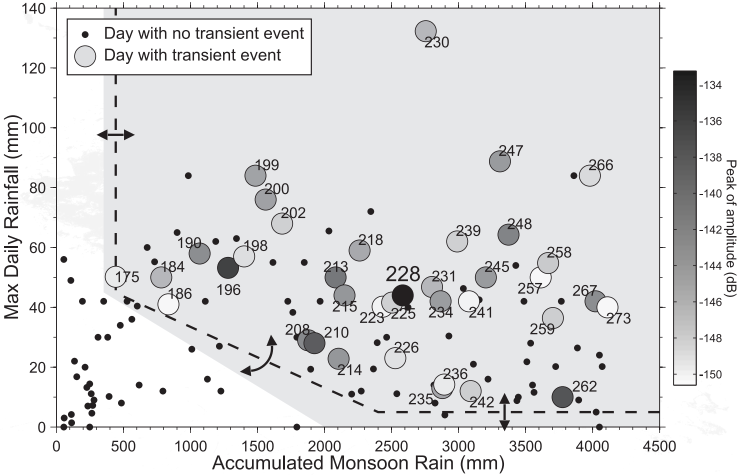
## Transient event occurrences – River sediment load – Landslide monitoring




Precipitation from Gabet *et al.* (2004)

# Temporal variations

## Transient event occurrences – River sediment load – Landslide monitoring



# What is a transient event?

- The burst of high-frequency seismic energy reveals an intense sediment transport in gullies or landslide scars
- The induced erosion may alter the stability of slopes (stream incision, bank erosion. . . ) and may trigger a mass movement (*cf.* the Ramche Debris Flow)
- The debris removal will thus contribute to the generation of high-frequency seismic energy
- These episodes of seismic noise are clearly consistent with peaks of sediment load presumably associated to landslides
- Towards a seismic measurement of eroded volumes, sediment input and denudation rates ?

# What is a transient event?

- The burst of high-frequency seismic energy reveals an intense sediment transport in gullies or landslide scars
- The induced erosion may alter the stability of slopes (stream incision, bank erosion. . . ) and may trigger a mass movement (*cf.* the Ramche Debris Flow)
- The debris removal will thus contribute to the generation of high-frequency seismic energy
- These episodes of seismic noise are clearly consistent with peaks of sediment load presumably associated to landslides
- Towards a seismic measurement of eroded volumes, sediment input and denudation rates ?

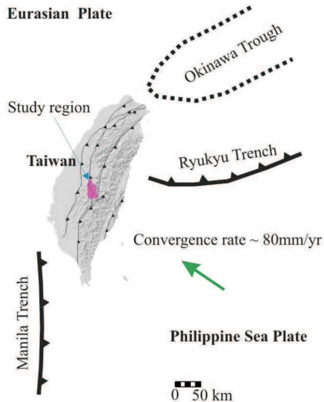
# What is a transient event?

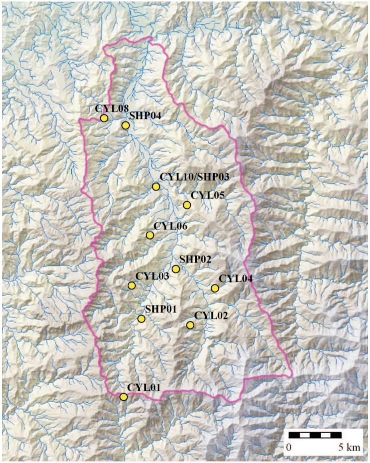
- The burst of high-frequency seismic energy reveals an intense sediment transport in gullies or landslide scars
- The induced erosion may alter the stability of slopes (stream incision, bank erosion. . . ) and may trigger a mass movement (*cf.* the Ramche Debris Flow)
- The debris removal will thus contribute to the generation of high-frequency seismic energy
- These episodes of seismic noise are clearly consistent with peaks of sediment load presumably associated to landslides
- Towards a seismic measurement of eroded volumes, sediment input and denudation rates ?

1. Landscape Evolution
   - Erosion Processes
   - Monitoring Sediment Transport
2. River Seismic Noise
   - Monitoring Bed Load Transport
   - Location of Sediment Transport
3. Hillslope Processes
   - Debris Flow Monitoring
4. Dedicated Experiments
   - Taiwan

# Monitoring extreme geomorphic events

## The Chenyoulan catchment



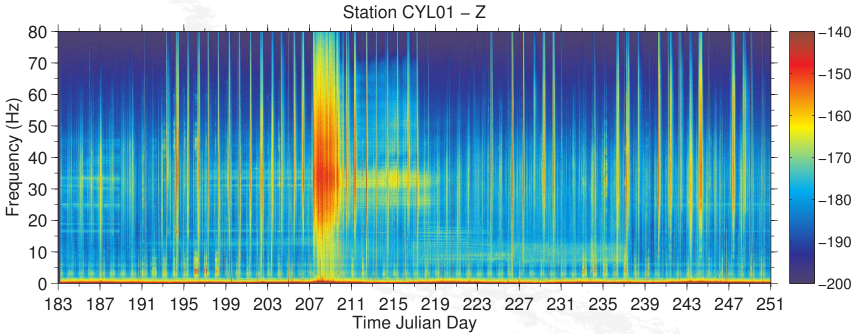

Typhoon season (June to October 2010):
10 broadband stations and 4 short period sensors

# Monitoring extreme geomorphic events

## The Chenyoulan catchment

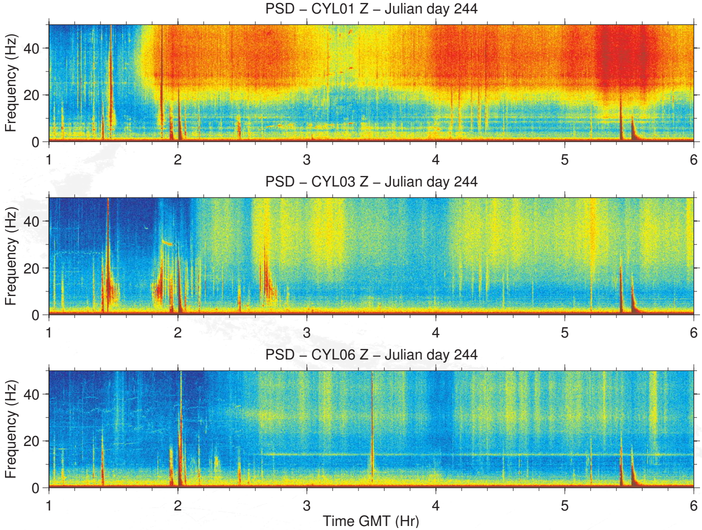
# Monitoring extreme geomorphic events

## First results



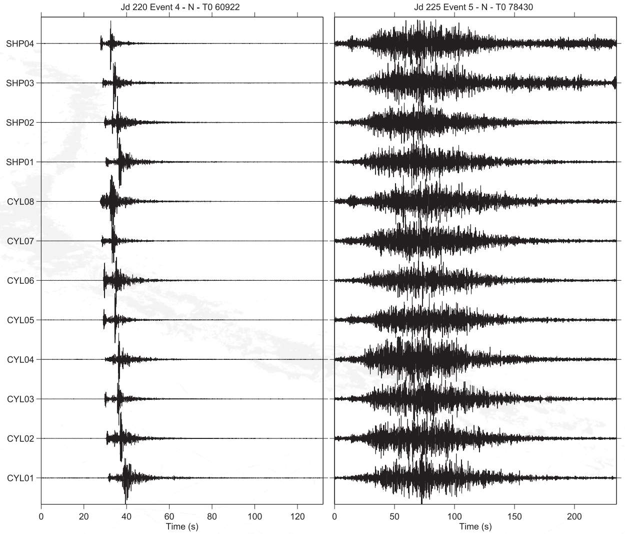
# Monitoring extreme geomorphic events

## First results



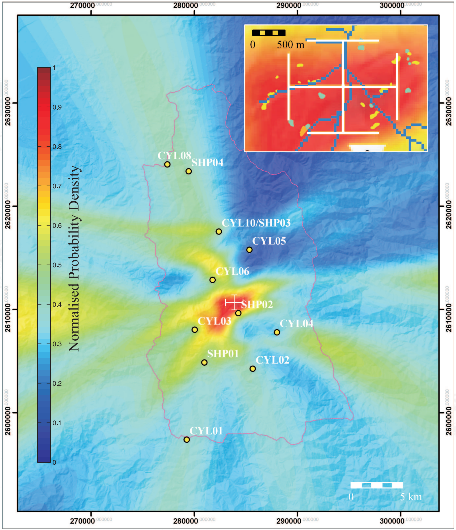
# Monitoring extreme geomorphic events

## First results



# Monitoring extreme geomorphic events

## First results



# Conclusions & future works

- Analysis of high-frequency river seismic noise depicts a potential to monitor spatially and continuously the bed load transport
- Location of sediment transport along rivers can be performed using cross-correlation of seismic noise at pairs of stations
- High-frequency seismic noise also reveals interesting features for the detection and the location of debris flows
- Such a monitoring of surface processes can lead to seismically measure erosion and its spatio-temporal variations
- Dedicated experiments are required to translate seismic signals into geomorphic observations like sediment transport, erosion rates…