The chain of geohazards induced by the 2008 Wenchuan earthquake:

A decade of lessons, advances and challenges

Runqiu Huang

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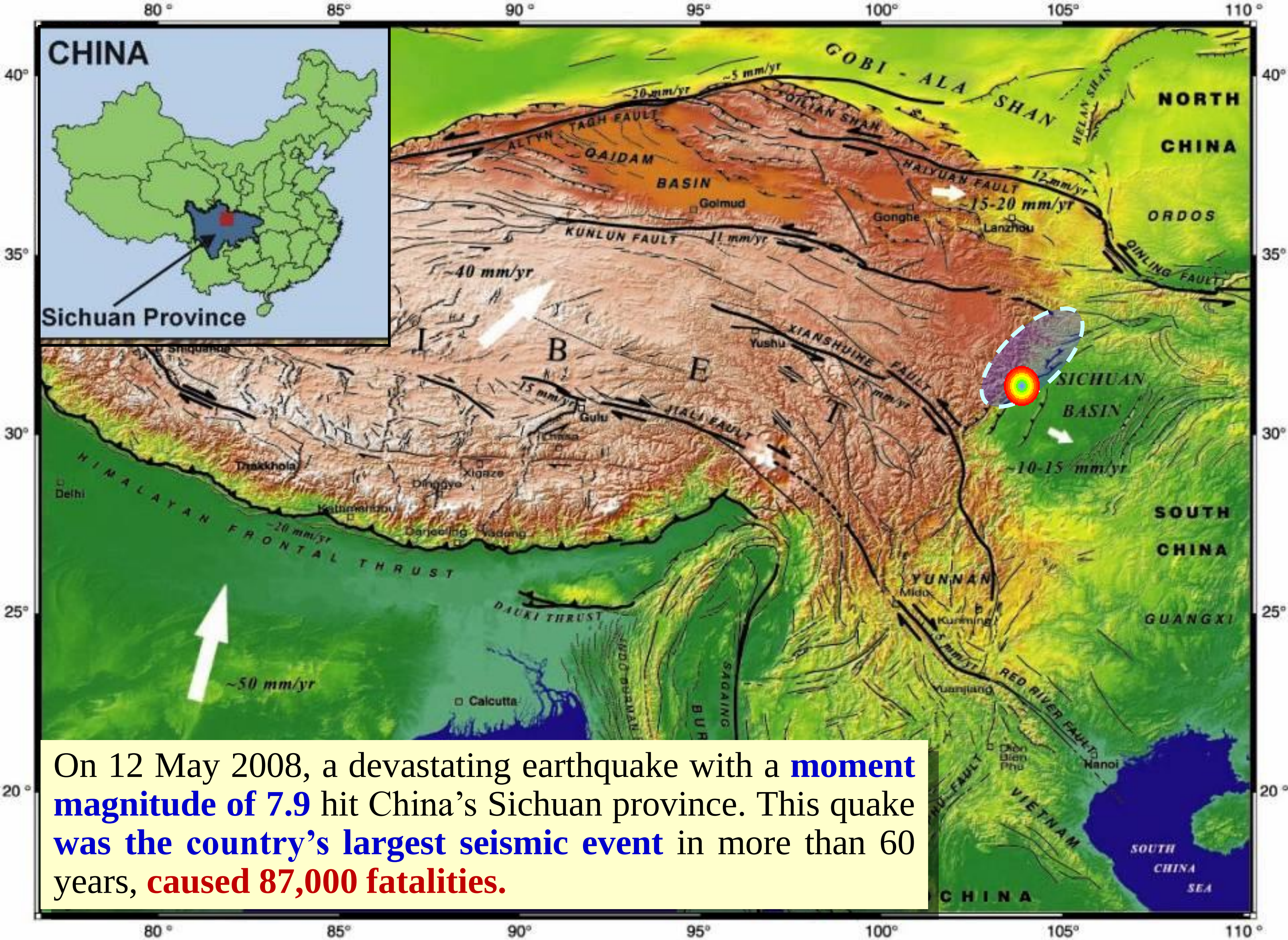
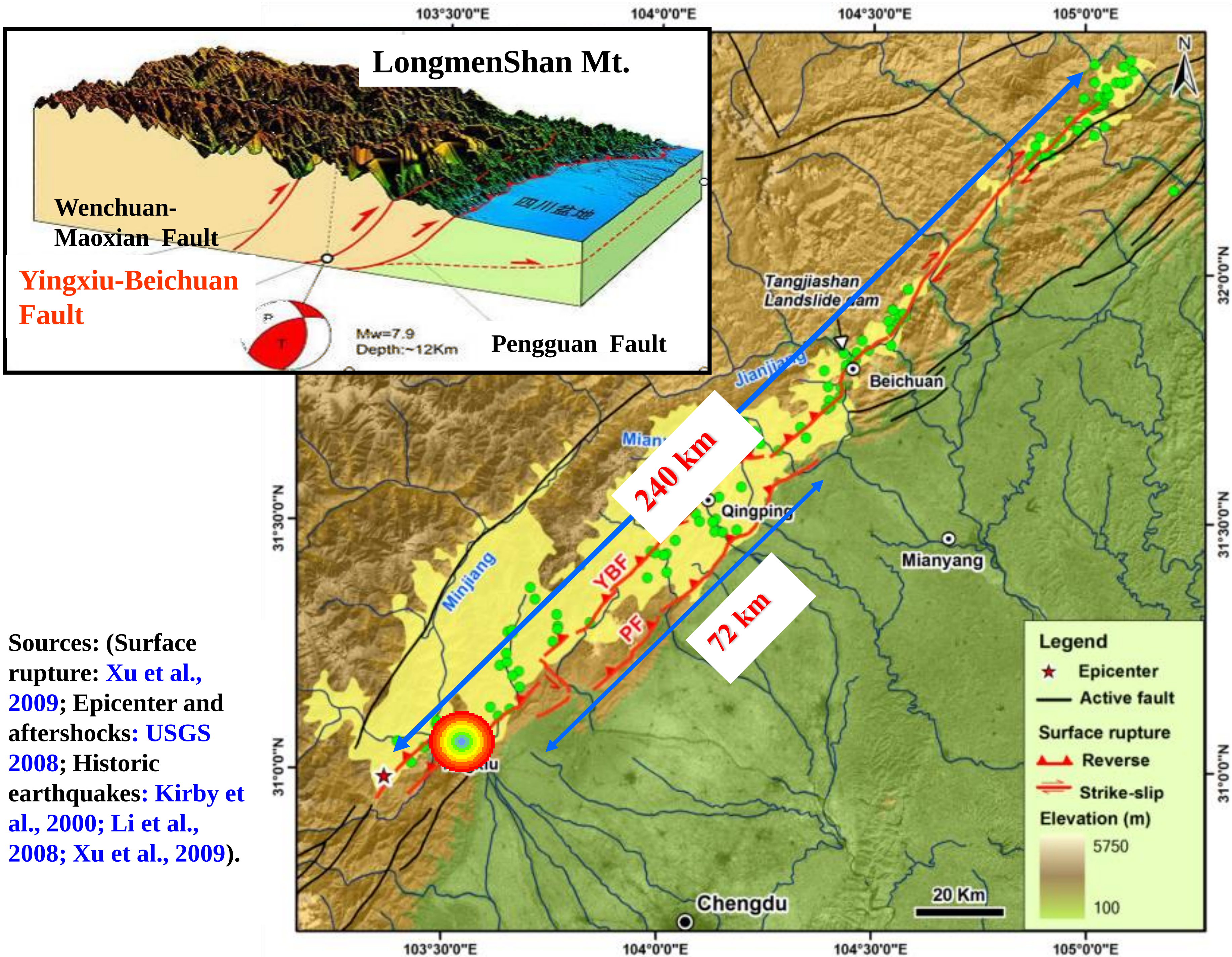
Chengdu University of Technology



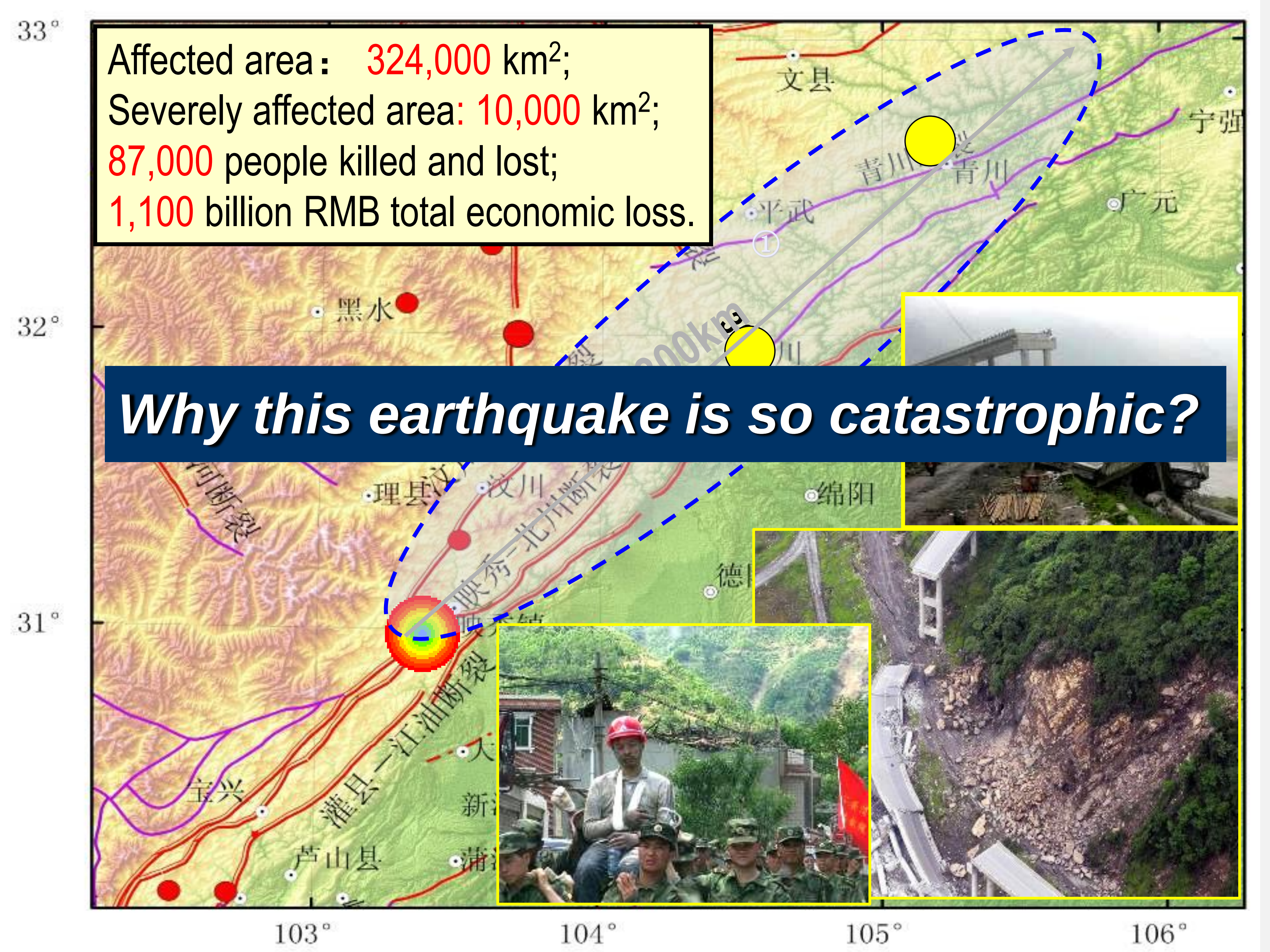
On 12 May 2008, a devastating earthquake with a **moment magnitude of 7.9** hit China's Sichuan province. This quake **was the country's largest seismic event** in more than 60 years, **caused 87,000 fatalities.**



Sources: (Surface rupture: Xu et al., 2009; Epicenter and aftershocks: USGS 2008; Historic earthquakes: Kirby et al., 2000; Li et al., 2008; Xu et al., 2009).

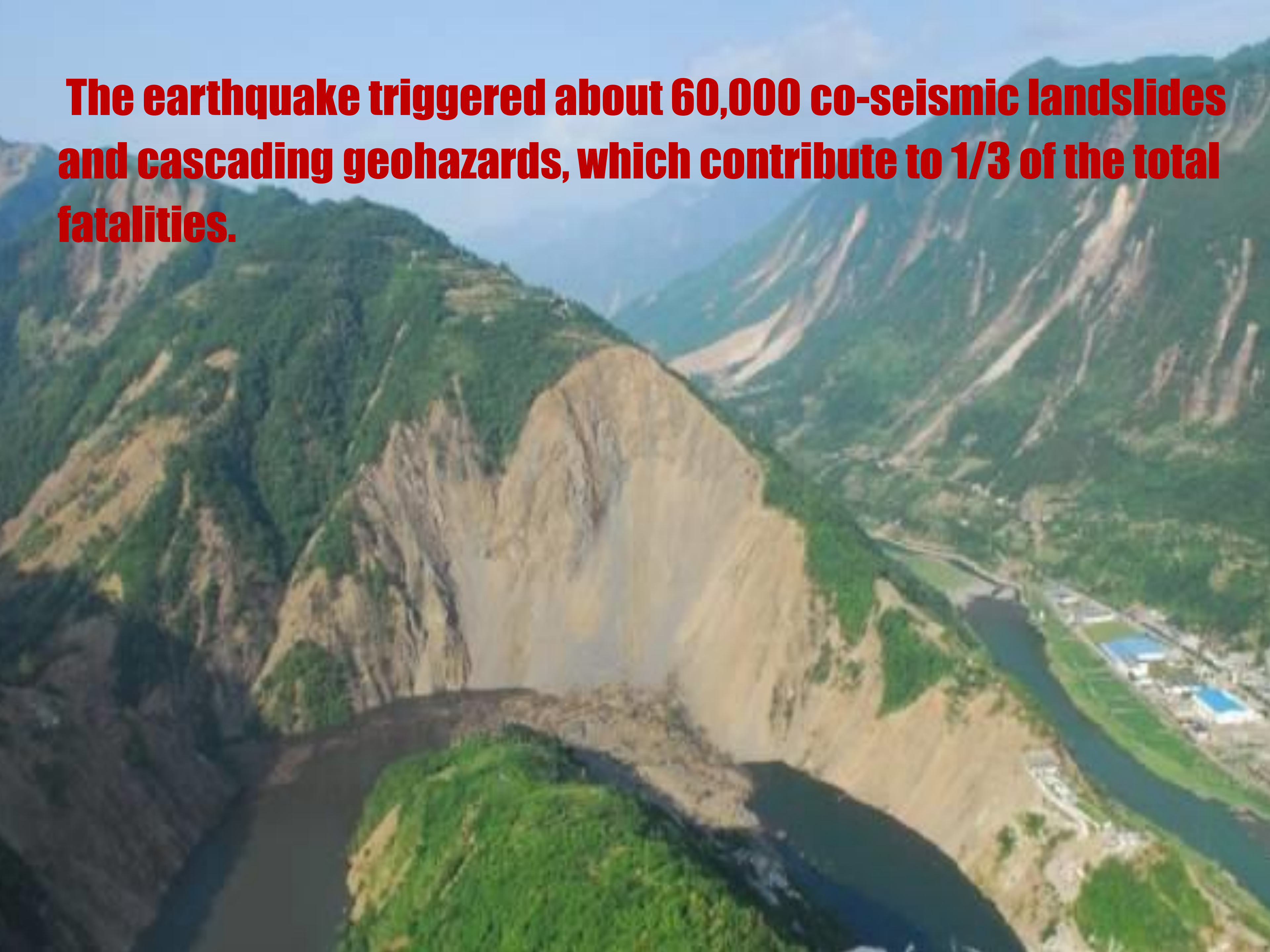
Yinxiu Town: 92% of the buildings collapsed

Beichuan county: 80% of the buildings collapsed



Affected area： 324,000 km²;
Severely affected area: 10,000 km²;
87,000 people killed and lost;
1,100 billion RMB total economic loss.
Why this earthquake is so catastrophic?
33°
32°
31°
103°
104°
105°
106°
文县
青川
广元
平武
黑水
理县
汶川
绵阳
映秀－北川断裂
灌县－江油断裂
宝兴
芦山县

The earthquake triggered about 60,000 co-seismic landslides and cascading geohazards, which contribute to 1/3 of the total fatalities.

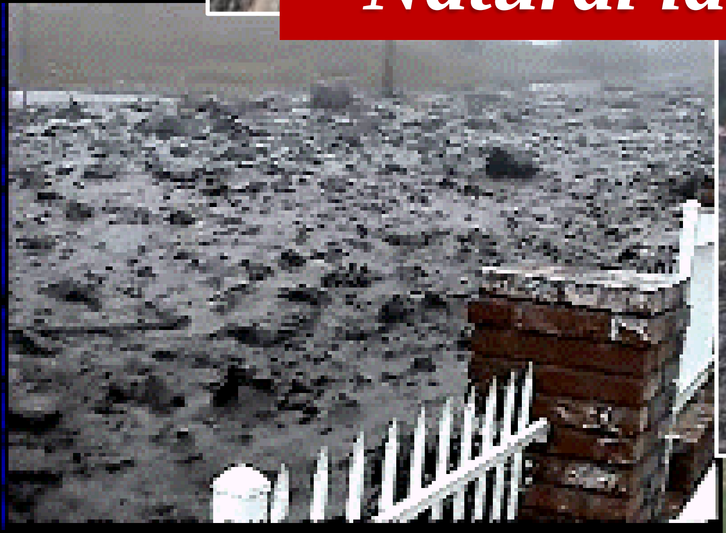



Beichuan County town
before the quake

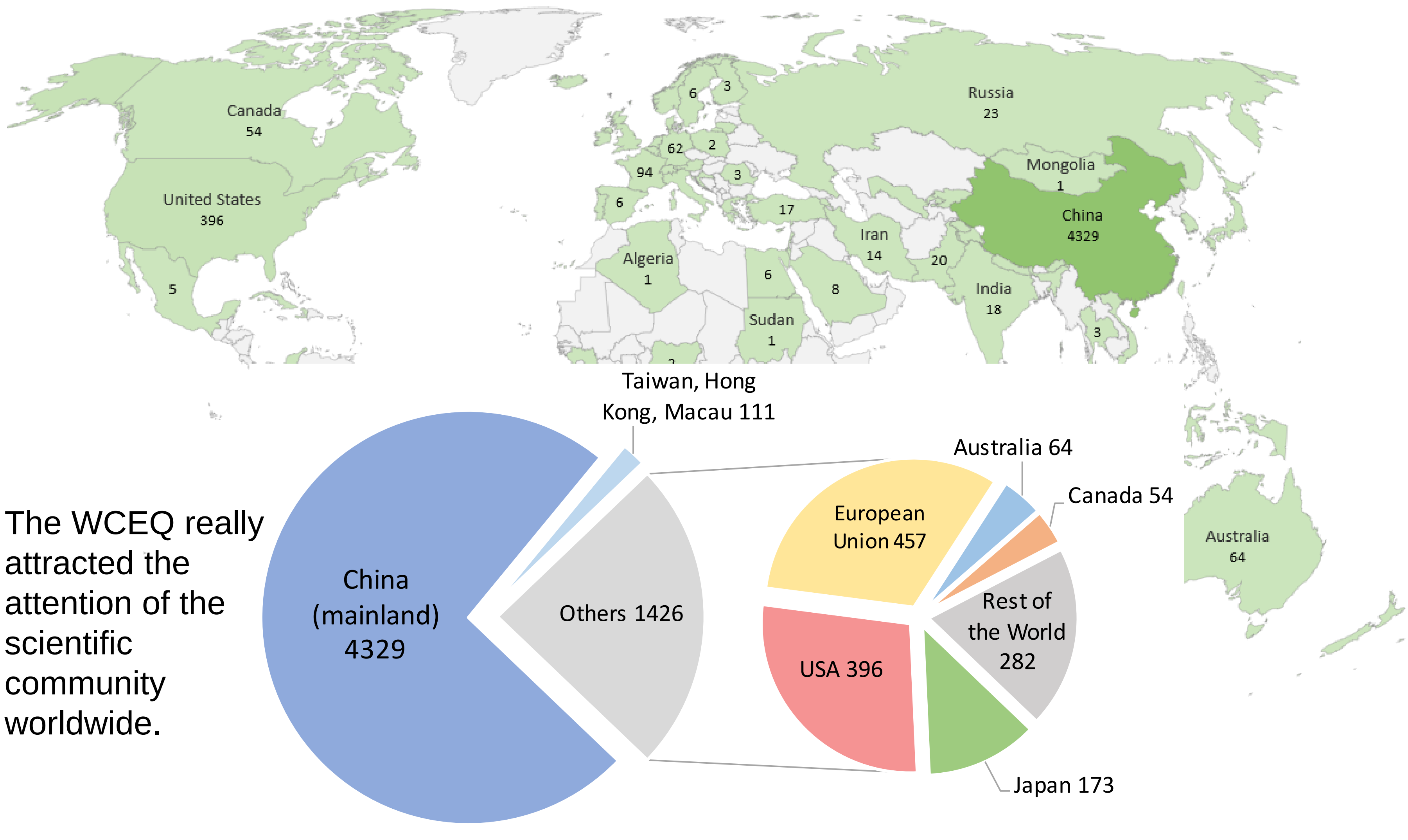

New area
700 deaths
Beichuan middle school Avalanches
1600 deaths
Old area
Wangjiayan landslide

The earthquake also induced numerous post-seismic landslides and debris flows, attracted the interests of scholars from all over the world.


Natural laboratory for geohazards

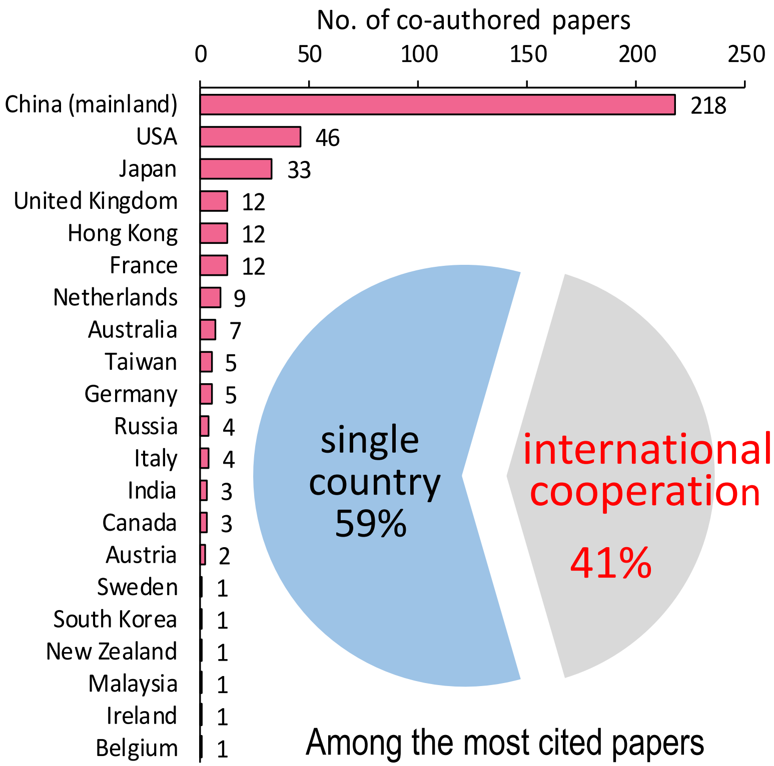



6,219 papers referring to the Wenchuan Earthquake either *in title, keywords or abstract*, were written by scholars from 67 countries in all continents; among them over 1000 papers focusing on geo-hazards induced by the EQ.

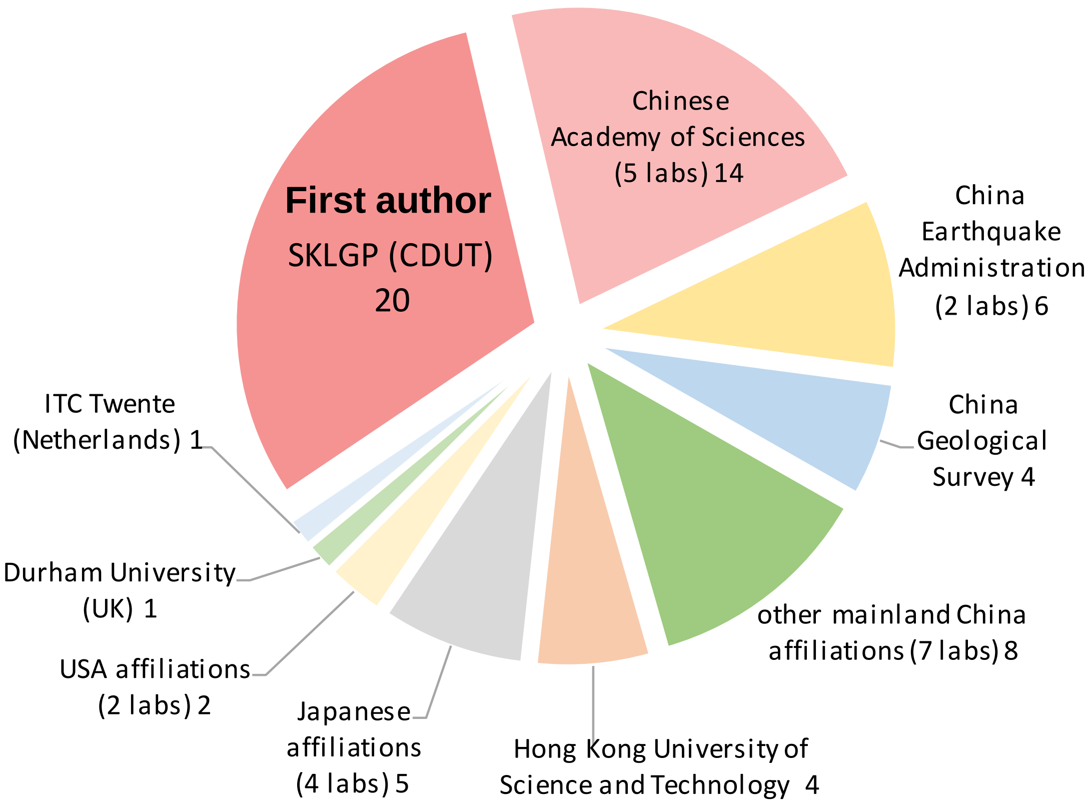


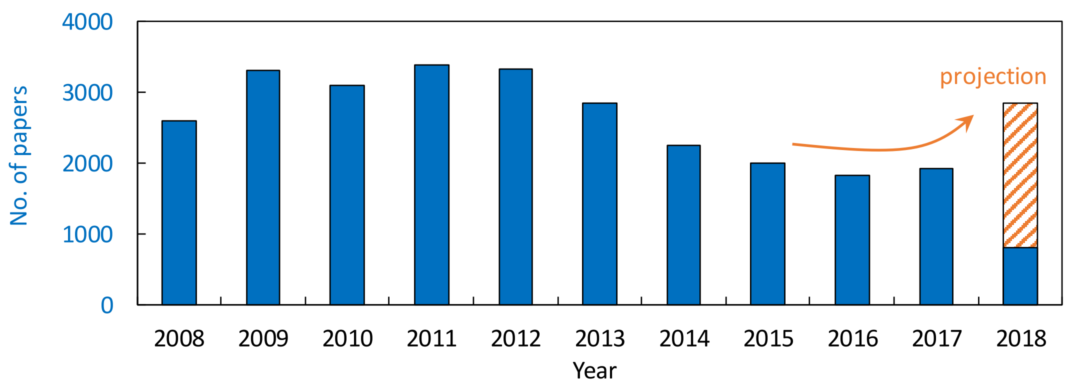
The WCEQ really attracted the attention of the scientific community worldwide.

52 out of the TOP 65 most cited papers on geo-hazards are from Chinese institutions, among them 20 are from SKLGP. It is by far *the largest contributing institution.*



Among the most cited papers





The Wenchuan earthquake is still very hot topics!
5 papers referring to it are published each day, and the trend is increasing again.

A review paper on:
What we have learned from the 2008 Wenchuan earthquake and its aftermath: A decade of research and challenges

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Short Communication

What we have learned from the 2008 Wenchuan Earthquake and its aftermath: A decade of research and challenges

Check for updates

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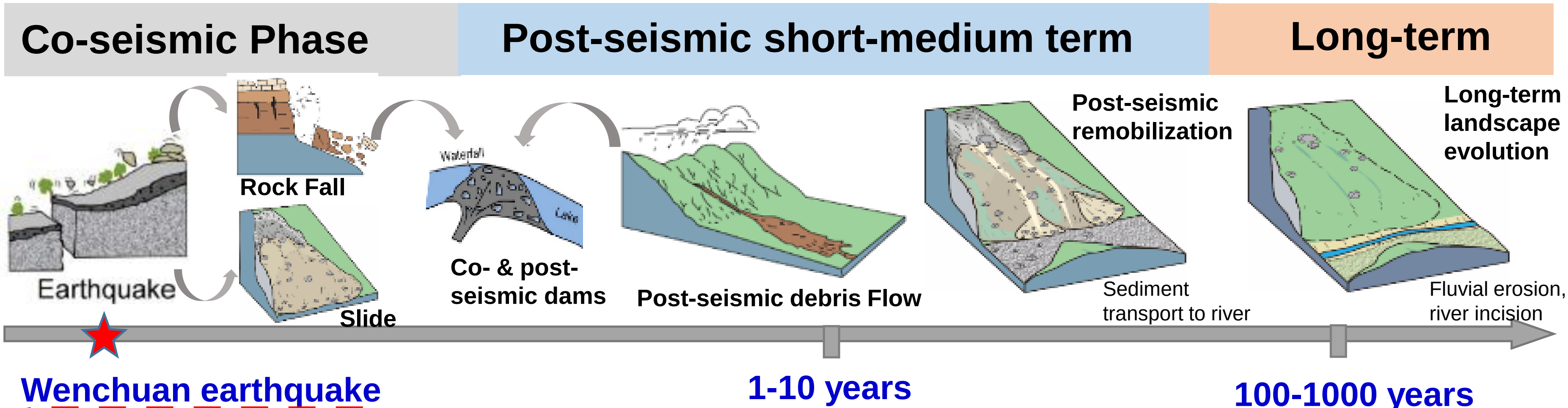
Landslide remobilization
Landscape evolution

ABSTRACT

The 2008 M_w 7.9 Wenchuan Earthquake (Sichuan, China) was possibly the largest and most destructive recent earthquake as far as the geo-hazards are concerned. Of the nearly 200,000 landslides triggered originally, many remobilized within a few years after the initial event by rainfall, which often caused catastrophic debris flows. The cascades of geo-hazards related to the Wenchuan Earthquake motivated research worldwide to investigate the triggering and mechanisms of co-seismic landslides, their rainfall-induced remobilization, the generation of debris flows, the evolution of their controlling factors, and the long-term role of earthquakes in shaping the topography. On the eve of the 10th anniversary of the 2008 Wenchuan Earthquake, we present a short review of the recent advances in these topics, discuss the challenges faced in the earthquake-related geo-hazards mitigation practice, and suggest priorities and guidelines for future research.

Summary of the main research aspects on geo-hazards and their evolution at different temporal scales



Triggering and development of co-seismic geo-hazards

- Mapping, spatial distribution patterns
- Initiation and failure mechanism analyses
- Evaluation of runout characteristics
- Formation and failure of co-seismic landslide dams

Post-seismic debris flows

- Case studies and inventory
- Initiation and runout: mechanisms and modelling
- Observations and modelling of changing rainfall threshold
- Risk management and mitigation (including structural and non-structural measures)

Post-seismic landslides and their hazard assessment

- Spatial and temporal evolution
- Controls on the post-earthquake geo-hazards evolution
- Hazard assessment
- Risk assessment and reconstruction strategies

Long-term impact of strong earthquakes

- Weathering related post-seismic landsliding
- Sediment cascade and yield after a strong earthquake
- Long-term landscape evolution: the mass balance problem

1. Triggering and development of coseismic geo-hazards

- Mapping, spatial distribution patterns
- Initiation and failure mechanism analyses
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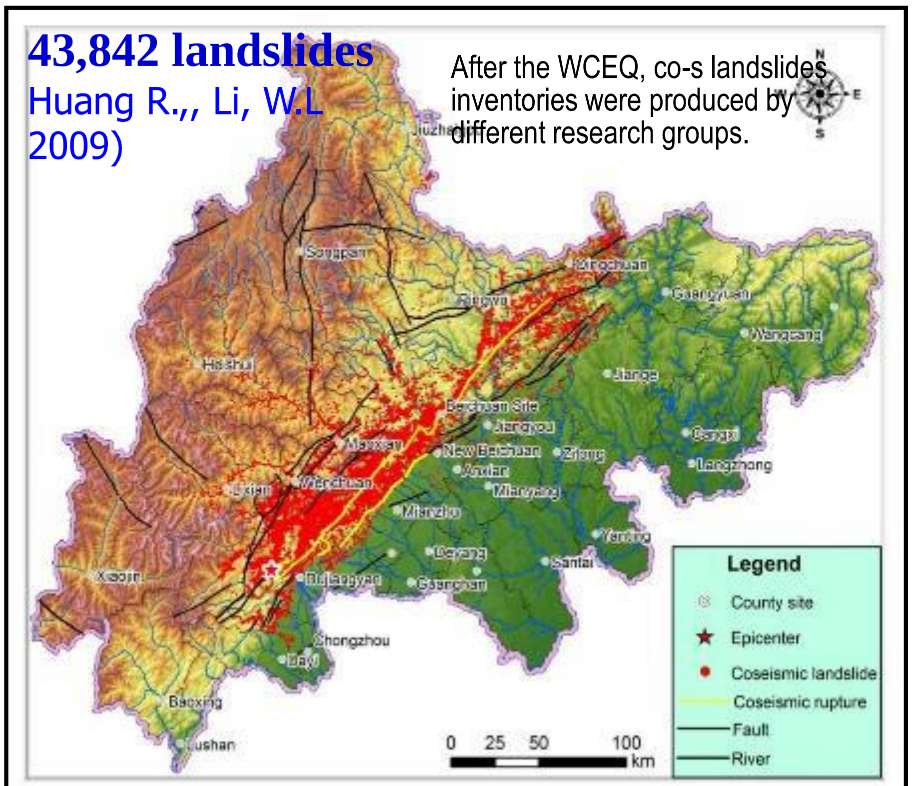
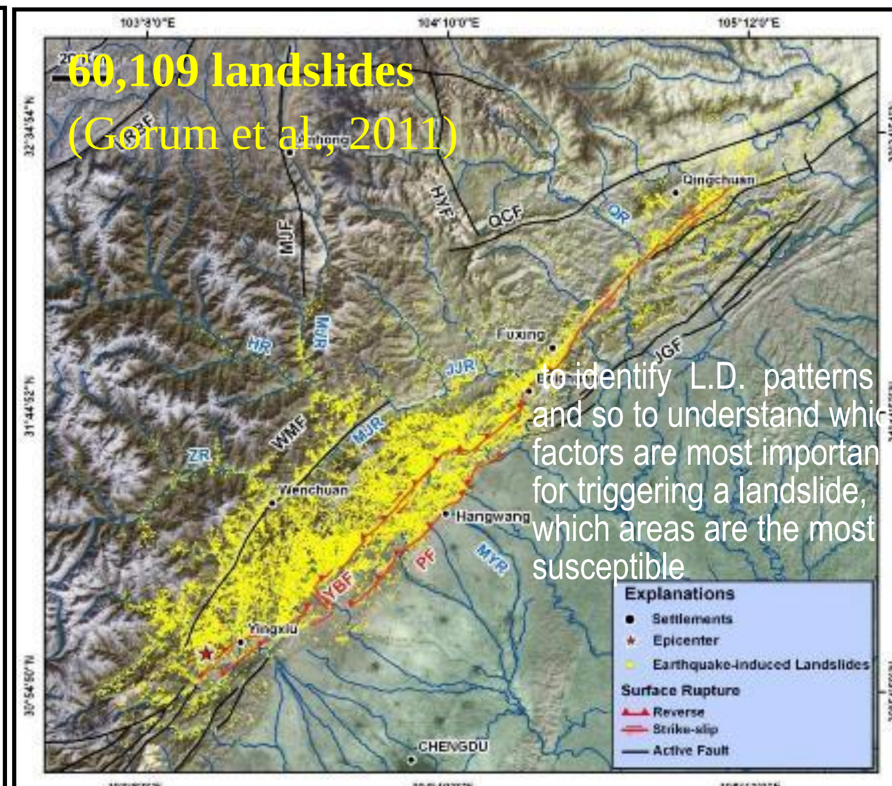
- Formation and failure of co-seismic landslide dams

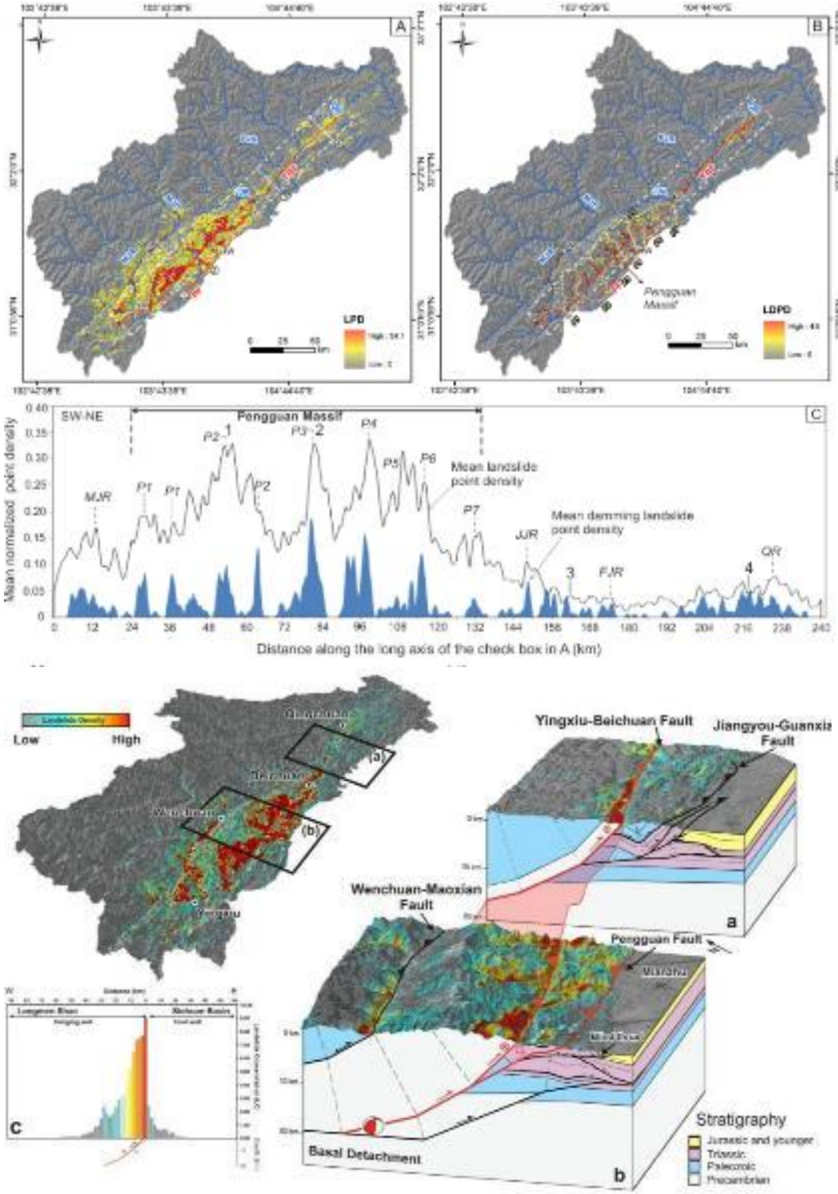
Mapping and spatial distribution patterns

Total number of landslides	Data type	Total landslide area (km^2)	Reference
43,842	points	-	Huang and Li (2009)
13,114	points	-	Qi et al. (2010)
59,108	polygons	812.2	Dai et al. (2011)
60,109	points	-	Gorum et al. (2011)
197,481	polygons	1159.9	Xu et al. (2014)
57,150	polygons	396	Li et al. (2014)





Mapping and spatial distribution patterns



Fan et al. (2012); Gorum et al. (2011)

Controlling factors for coseismic landslides (dams)

Seismic factors
- *Distance to fault*
- *Fault type*
- *Hanging/foot wall effect*
- *Locking section effect*

Terrain factors
- *Slope; Aspect*
- *Internal relief*
- *Micro-topography*

Geological factors
- *Lithology*
- *Geological structure*

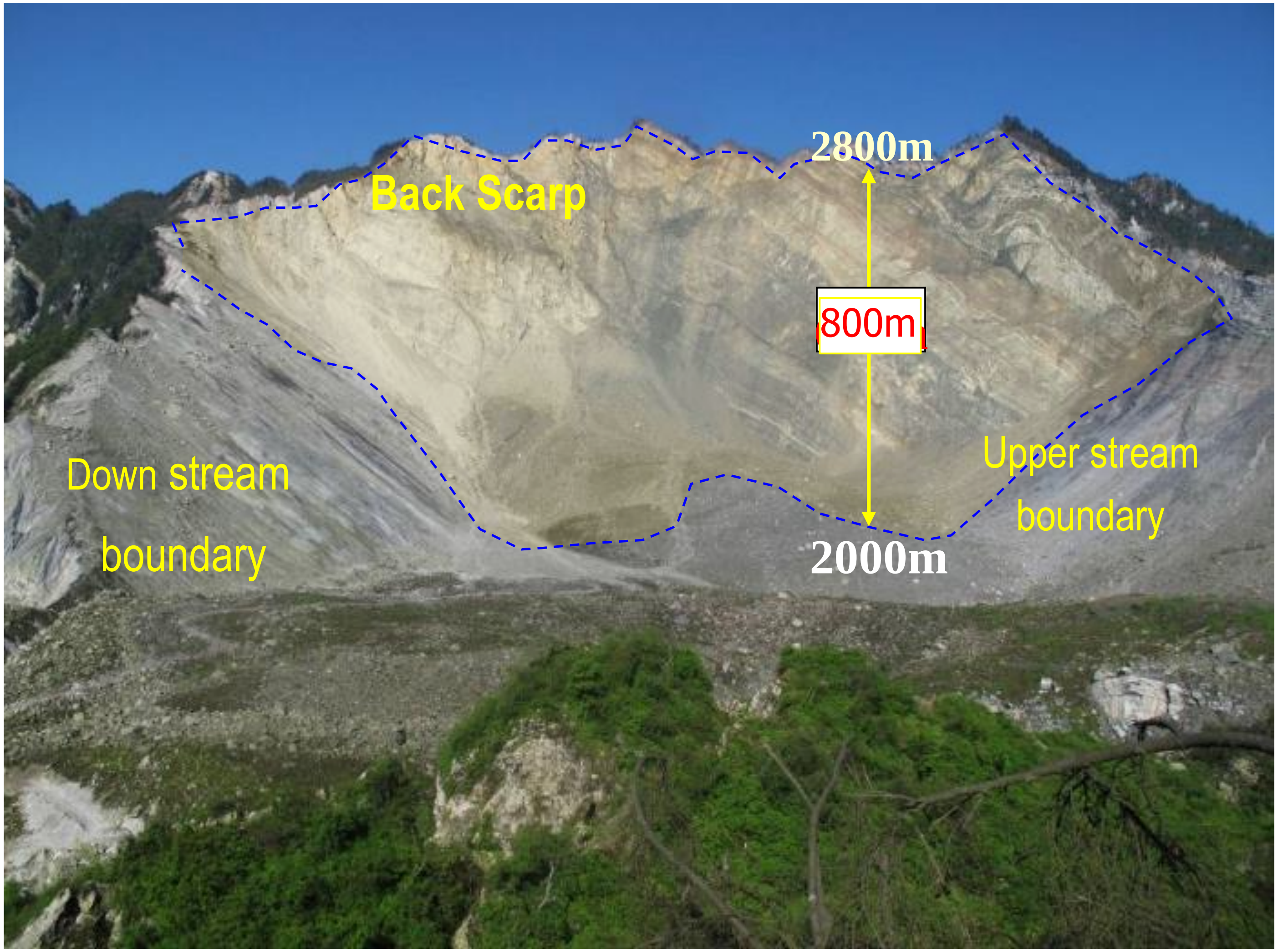
Hydrological factors
- *Distance to river*
- *Stream power index*
- *Drainage density*

Initiation and failure mechanism analyses

The Largest: Daguangbao landslide (1.35 km^3)

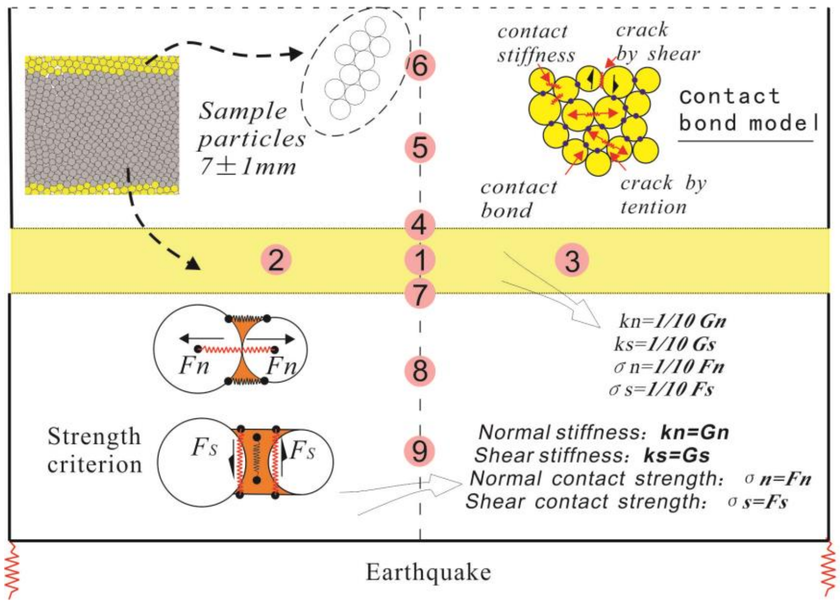
Initiation and failure mechanism analyses

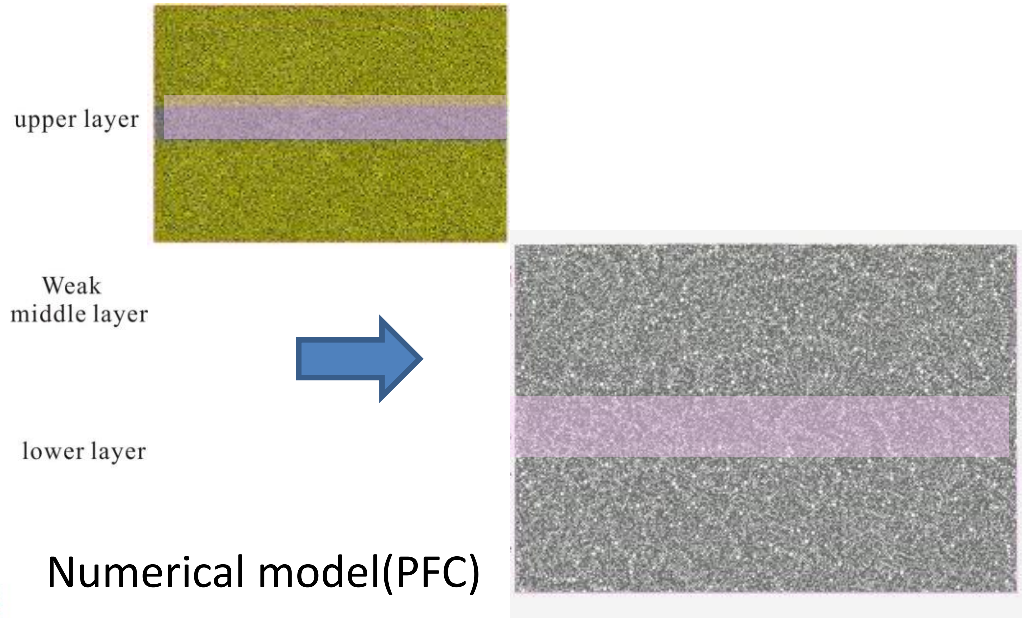
The Largest: Daguangbao landslide (1.35 km^3)

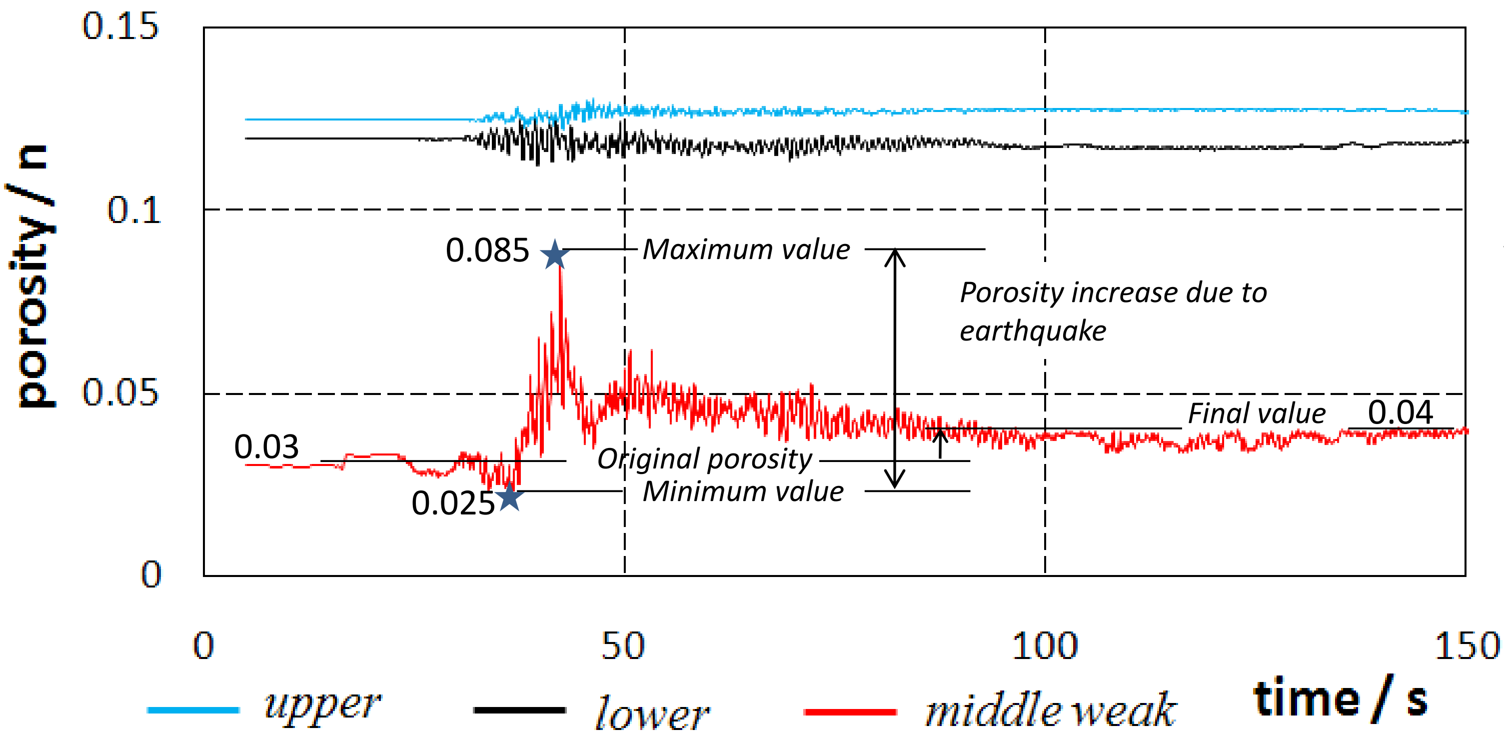


Initiation and failure mechanism analyses

The Largest: Daguangbao landslide (1.35 km^3)



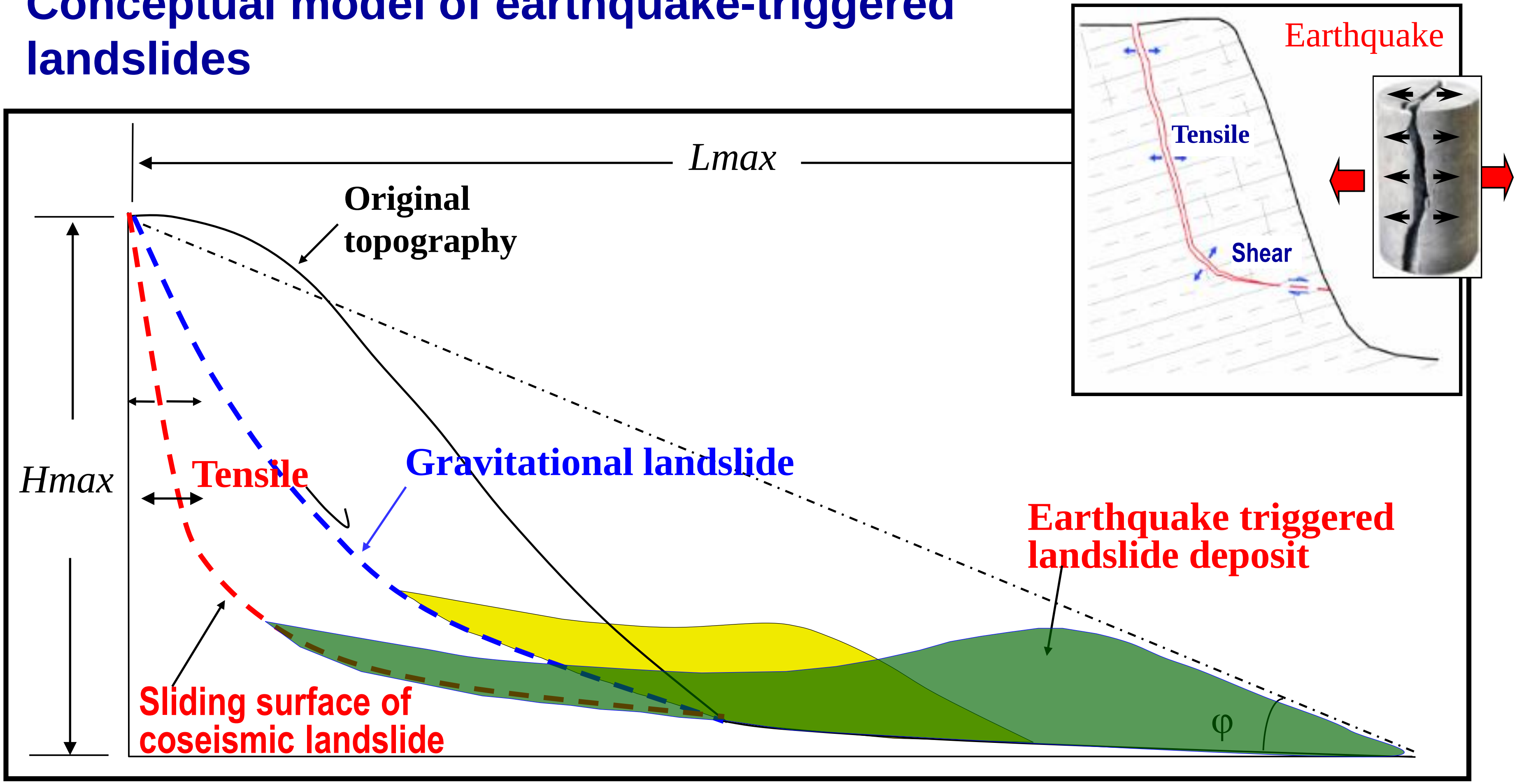




The sudden dilatancy of rock mass caused underground water penetrated into slip zone quickly, largely reducing the shearing strength of the sliding surface.

The failure mechanism of large-scale landslides triggered by the Wenchuan earthquake is dominated by tensile failure, forming steep scarp and deep-seated failure.

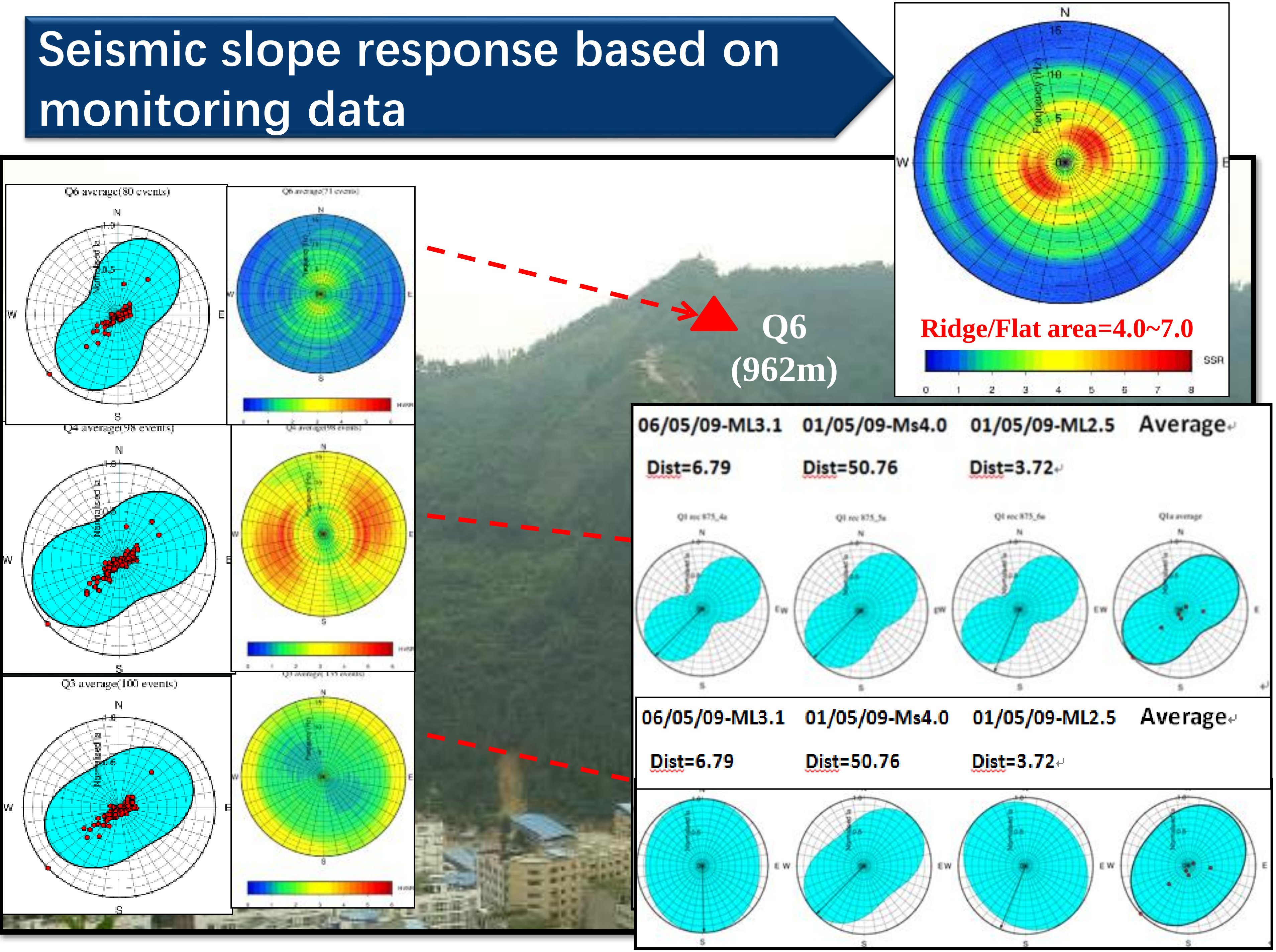
Conceptual model of earthquake-triggered landslides



Seismic slope response based on monitoring data

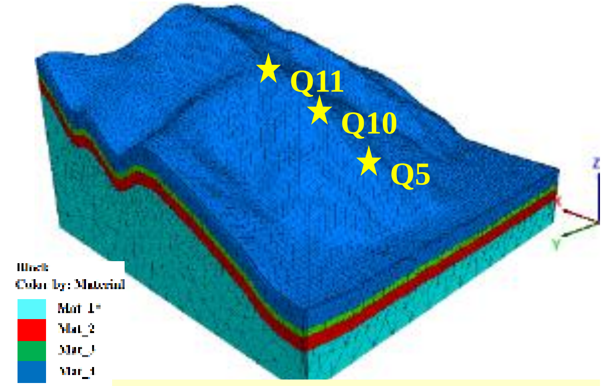
15 accelerometer monitoring stations were installed in Qing Chuan, since 2008, capturing about **10 years' data to analyze the site amplification phenomena**

Seismic slope response based on monitoring data



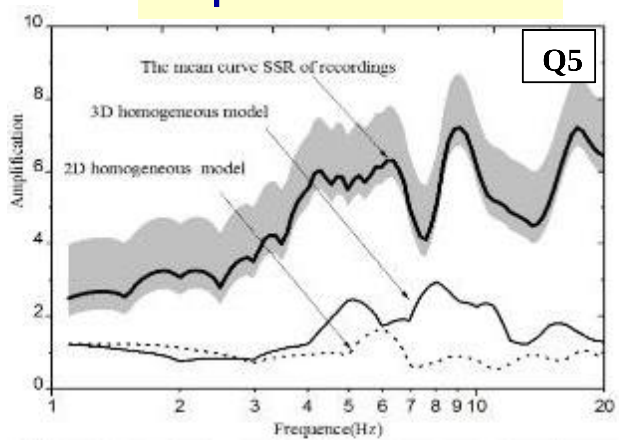
Apart from local topography, the geological structure also has strong influence on the site amplification.

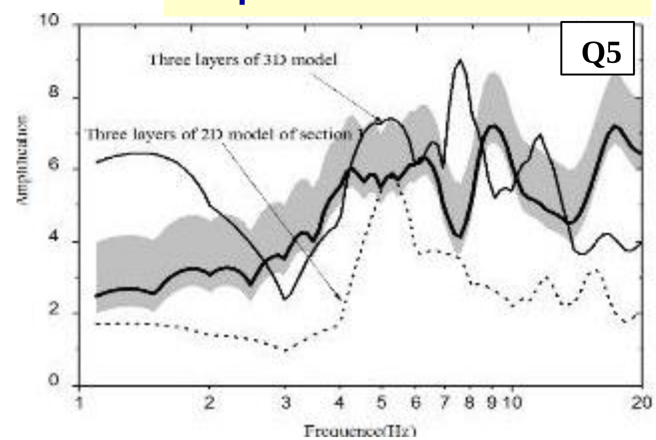
Pure topographic amplification effect



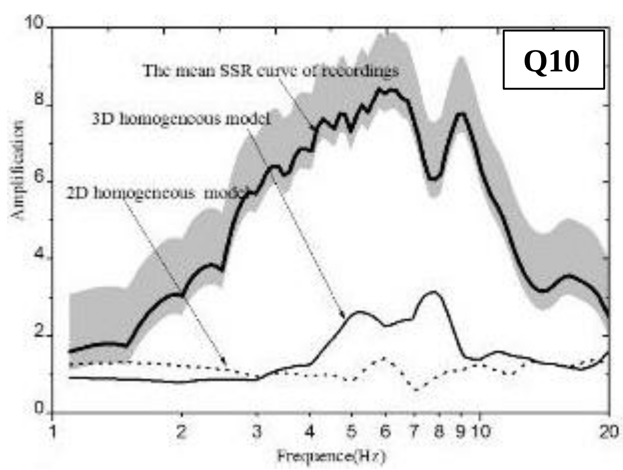
Topography & lithology amplification effect

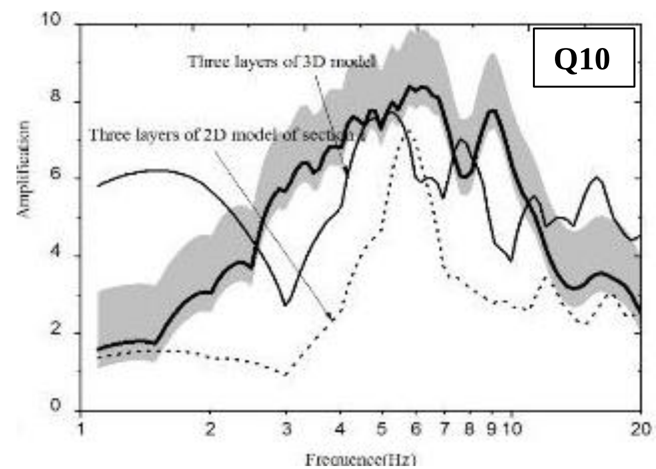
Amplification factor of pure topography is < 3.0 at 3~7Hz much lower than the site monitoring data.





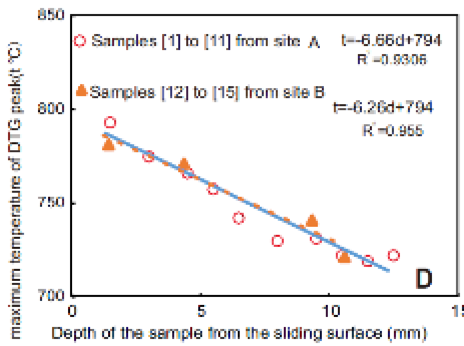
Adding lithology to the model has a significantly amplification of >9.0 at 3~7Hz, which has a good coupling with the recordings.





Evaluation of runout characteristics and mechanism

Thermo-decomposition mechanism at the bottom of large rock avalanche



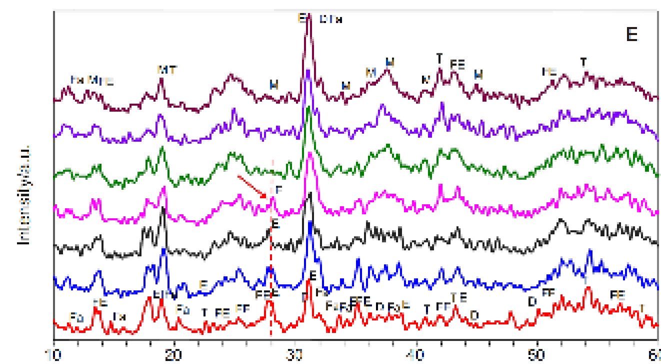
The discovery of Jiweishan landslide and the slickensides. The thermo-grammetry decomposition temperature decrease with the increase of the depth of sliding surface

THE GEOLOGICAL SOCIETY OF AMERICA®

Mineral changes quantify frictional heating during a large low-friction landslide

Wei Hu[1], Runqiu Huang[1*], Mauri McSaveney[2], Xiang-hui Zhang[3], Lu Yao[4], and Toshi Shimamoto[4]
[1]State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China
[2]GNS Science, Lower Hutt, New Zealand
[3]College of Materials, Chemistry and Chemical Engineering, Chengdu University of Technology, Chengdu 610059, China
[4]State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China

Hu et al, Geology, 2018



For talc(Wesolowski, 1984)

$2Mg_3Si_4O_{10}(OH)_2 \rightarrow 2Mg_3Si_4O_{11}$ (Anhydrous magnesium silicate) $+ 2H_2O$ (gas) (1)

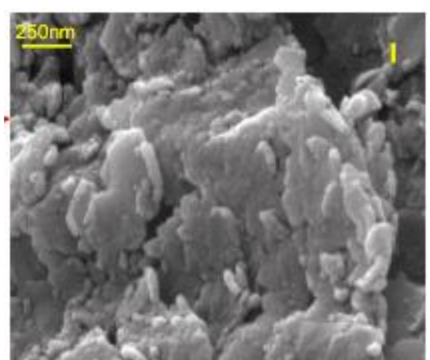
$2Mg_3Si_4O_{11}$ (Anhydrous magnesium silicate) $\rightarrow 3Mg_2(Si_2O_6)$ (enstatite) $+ 2SiO_2$ (amorphous) (2)

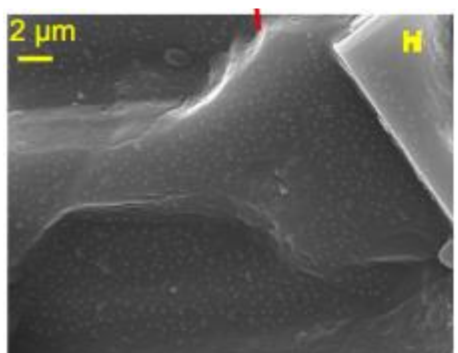
For Dolomite at 750–800°C (Ptáčeka et al.,2014)

$MgCa(CO_3)_2 \rightarrow CaCO_3 + MgO + CO_2$ (3)

Between 840 and 950°C

$CaCO_3 \rightarrow CaO + CO_2$ (4)

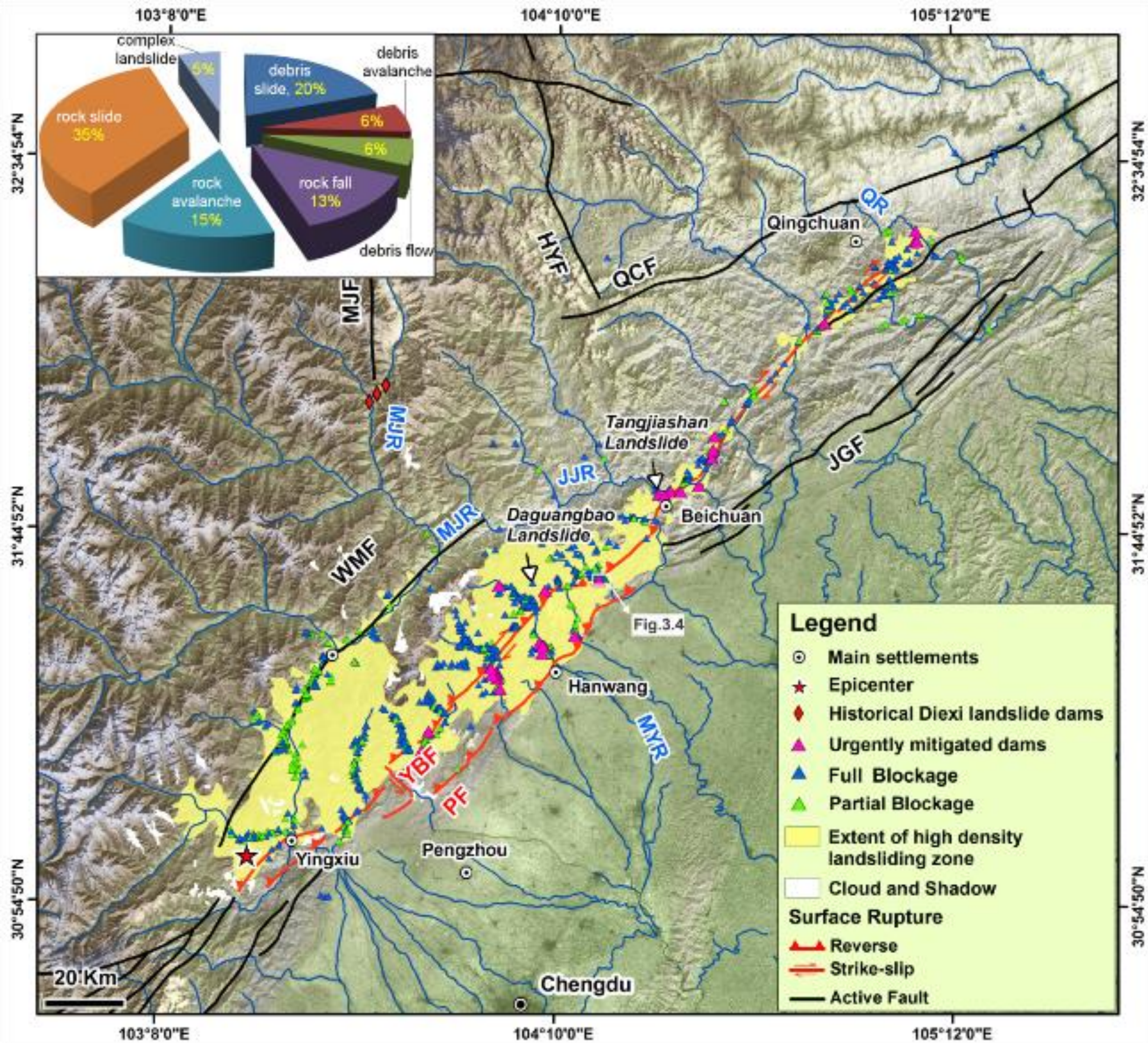




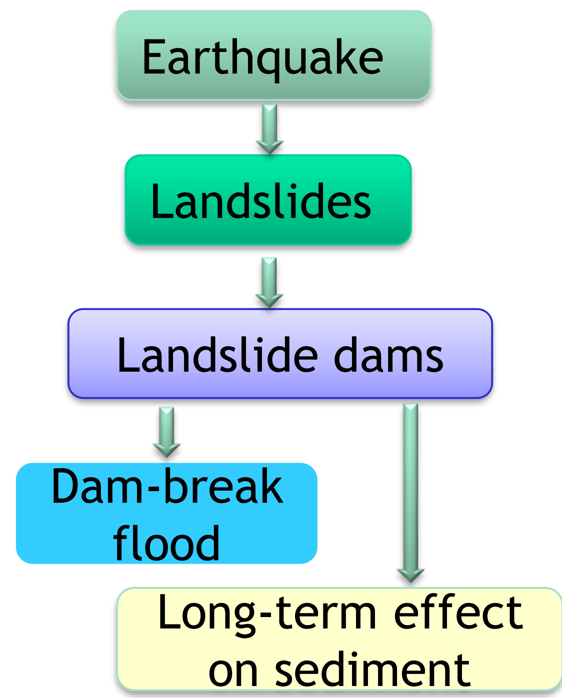
The field micro-evidence of the thermodecompostion

The mineral decomposition during the high speed shearing of landslide.

Formation and failure of coseismic landslide dams

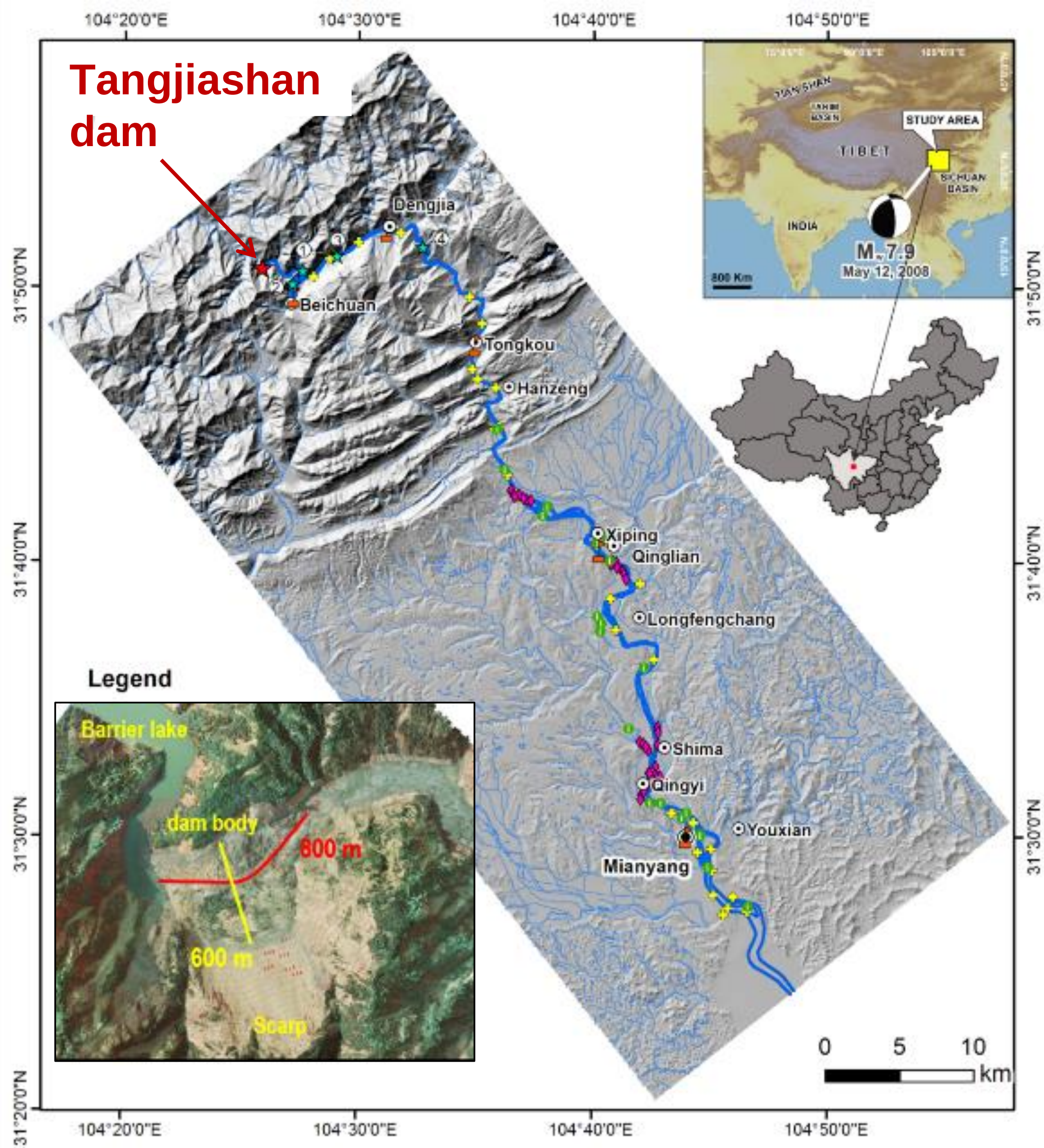


The Wenchuan earthquake also induced the largest number of landslide dams: **828,** posing serious threats to people downstream due to possible **dam-break floods.**



Fan et al. Geomorphology, 2012; Fan et al., ESPL, 2014

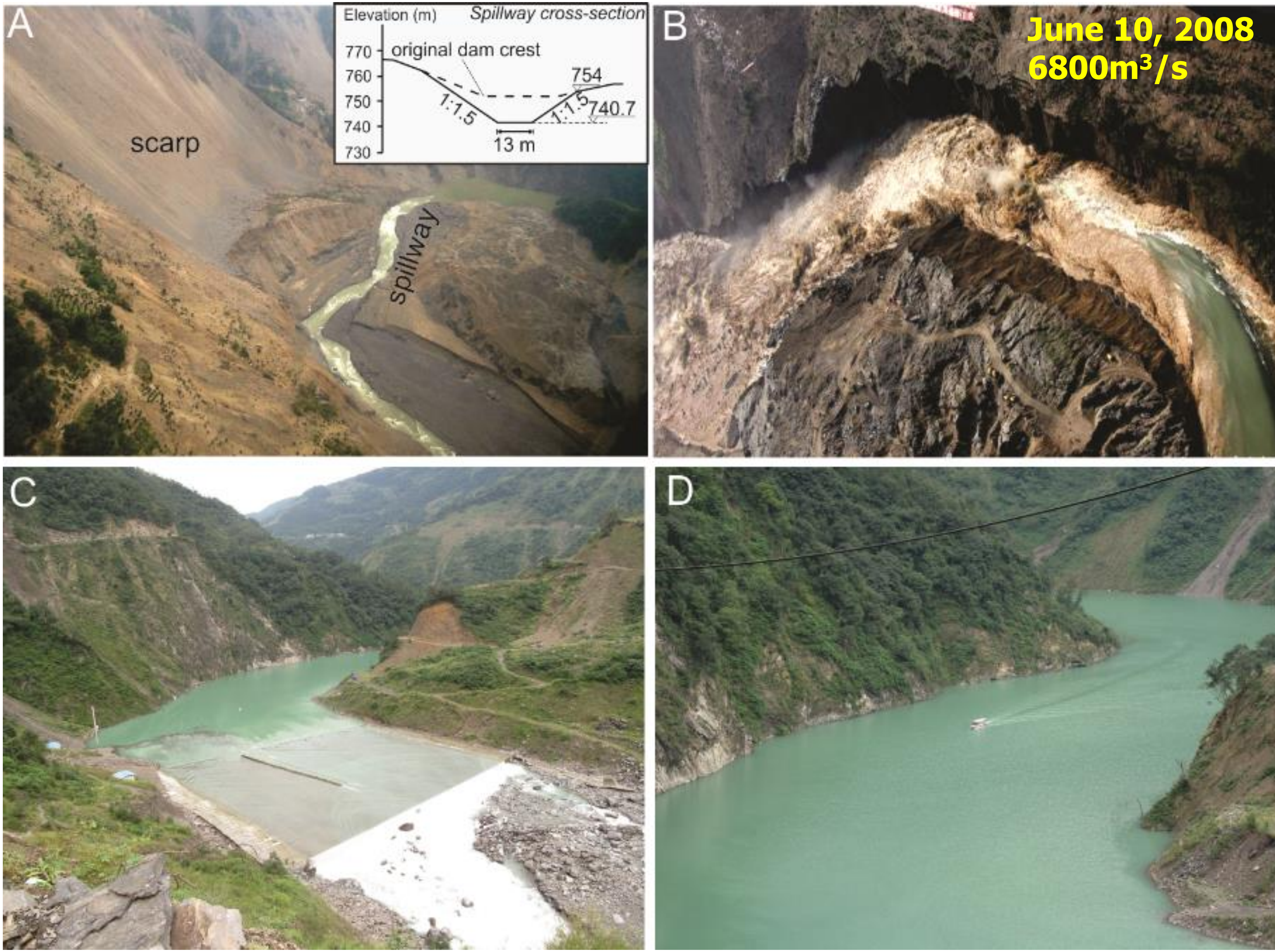
Formation and failure of coseismic landslide dams



Tangjiashan landslide dam

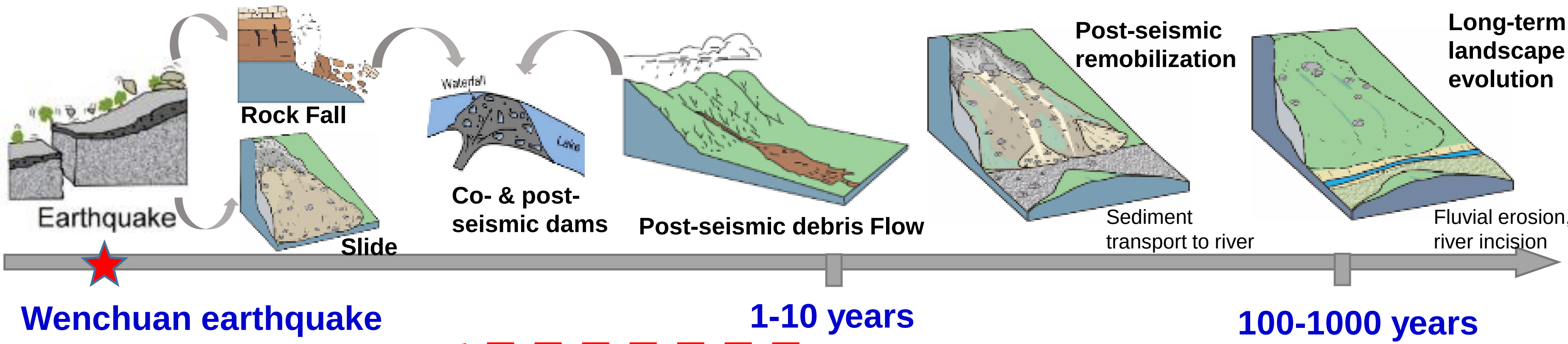
Lake capacity: 3×10^9 m^3

More than **2 million** people downstream were threatened by the potential **dam-break flood**, including the second largest city, Mianyang in Sichuan province.


A
Elevation (m)
Spillway cross-section
770
760
750
740
730
original dam crest
754
1:1.5
1:1.5
740.7
13 m
scarp
spillway
B
June 10, 2008
6800m³/s
C
D

Summary of the main research aspects on geo-hazards and their evolution at different temporal scales

Co-seismic Phase	Post-seismic short-medium term	Long-term



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Long-term impact of strong earthquakes

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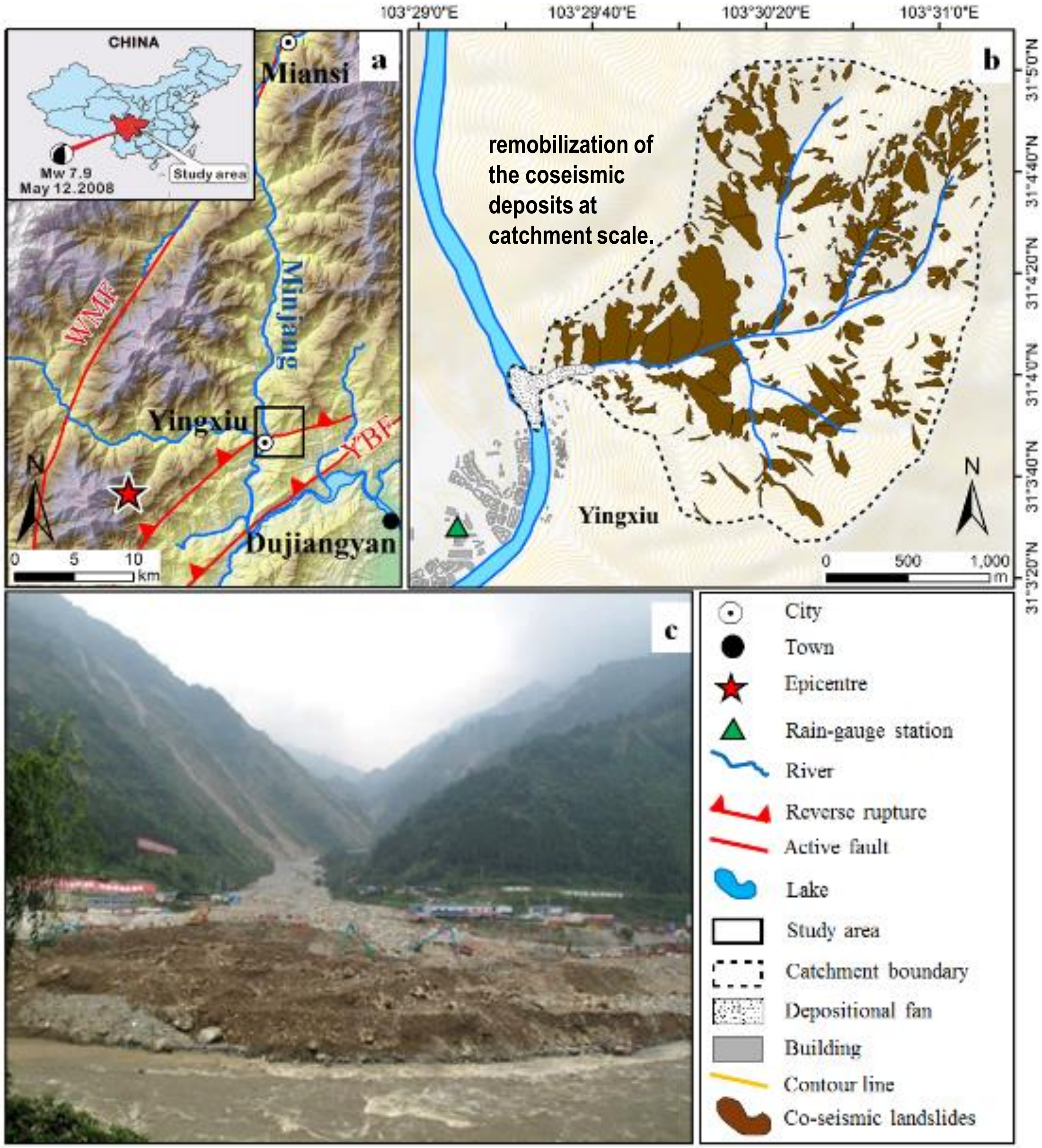
- Sediment cascade and yield after a strong earthquake
- Long-term landscape evolution: the mass balance problem

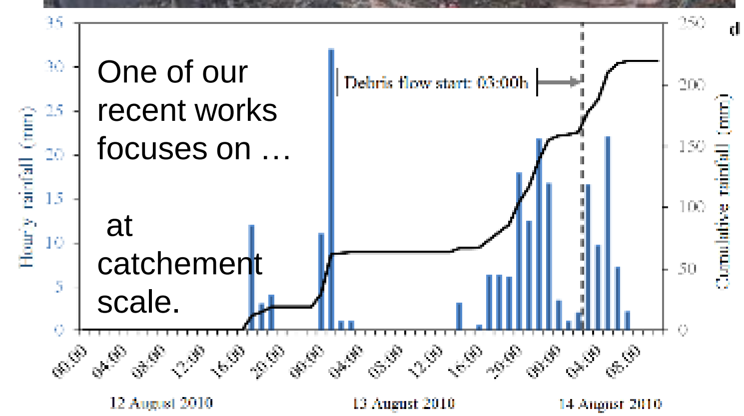
2. Post-seismic debris flows

- Case studies and inventory
- **Initiation and runout mechanisms and modelling**
- **Observations and modelling of changing rainfall threshold**
- Risk assessment and mitigation

Initiation and runout: mechanisms and modelling

Simulation of Hongchun debris flow occurred in August 2010 using PCRaster

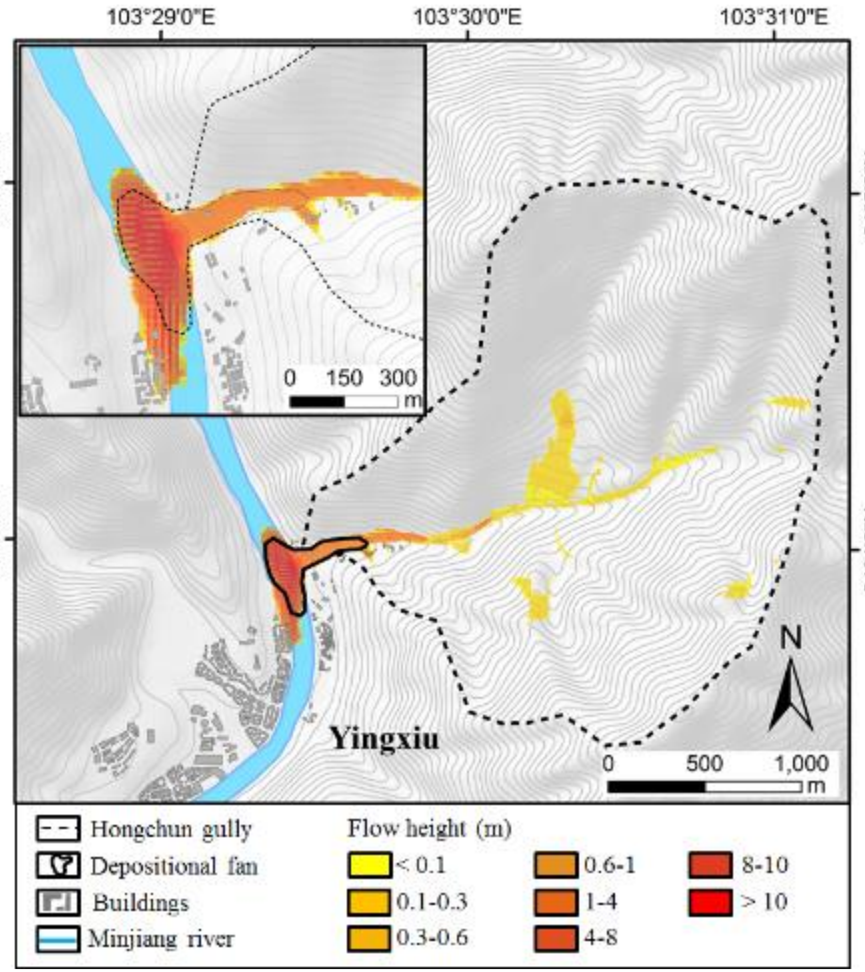


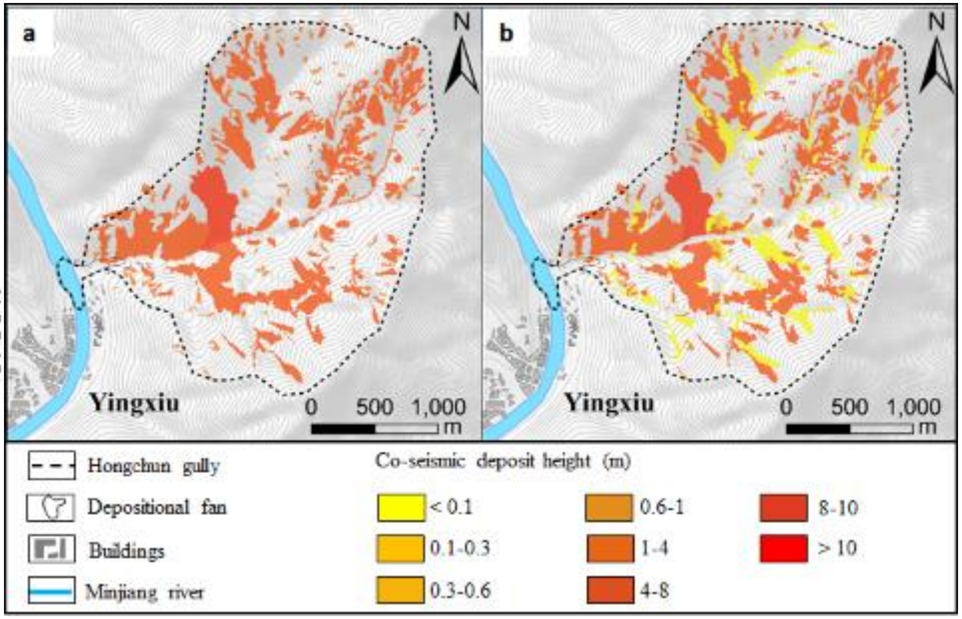


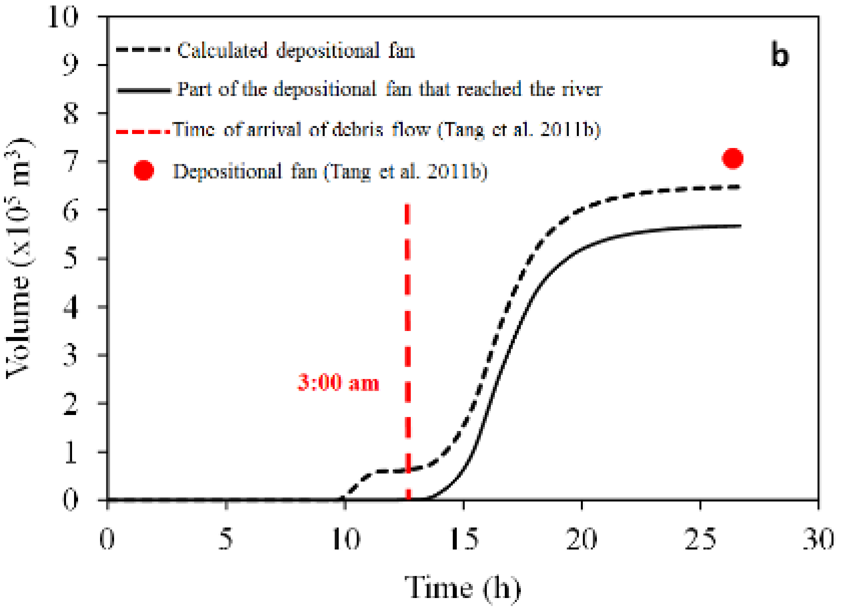
Domènech , Fan*, Scaringi, van Ash, Huang, Xu, Dai, Yang (*Engineering Geology, 2018*)

Initiation and runout: mechanisms and modelling

Calibration of the 14 August debris flow event







Domènech , Fan*, Scaringi, van Ash, Huang, Xu, Dai, Yang (*Engineering Geology, 2018*)

Observation of changing rainfall threshold

Before the Earthquake		After the earthquake		Decrease of critical rainfall	
Accumulated rainfall (mm)	Critical rainfall (mm/hr)	Accumulated rainfall (mm)	Critical rainfall (mm/hr)	Accumulated rainfall (mm)	Critical rainfall (mm/hr)
320-350	**55-60**	**272.7**	**41**	**15.0%～22.0%**	**25.0% ～32.0%**

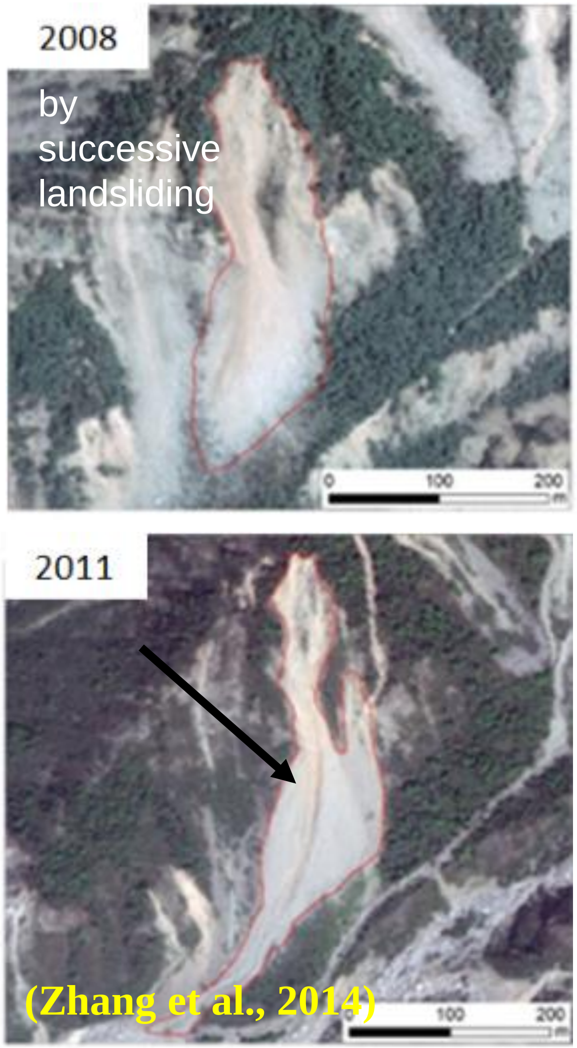
This trend is similar to that of 1999 Taiwan Chi-Chi earthquake area, where the accumulated rainfall and critical per-hour rainfall intensity **were 1/3 lower** than before the earthquake. Generally in WCEQ area, 320~350mm means once every 50 years, but 270mm means once only every 10 years.

However, the rainfall threshold was observed to recover gradually to the pre-earthquake level with time.

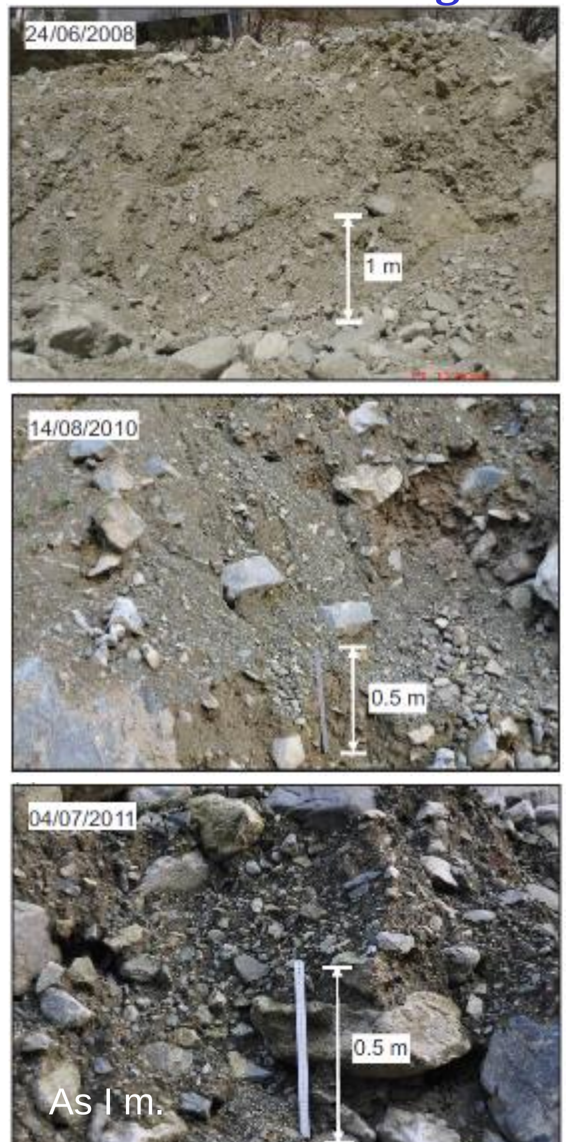
Modelling of changing rainfall threshold

Changes of amount of source material, properties of coseismic deposits

Reduction of source material with time



Grain coarsening

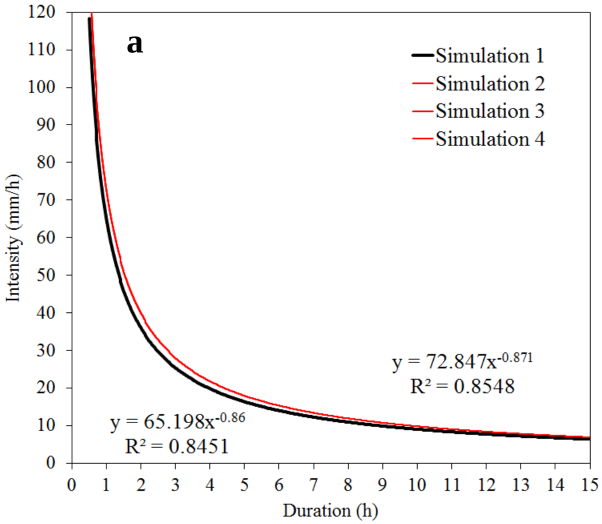


Revegetation

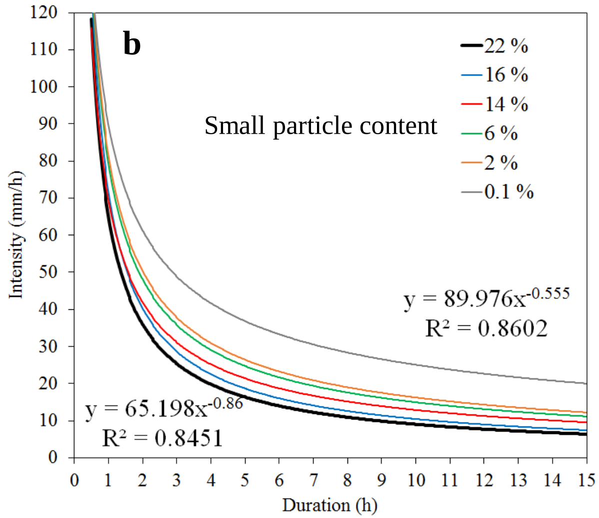
Modelling of changing rainfall threshold

1. Calibration of the 14 August 2010 debris flow event in Hongchun gully
2. Integration of the material depletion, grain coarsening and revegetation of the co-seismic deposits into the model (van Asch et al., 2014).
3. Definition of thresholds for a run-out distance until the outlet of the catchment
4. Assessment of the evolution of the rainfall thresholds according to three process

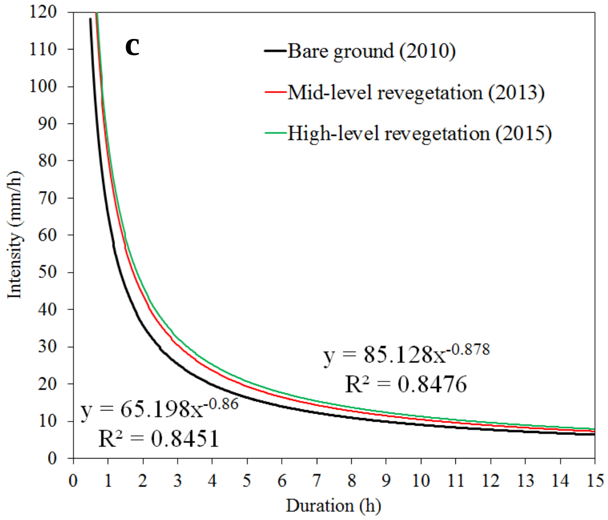
Material depletion



Grain coarsening



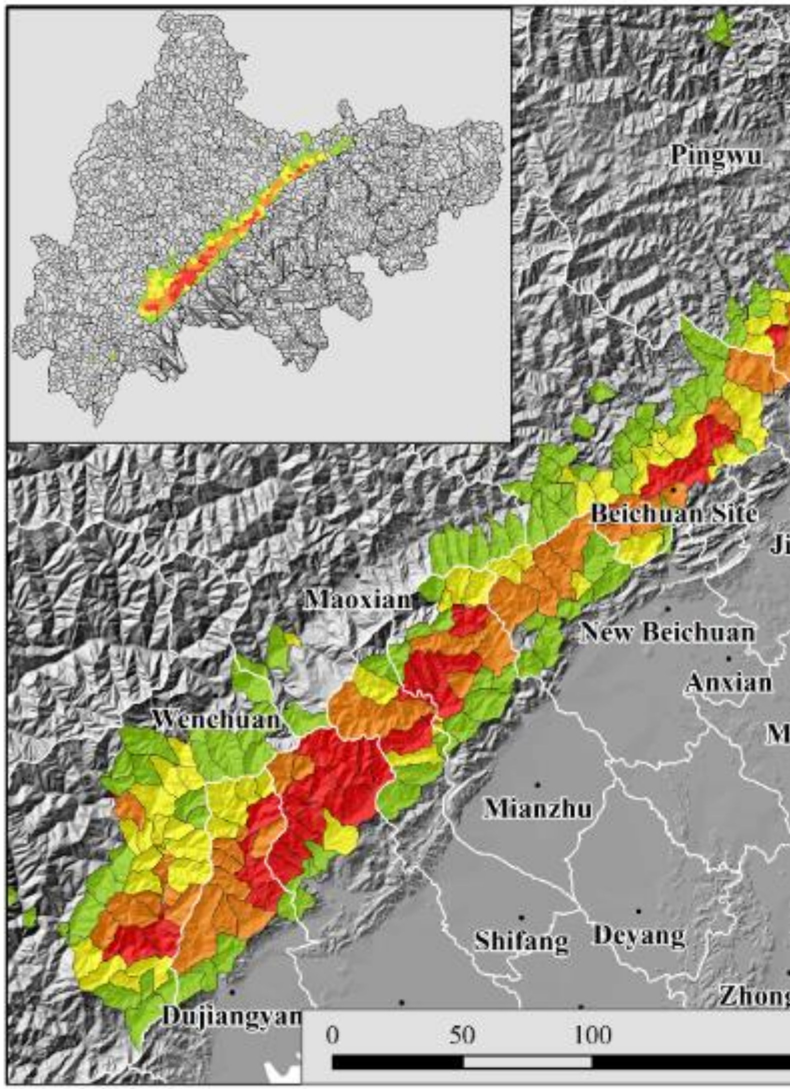
Revegetation



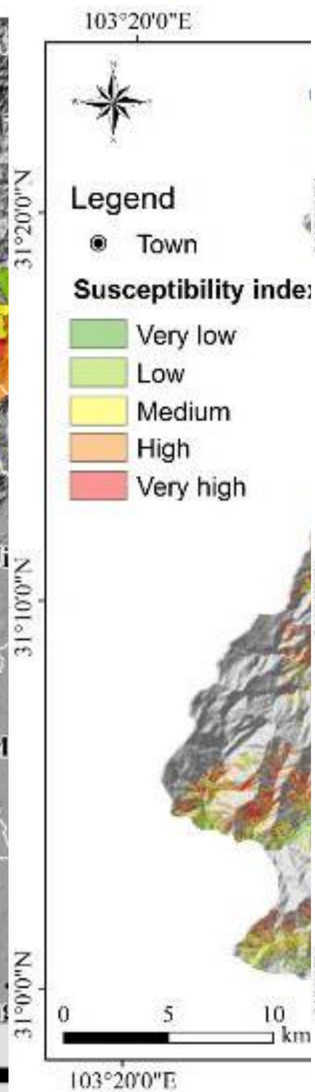
…The grain coarsening is the most significant factor affecting the rainfall threshold for post-seismic debris flows, while the depletion of the material and the revegetation cannot produce the large changes that we observed in the field.

Hazard and risk assessment at different scales

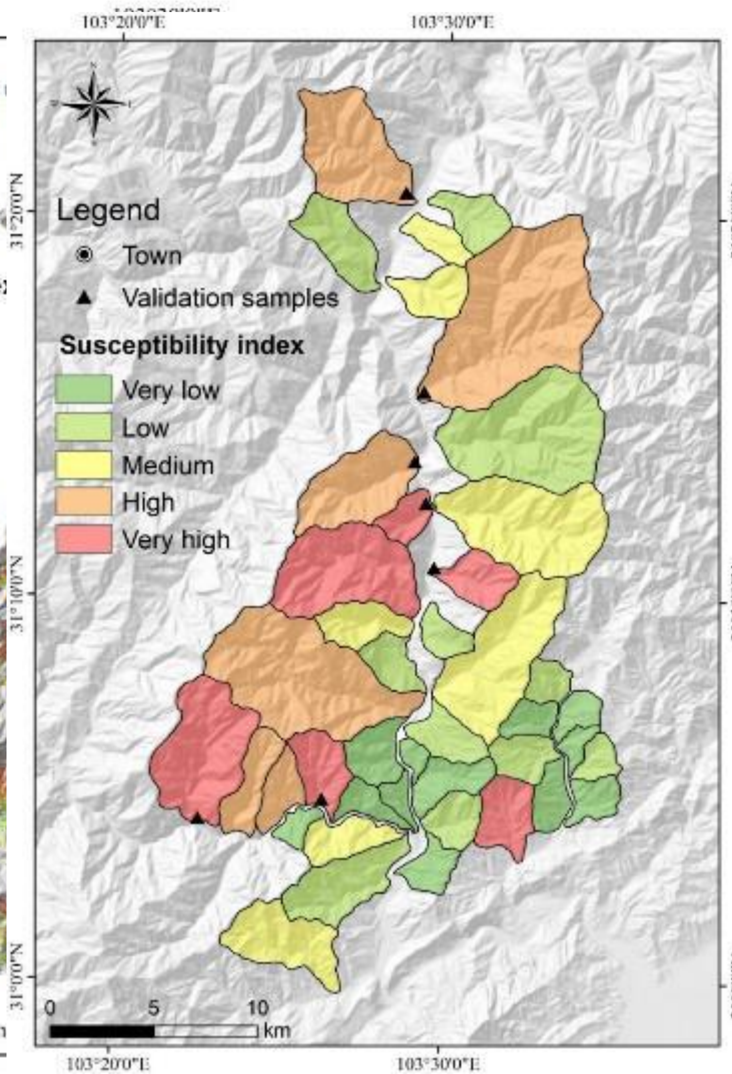
Post-seismic debris flow assessm
earthquake hit region



Post-se
Susceptil

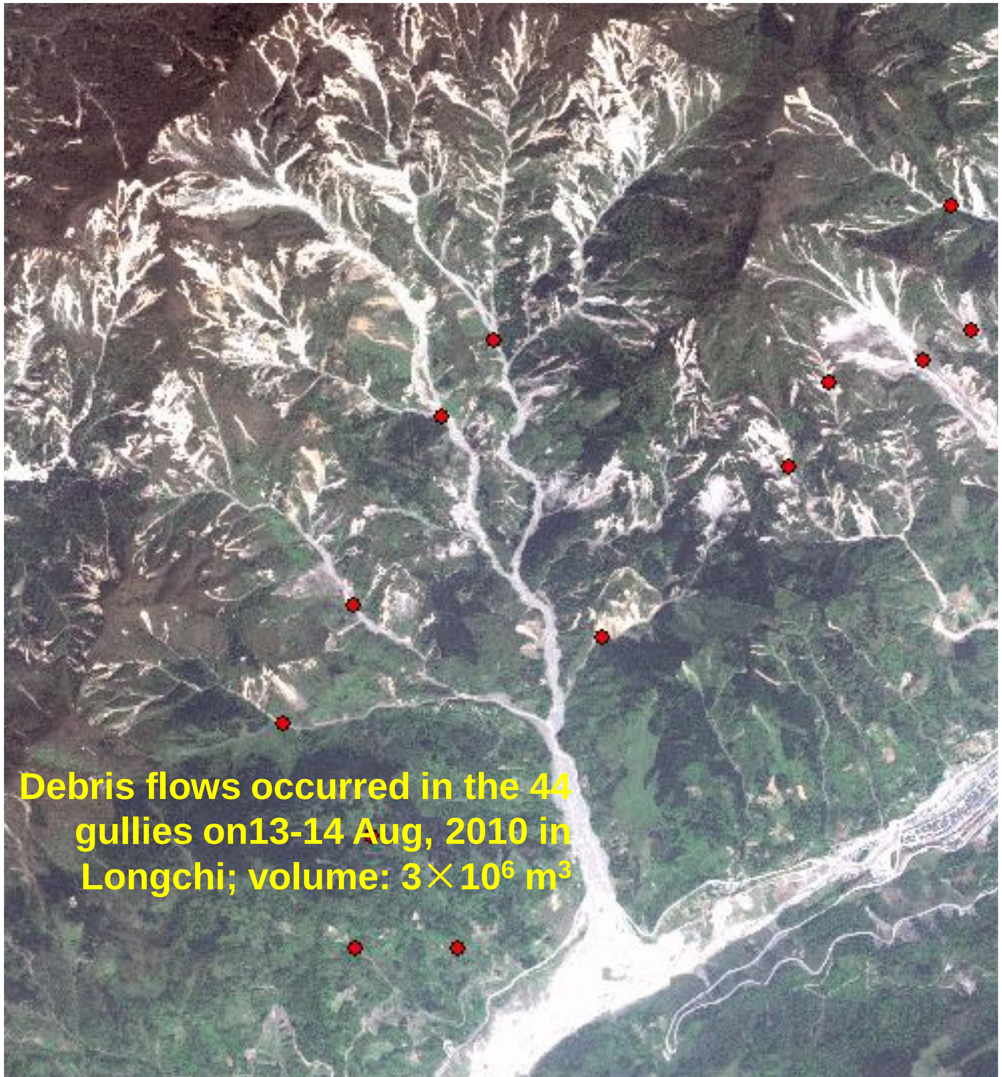


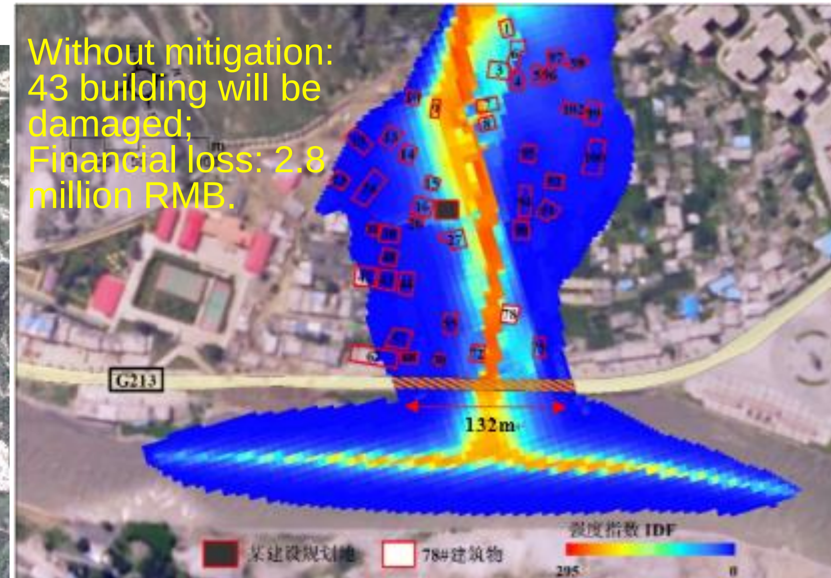
Post-seismic debris flow
susceptibility assessment

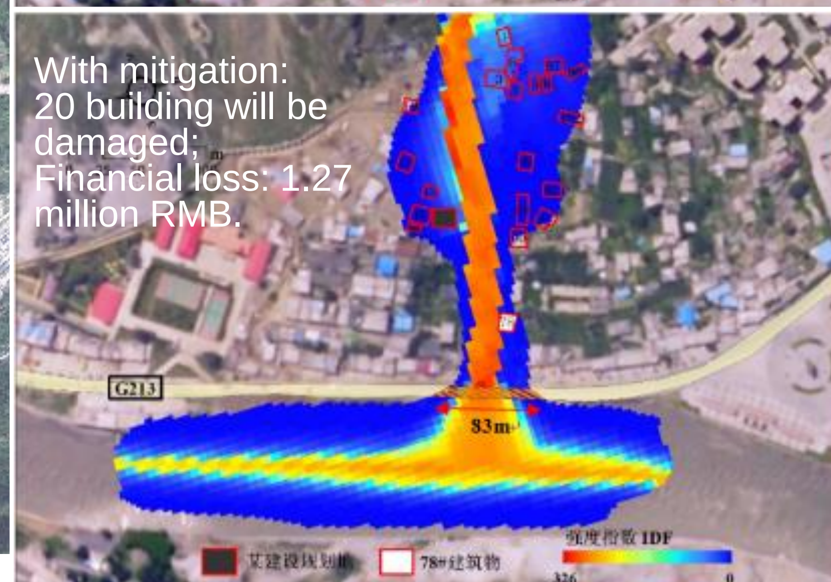


Hazard and risk assessment at different scales

Hazard assessment for individual debris flow catchments at Longchi





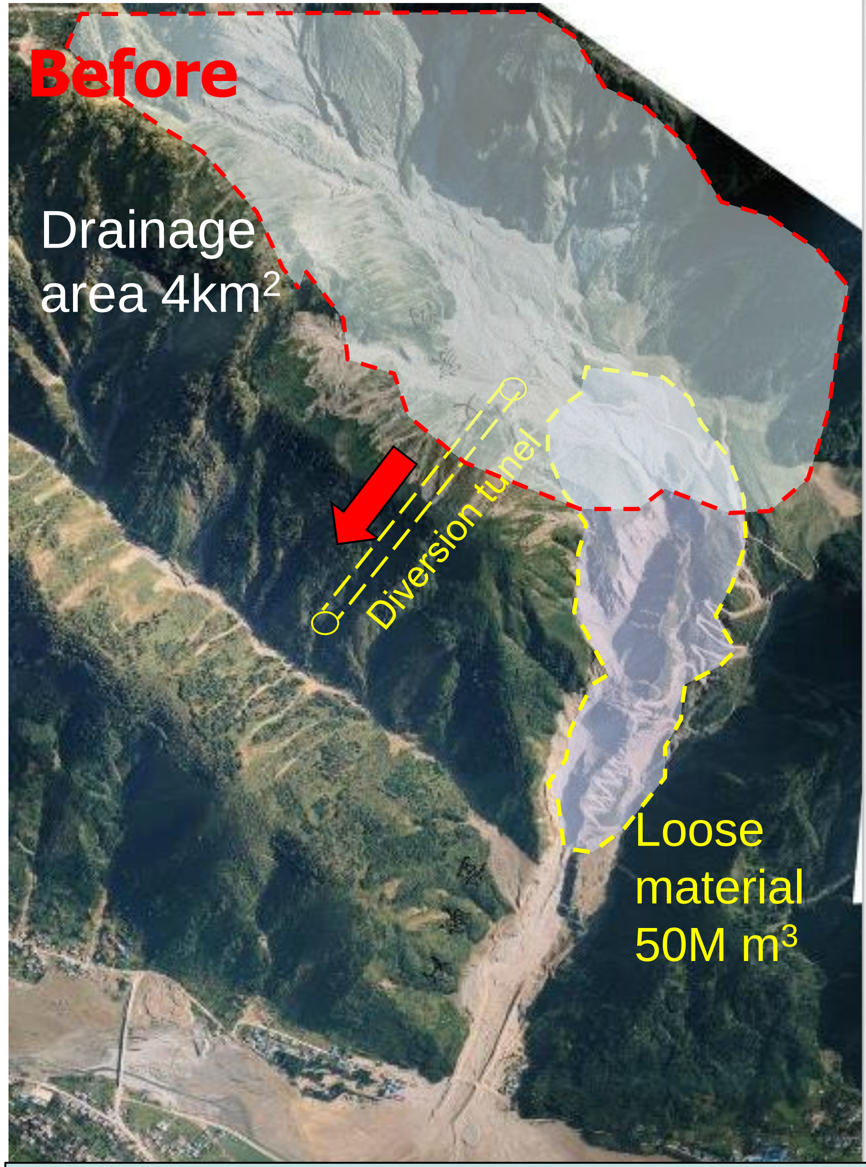


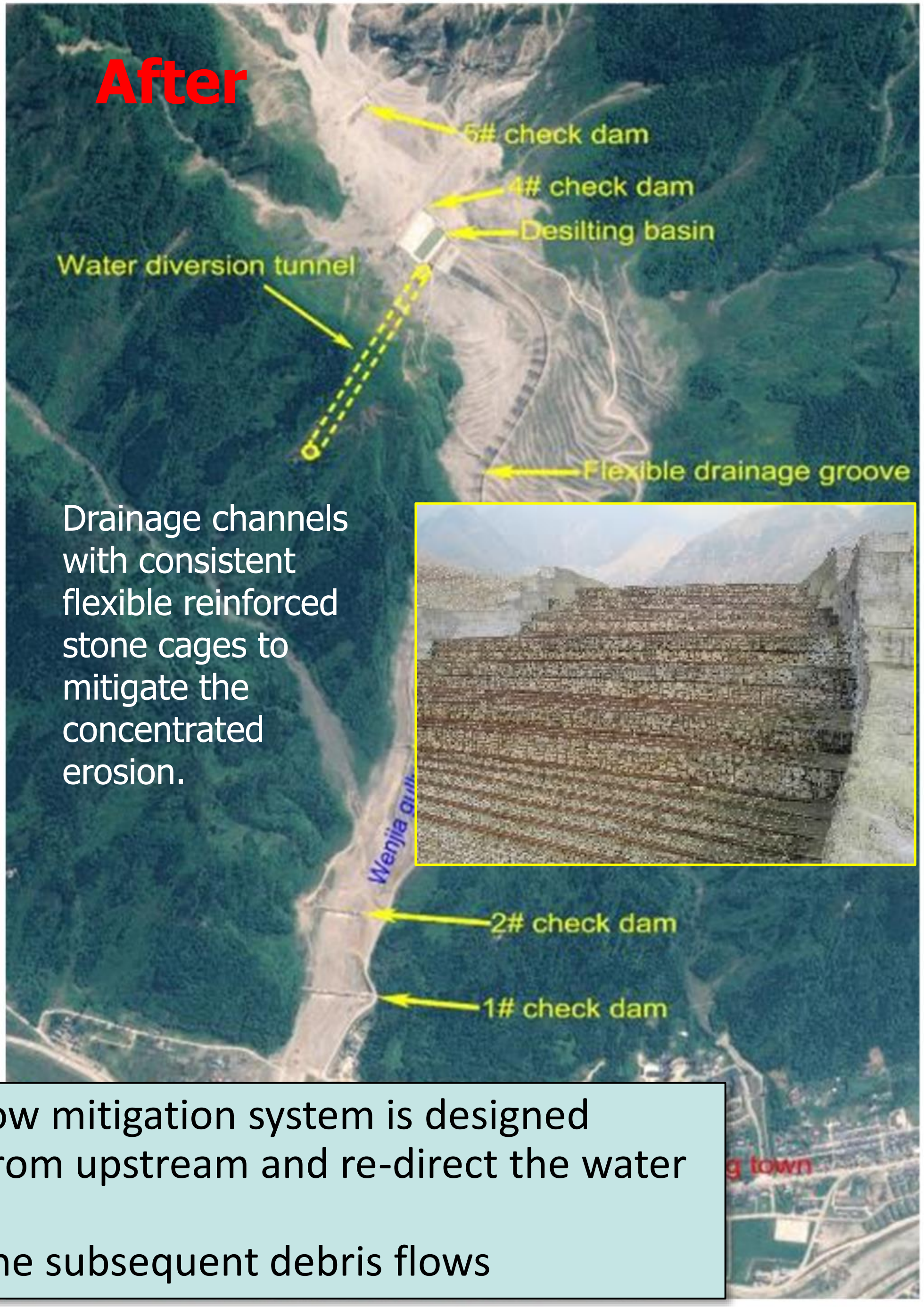
From PhD thesis of Dr. Ming Chang, and Dr. Xun Huang

Risk mitigation: structural measures (engineering work)

The Wenjia gully debris flow: one important example of structural mitigation countermeasures

- **Conventional debris flow prevention design failed to mitigate such large magnitude of debris flows. A great risk imposed to the downstream community.**

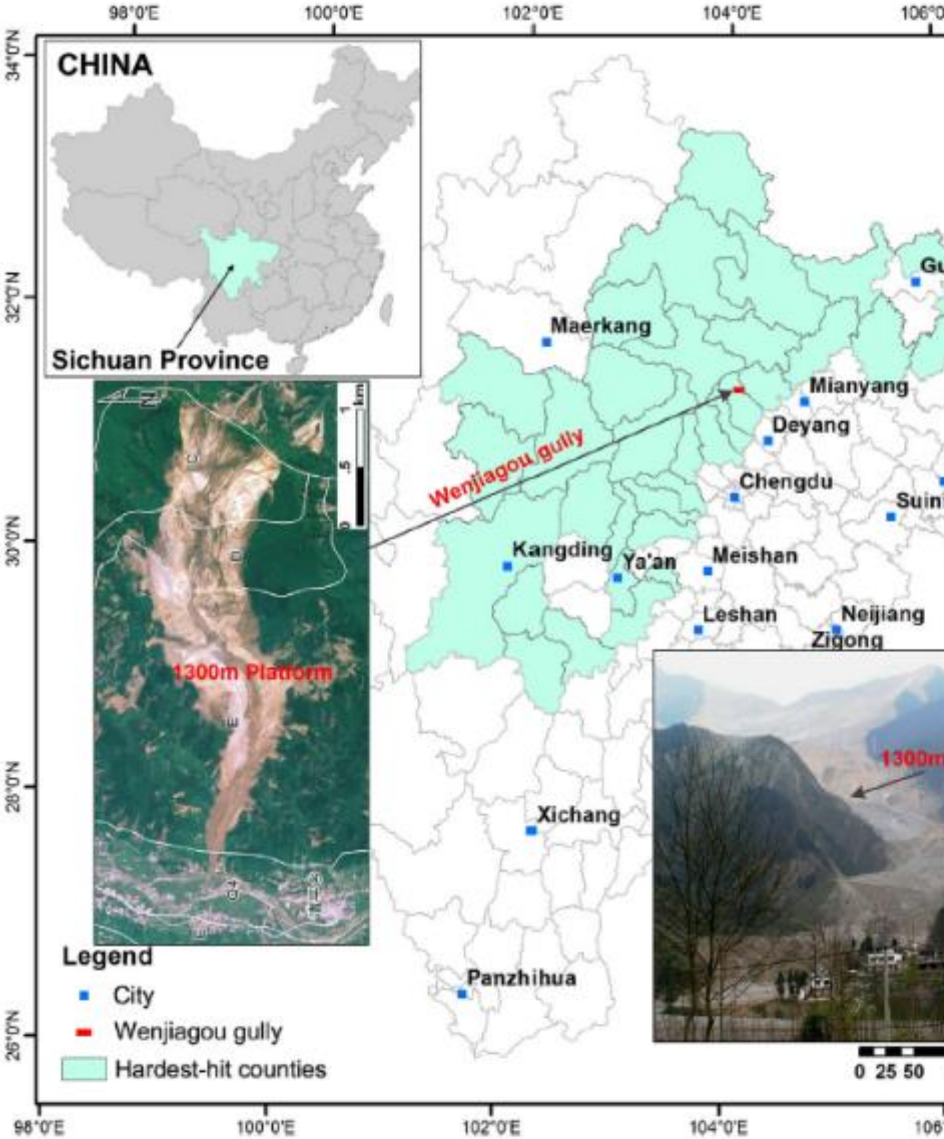




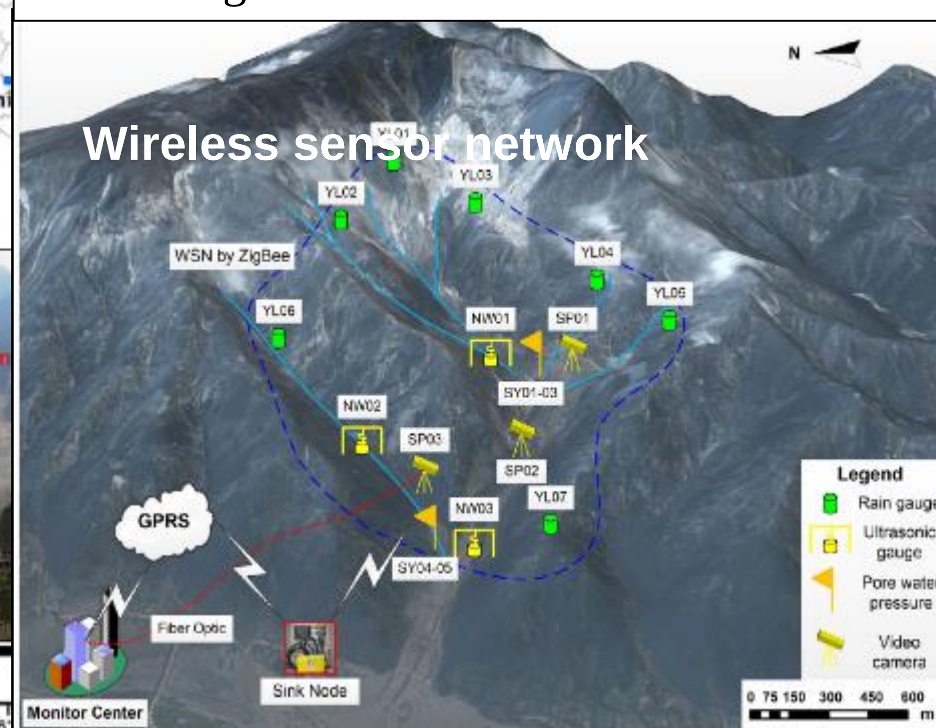
- A novel resilient and sustainable debris flow mitigation system is designed
- The system segregates debris and water from upstream and re-direct the water to the downstream through tunnel
- The system shows great performance in the subsequent debris flows

Risk mitigation: non-structural measures (early warning)

Field monitoring of the Wenjia debris flow gully

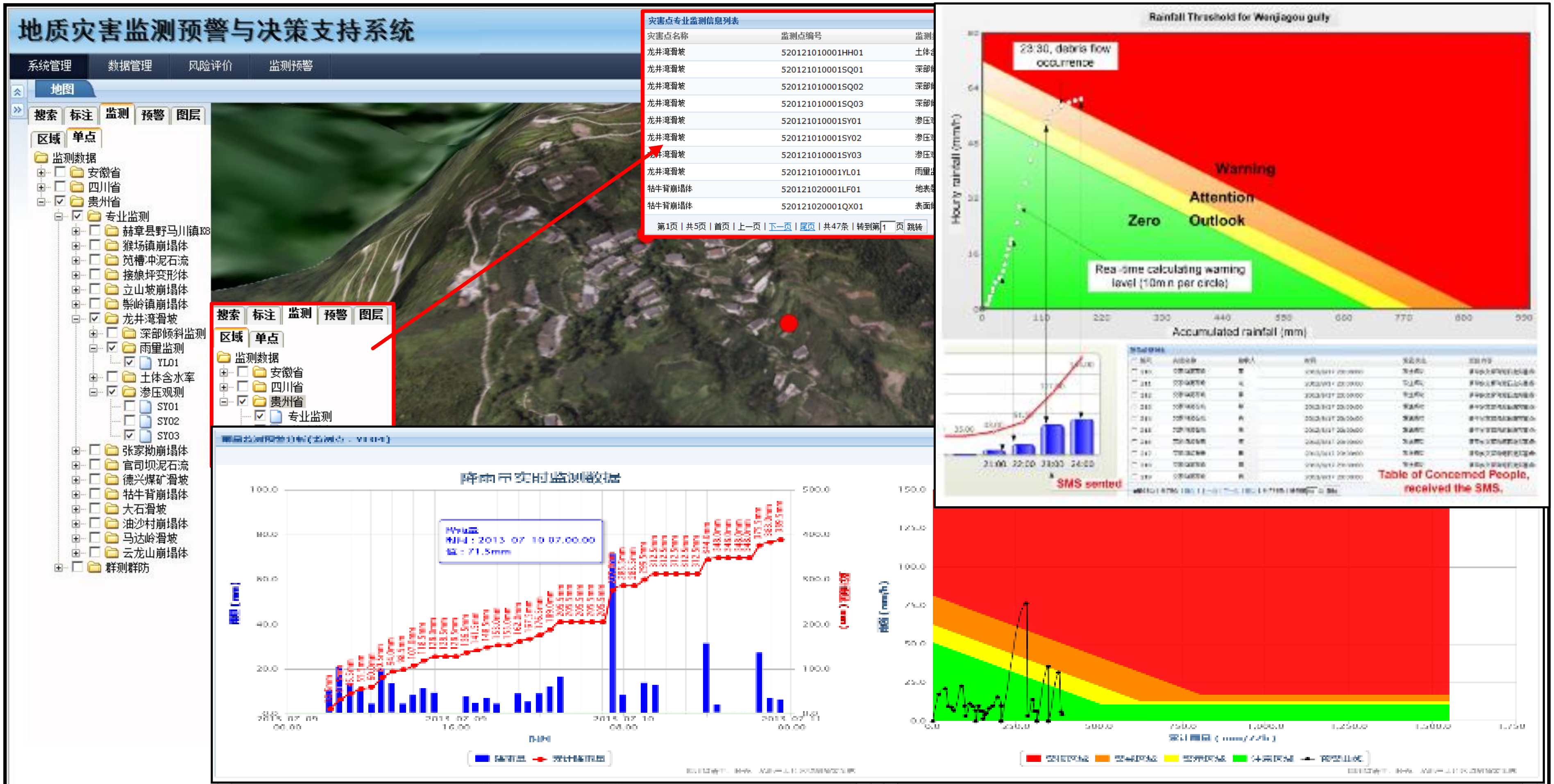


In the same site, non-structural mitigation measures are also implemented. An early warning system is in place that uses a rich network of wireless sensors (rain gauges, pore water pressure gauges, cameras, etc) that are connected through the GPRS network to a monitoring center.



Risk mitigation: non-structural measures (early warning)

3D-WebGIS platform for debris flow and landslide early warning

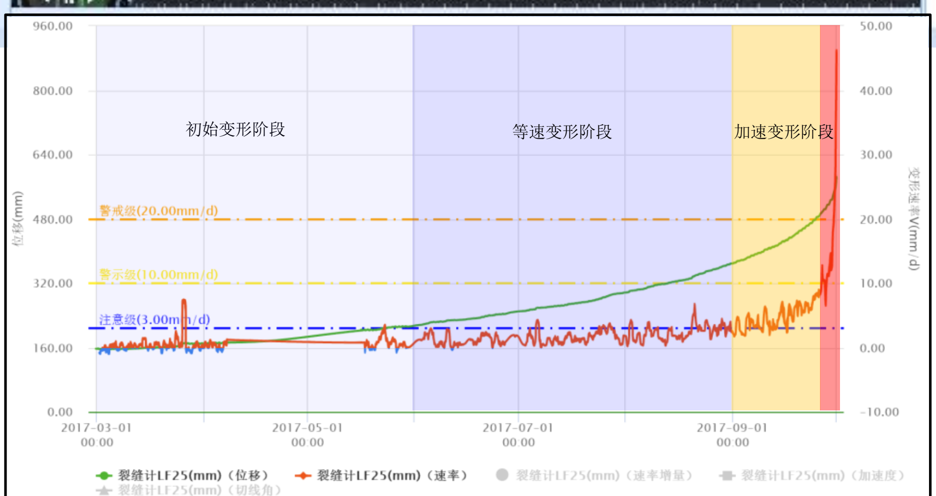


The warning is implemented in a 3D-WebGIS platform and it is calculated in real time on the basis of a local-based rainfall threshold. The warning is issued to a list of concerned people that receive the alert messages. Using this system, we successfully forecasted several debris flows before them actually occurred including that huge one in Qingping in Aug. 2012

Risk mitigation: non-structural measures (early warning)

New generation of 3D-WebGIS platform for Landslide Early warning (2016-2018)

Web Service



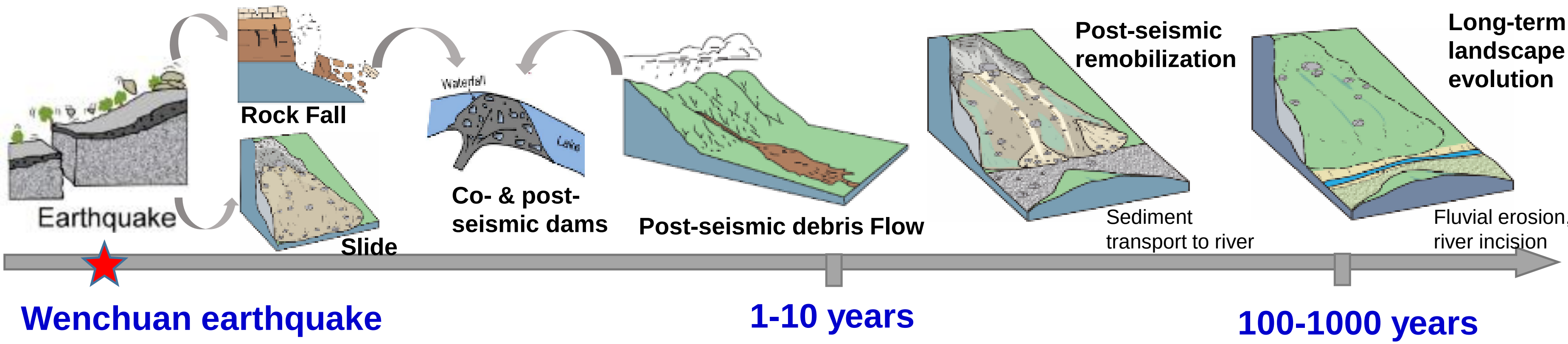
Mobile Servicec

Real-time process tracking warning method

Recently, we also developed a new generation of 3D-WebGIS platform for Landslide Early warning, which was also develop to an APP. It allows the general publics and professionals to check the monitoring data through smart phone.

Summary of the main research aspects on geo-hazards and their evolution at different temporal scales

Co-seismic Phase	Post-seismic short-medium term	Long-term



Triggering and development of co-seismic geo-hazards

- Mapping, spatial distribution patterns
- Initiation and failure mechanism analyses
- Evaluation of runout characteristics
- Formation and failure of co-seismic landslide dams

Post-seismic debris flows

- Case studies and inventory
- Initiation and runout: mechanisms and modelling
- Observations and modelling of changing rainfall threshold
- Risk management and mitigation (including structural and non-structural measures)

Post-seismic landslides and their hazard assessment

- Spatial and temporal evolution
- Controls on the post-earthquake geo-hazards evolution
- Hazard assessment
- Risk assessment and reconstruction strategies

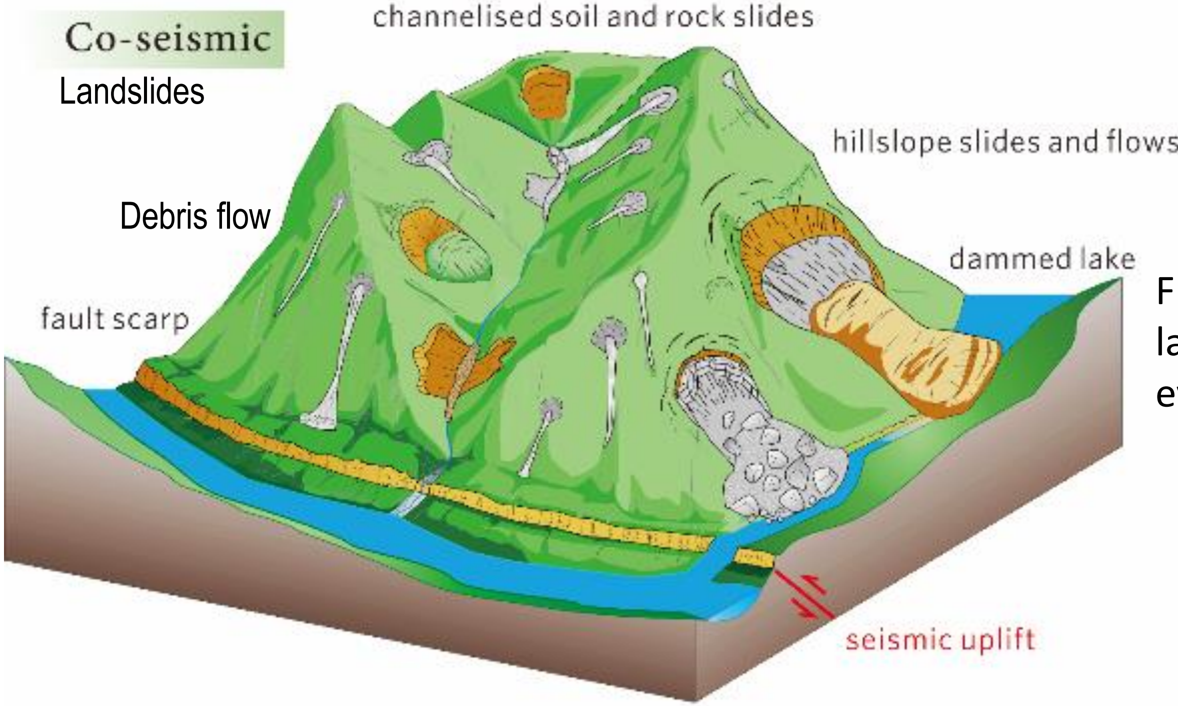
Long-term impact of strong earthquakes

- Weathering related post-seismic landsliding
- Sediment cascade and yield after a strong earthquake
- Long-term landscape evolution: the mass balance problem

3. Post-seismic landslides and long-term impact

- **Spatial and temporal evolution of post-seismic landslides**
- **Long-term landscape evolution**
- Hazard assessment and risk assessment
- Weathering related post-seismic landslides

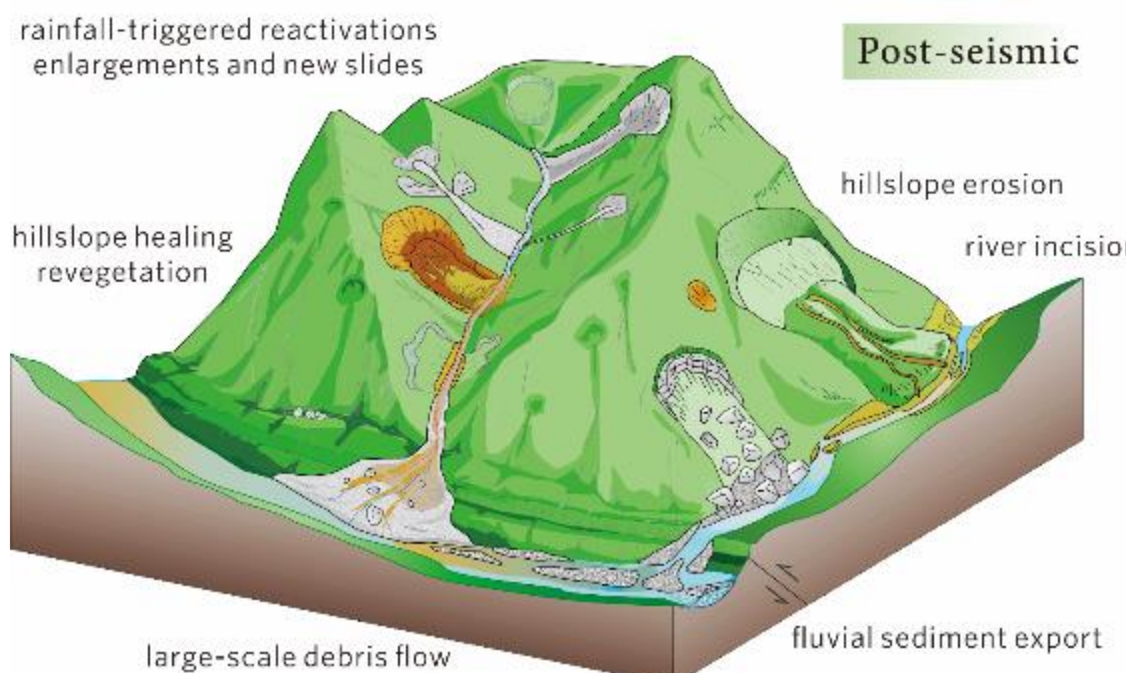
Chains of geo-hazards and landscape evolution after a strong earthquake



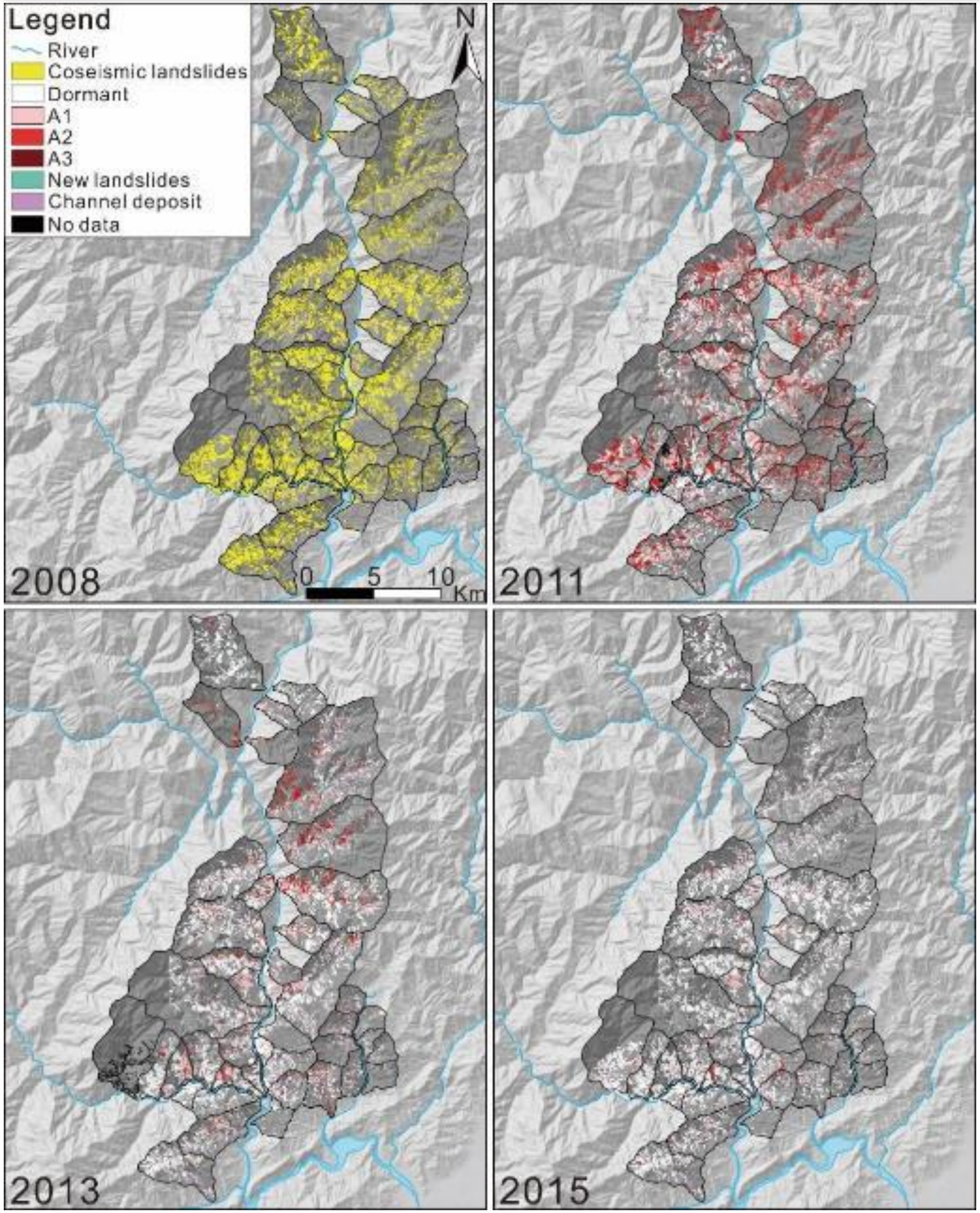
From earthquake-triggered landslides and river-damming events…

…to rainfall-triggered remobilizations, new slides, dam breaks; hillslope erosion and sediment export; and progressive hillslope healing and revegetation.

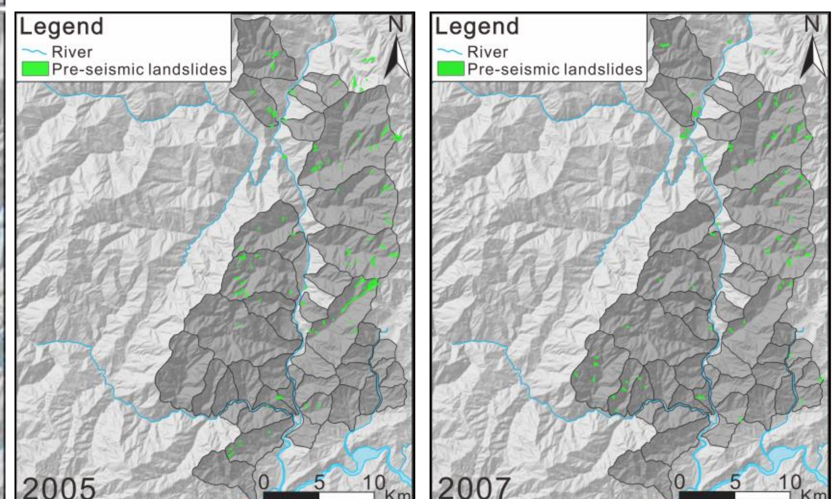
- ***where in the catchment and along the slope do they develop mostly?***
- ***How long do the various erosional phases last?***
- ***How long will it take before the erosional activity returns to the pre-earthquake situation?***
- ***Will there be long-term modifications of the landscape due to the earthquake?***



Spatio-temporal evolution of post-seismic landslides



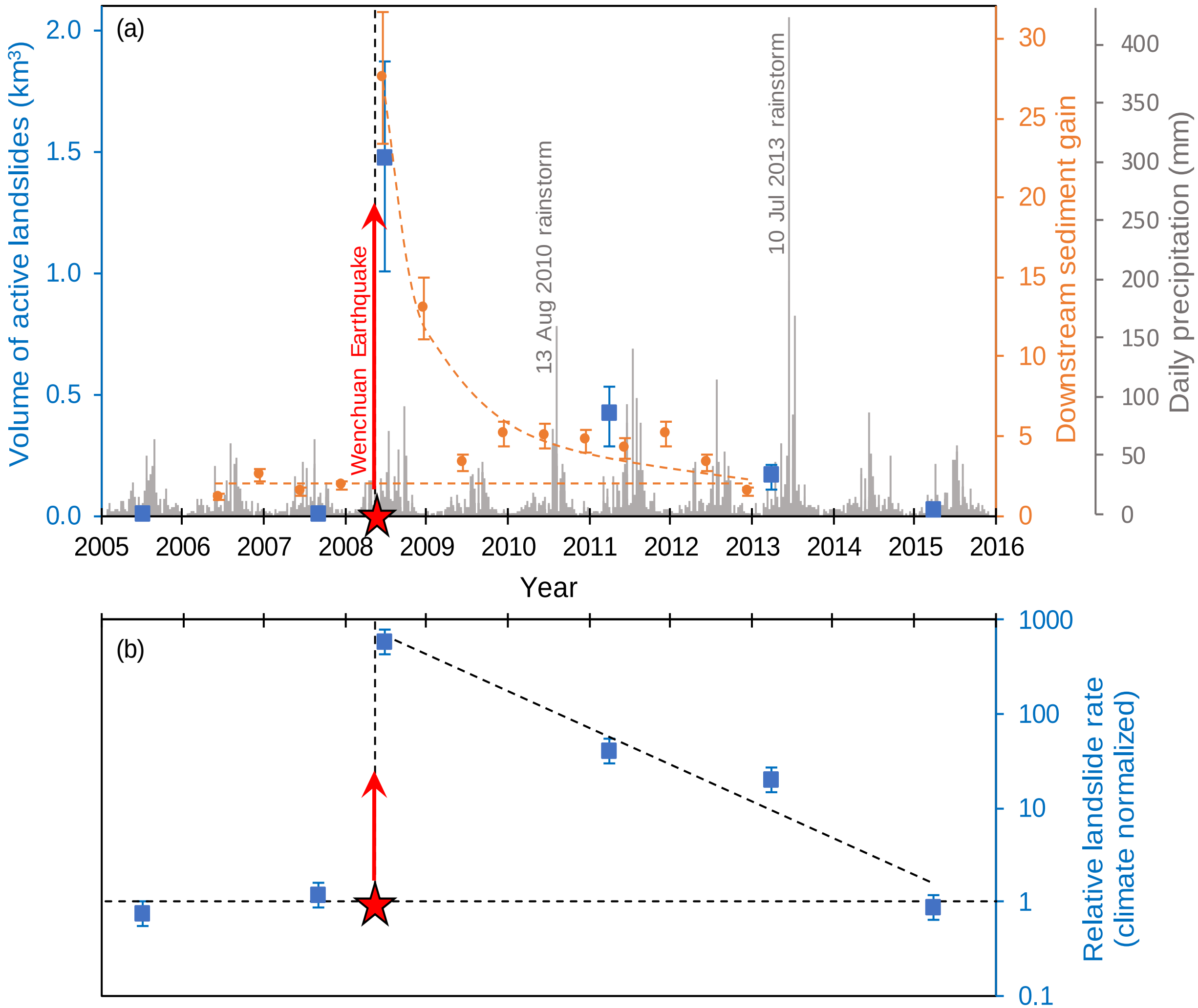
First of all, we compiled a **multi-temporal inventory** of co-s landslides, post-s remobilizations and new failure in a large area comprising **42 catchments** covering almost **500 km²** in the epicentral area of the WCEQ area. This is the most representative area as it features the highest concentration of the geohazards induced by the earthquake and is the largest area ever studied systematically in this region.



Fan, Domènech , Scaringi, Huang, Xu, Hales, Dai, Yang, Francis (*Landslides,* in review)

Spatio-temporal evolution of post-seismic landslides

Post-seismic decay and normalization of landslide rates

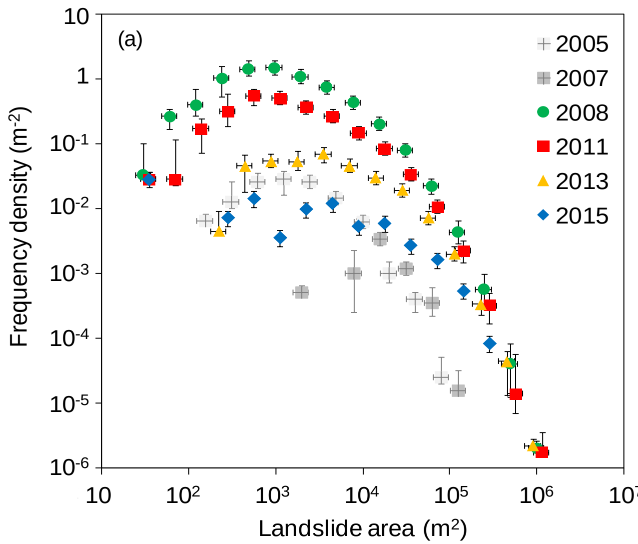


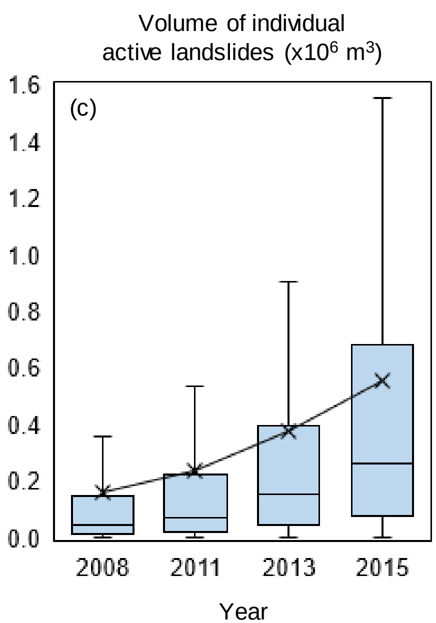
After the initial increase of co-seismic landslides , the volume of material invo-lved in active landsliding decays quickly, and so does the sediment export by rivers.

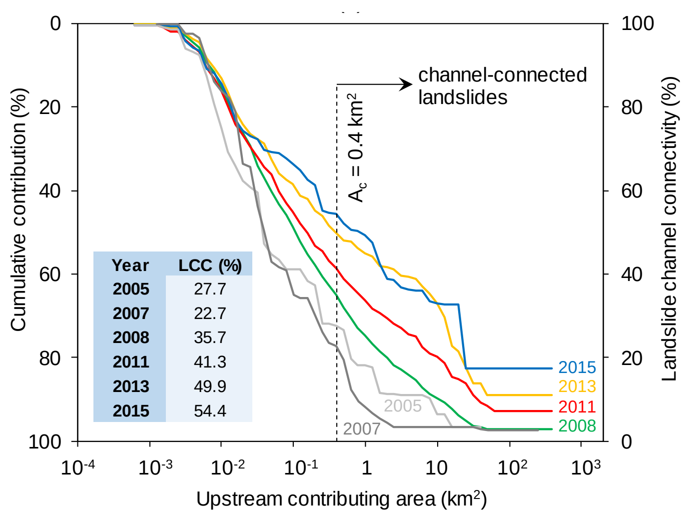
Even though initially we thought that the increased landslide activity would last for decades, our data demonstrate that the landslide rates returned to pre-earthquake levels in less than a decade.

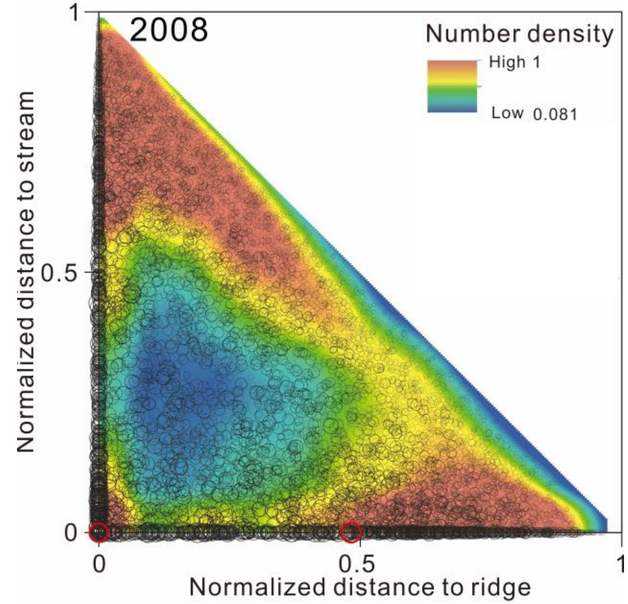
Post-seismic decay and normalization of landslide rates

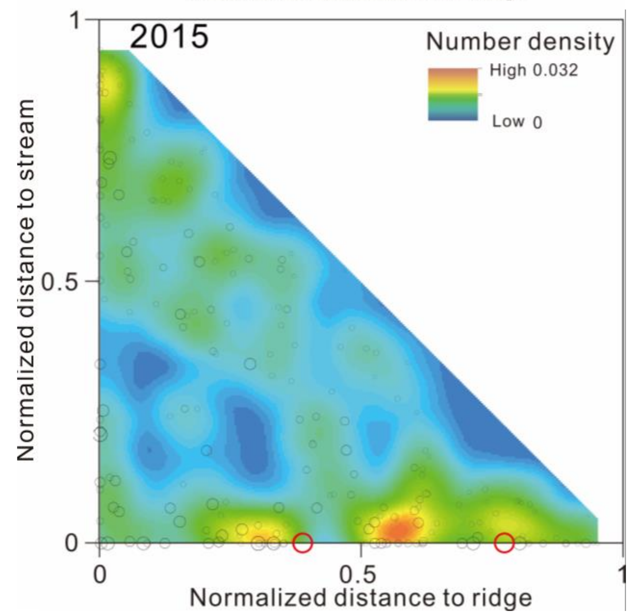
Prolonged activity of **large** co-seismic deposits & **increasing channel-connectivity**





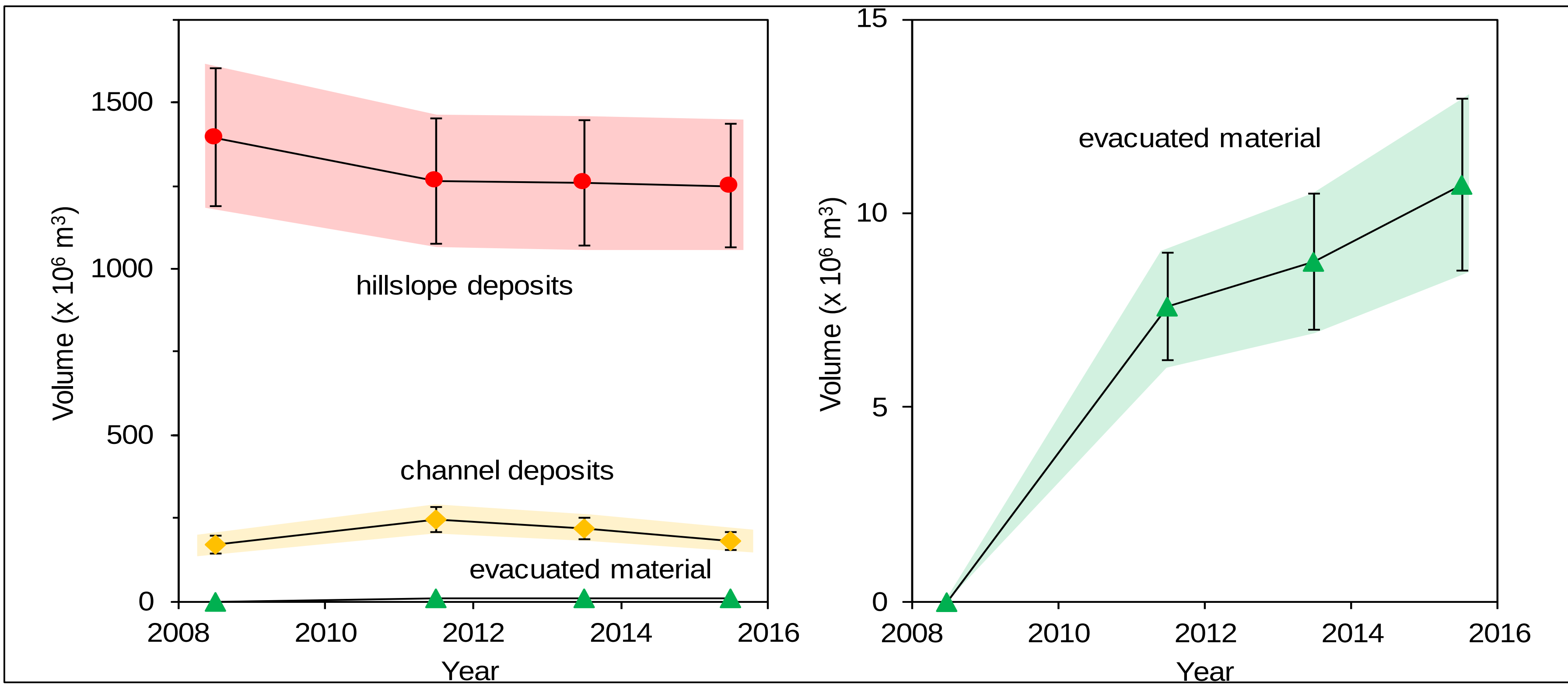






Sediment export after the Wenchuan Earthquake

The very important implication of the quick decay of landslide activity that we observed and quantified is that **as much as 80-90%** of the co-seismic debris **stabilized along the hillslopes** and in small gullies within the mountains , never reached the rivers. Landscape erosion by landslides in the WC area doesn't seem to contribute to the export of sediments substantially.



3. Post-seismic landslides and long-term impact

- Spatial and temporal evolution of post-seismic landslides
- Long-term landscape evolution
- **Hazard assessment and risk assessment**
- Weathering related post-seismic landslides

地质灾害防治与地质环境保护国家重点实验室（成都理工大学）
State Key Laboratory of Geohazard Preventionand Geoenvironment Protection
(Chengdu University of Technology)

RLesilience to EArthquake-induced Landslide Risk in CHina (REACH)

To understand the relationship between landslide hazards and social vulnerability through the hazard chain to improve resilience

The Earthquake Hazard Chain

Fractured social networks focused on survival

Hazard concentrating from a wide spatial area to river valleys at decreasing frequency

Debris flows

Increasingly resilient communities with stronger social networks

Risk = Hazard × Vulnerability × Exposure

Social vulnerability **Building construction**

Hazard chain
Resilience
Reach

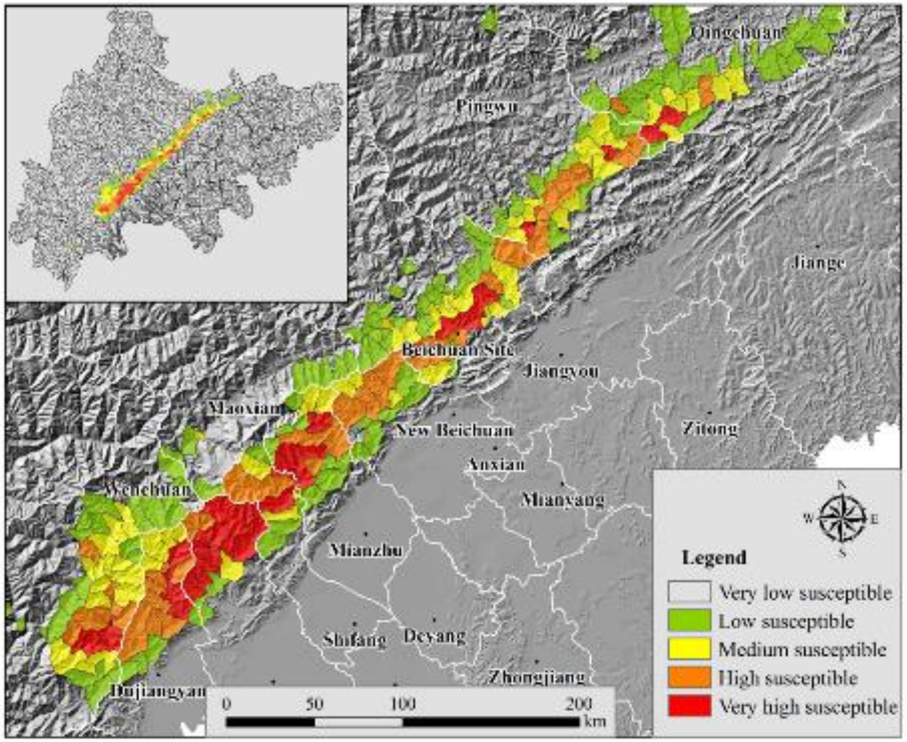
- What controls the temporal evolution of post-earthquake hazards? Risk reduction measures?
- How does social vulnerability, social cohesion, and built environment resilience change with evolving hazard?
- Integrating the hazard and vulnerability into measures of risk and resilience.
- Engaging with local communities and governmental organisations to improve resilience

Hazard and risk assessment at different scales

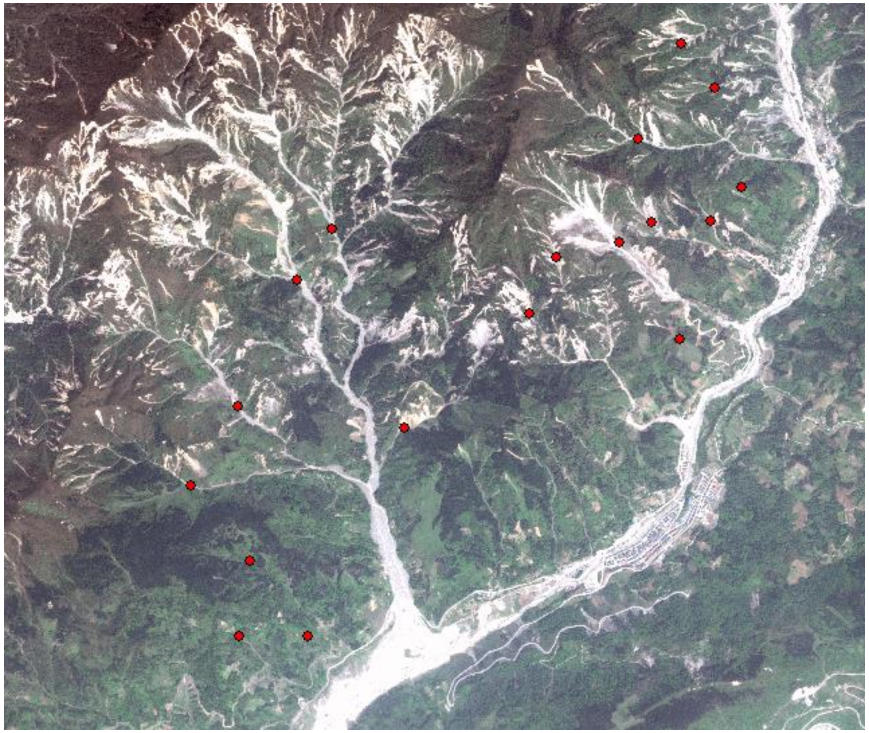
Where? —— **Hazard assessment**

How? —— **Numerical and physical models**

When? —— **Early warning system**

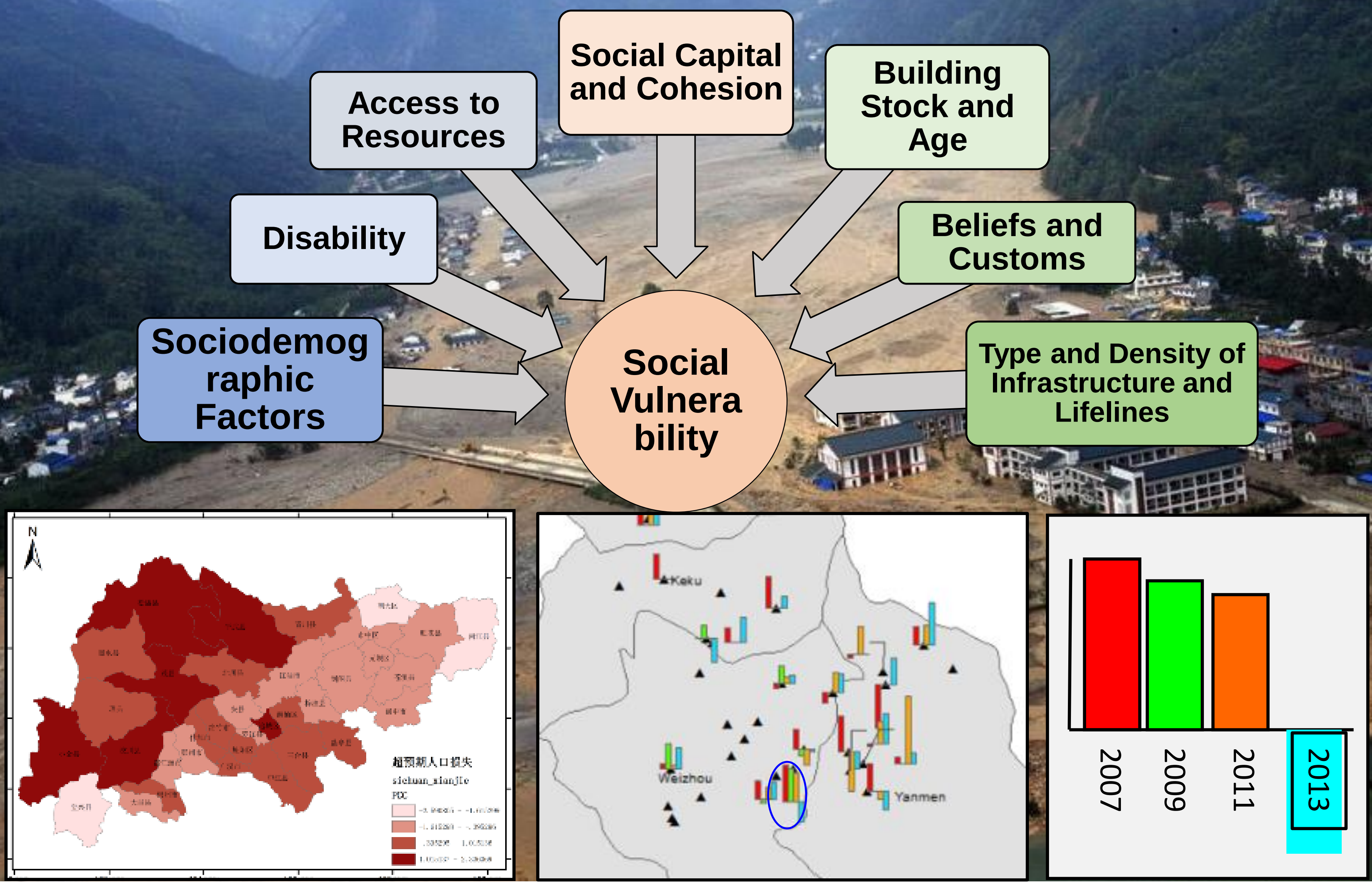


Susceptibility to debris flows at **regional scale**



Susceptibility to debris flows at **local scale**

Characterising the temporal evolution of social vulnerability



The input from the community

Engagement with governmental organisations and communities

Policy suggestions

Reduce the population density through rational planning

Promote an ecologically-sustainable economic development

Enhance the protection of regional economic systems

Enforce comprehensive strategies of disaster prevention, emergency relief, disaster and post-disaster management

Increasing the resilience of communities also by:

- increasing the risk awareness and promoting a rational risk perception (know what)
- providing practical instructions on behaviours and tasks to follow in case of natural disasters (know what to do)
- Improving social cohesion and strengthening community bonds (know what to do together, during and after the emergency).

3. Post-seismic landslides and long-term impact

- Spatial and temporal evolution of post-seismic landslides
- Long-term landscape evolution
- Hazard assessment and risk assessment
- **Weathering related post-seismic landslides**

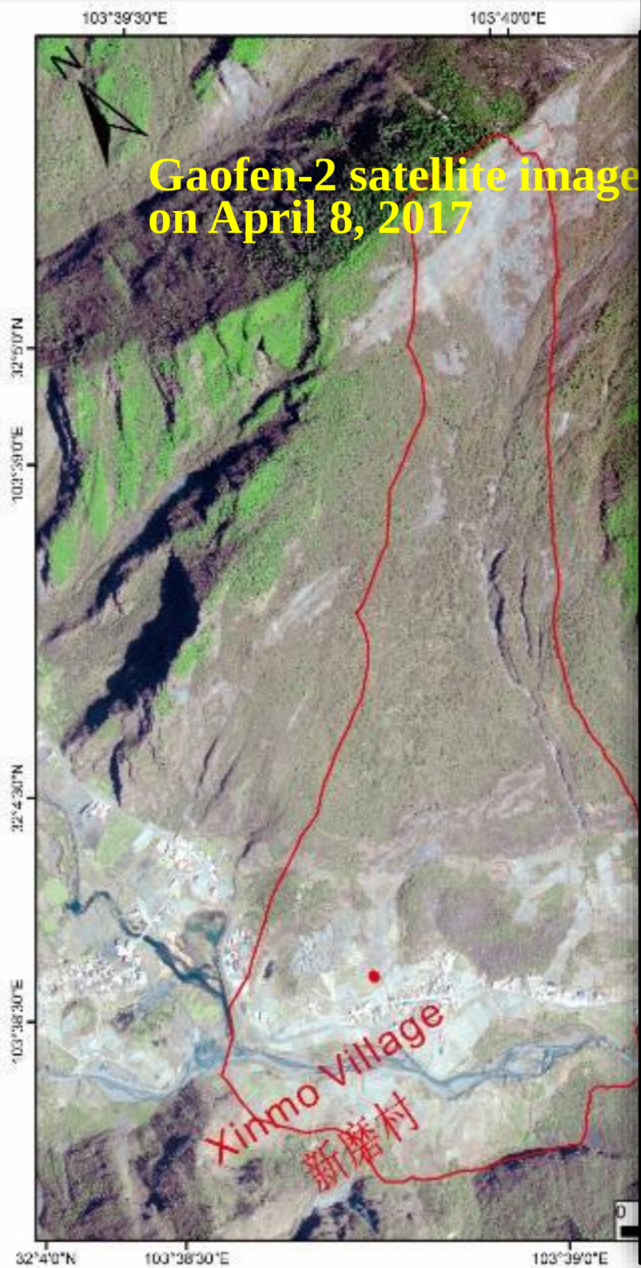
A case of the lasting effect of earthquake: Xinmo landslide on June 24, 2017

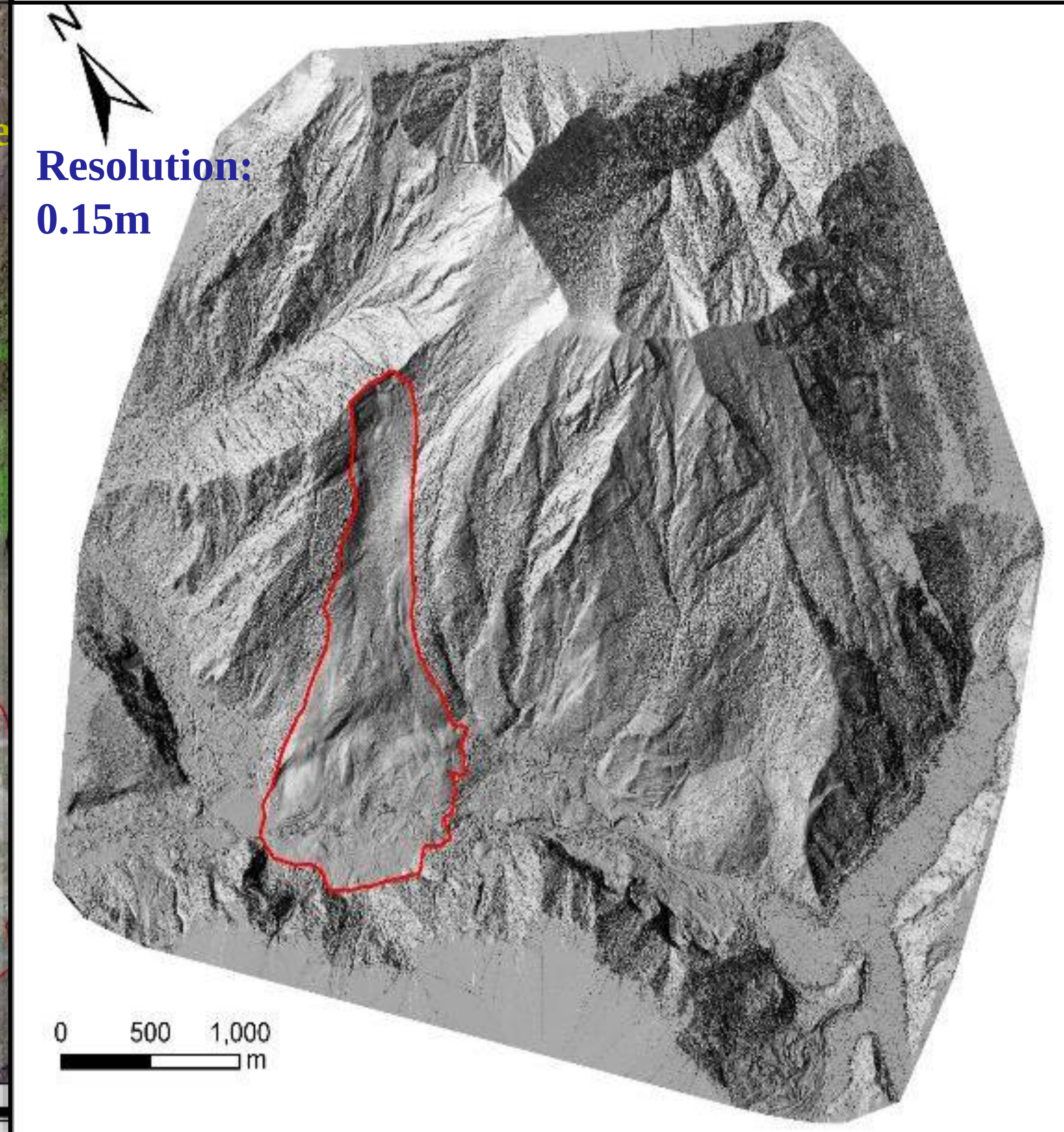
At 5:38 am on June 24, 2017, a high landslide instantaneously destroyed the whole village of Xinmo in Maoxian County, Sichuan Province, China, buring 64 farmer houses and 1500m long road, blocking the river 1000m, causing 10 deaths and 73 missing.

UAV image (2017.6.25)

Pre- and Post-failu

Digital Surface Model acquired by UAV

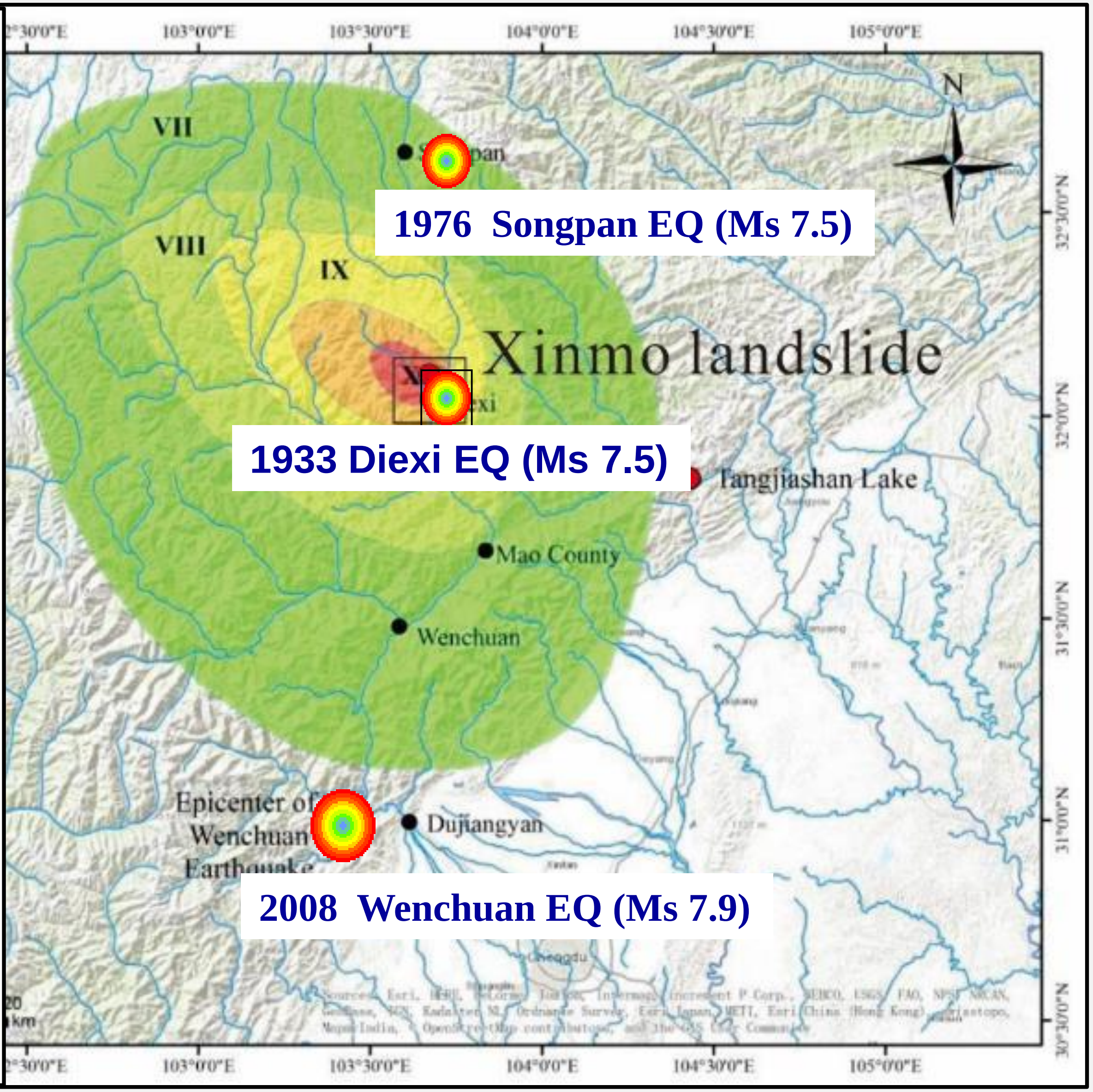




What makes it special and why it occurred in Songping?

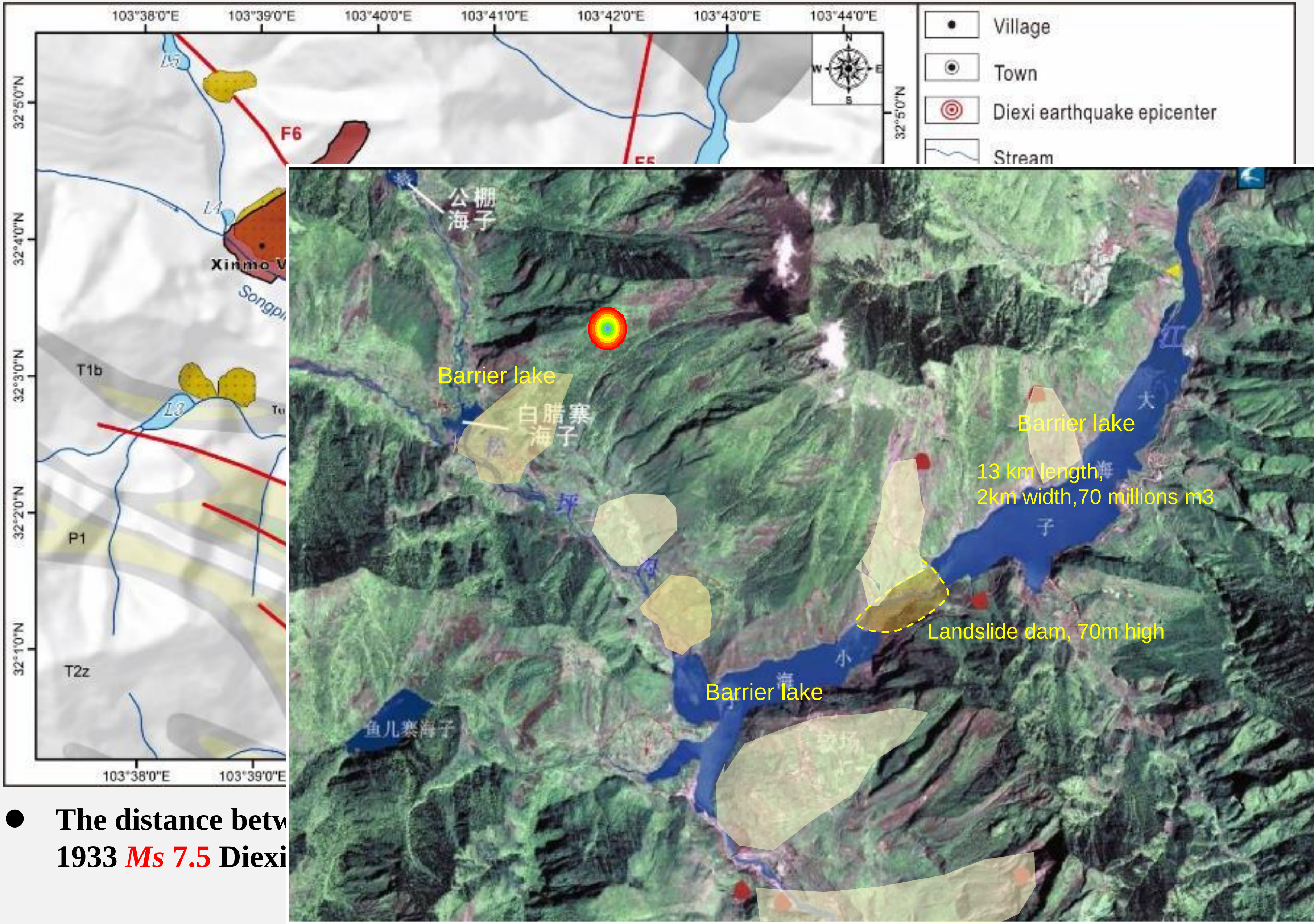
Songping Gully is located on the middle part of famous South North Seismic Belt, struck by strong earthquakes in the history.

- **1933 Diexi earthquake (Ms 7.5), local intensity reached X**
- **1976 Songpan earthquake (Ms 7.2), local intensity is VI**
- **2008 Wenchuan earthquake(Mw 7.9), local intensity is VII**



Chai et al. (1995) & Ling (2015)

Geological settings



- The distance betw
  1933 *Ms* 7.5 Diexi

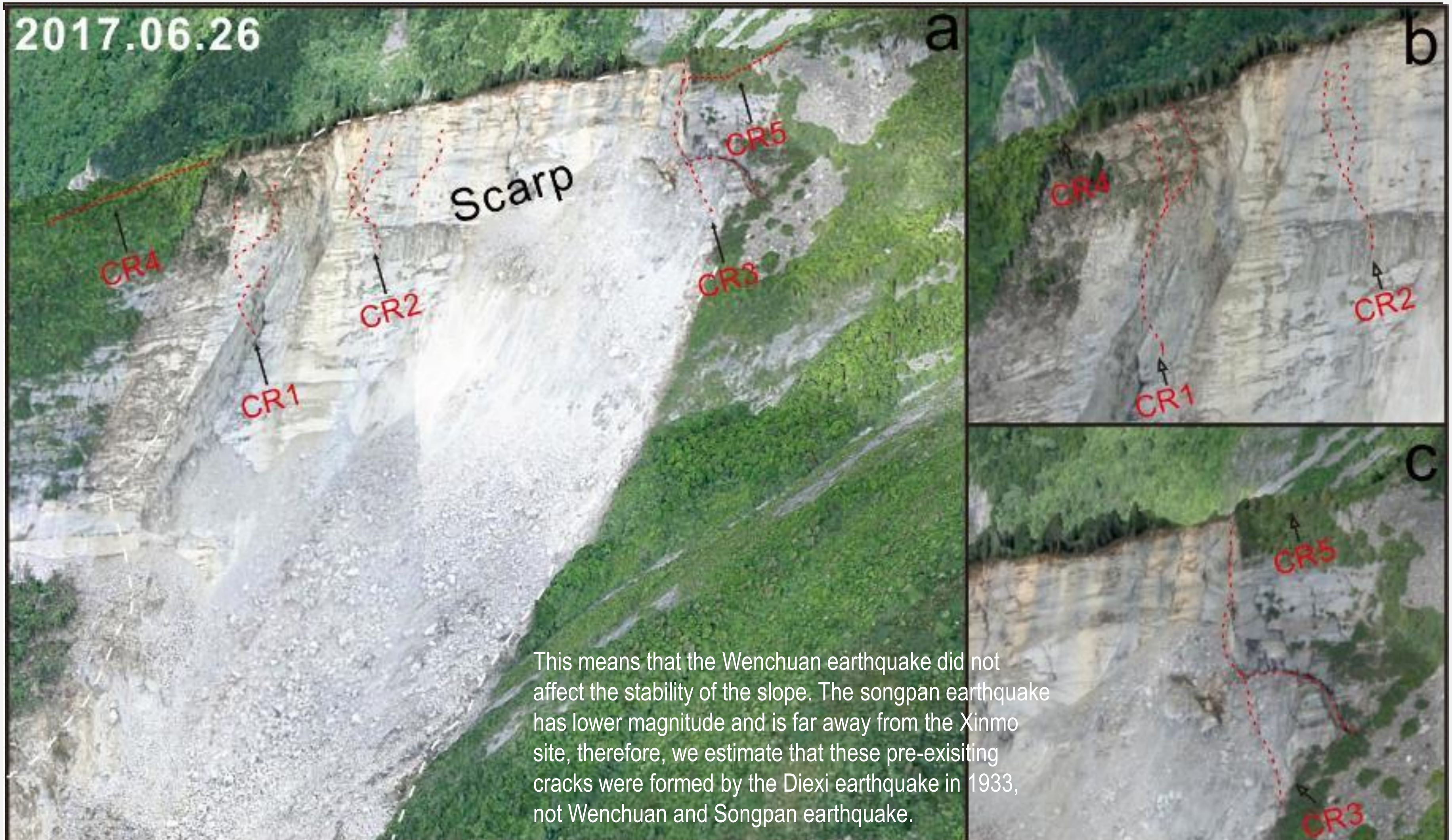

Rock slide
Deixi town,
550 death

- **Landslide dams in Diexi, Dahaizi and Xiaohaizi breached 45 days after the earthquake, which induced a giant flood that swept downstream 250km and killed about 2500 people.**

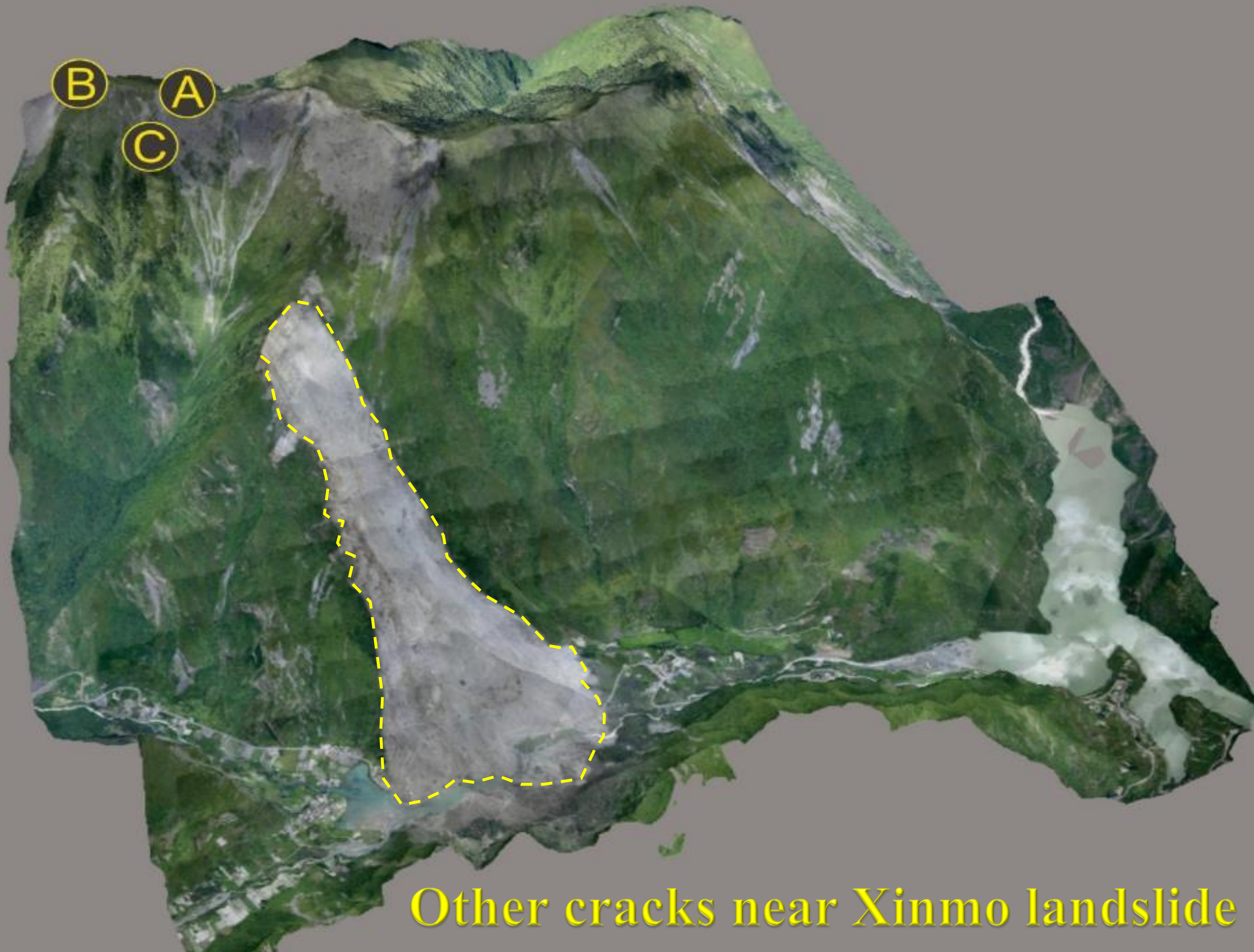
1933 Diexi earthquake

Photo by zhuang (1934.10)

Deformation history



This means that the Wenchuan earthquake did not affect the stability of the slope. The songpan earthquake has lower magnitude and is far away from the Xinmo site, therefore, we estimate that these pre-exisiting cracks were formed by the Diexi earthquake in 1933, not Wenchuan and Songpan earthquake.



Other cracks near Xinmo landslide

Challenges and Recommendation for future research

- **Undertaking a hazard and risk assessment of the chain of geo-hazards (multiple cascading hazards) caused by large magnitude earthquakes.** ***The challenge is particularly great given the difficulties in quantifying the interaction between hazards.***

- **Quantification of post-earthquake landslide evolution in time, space and in magnitude.** ***The challenge is to analyze the controlling factors for the post-seismic landslide evolution of different earthquakes in different regions.***

- **Developing integrated physically-based debris flow simulation models.** ***The present generation of debris flow numerical simulations is poorly suited for post-earthquake settings.***

Challenges and Recommendation for future research

- **Improving the understanding of the effect of large magnitude earthquakes on long-term landscape evolution.**

More research should be undertaken to assess

(i) the hazard and risk of landslides in mountainous areas affected by large magnitude earthquakes and

(ii) the impact of earthquakes on the sediment export and erosion of the mountainous landscape.

Final remarks

A decade on, we have learned a lot from the Wenchuan earthquake, albeit at a terribly high cost in human lives.

We hope that our improved knowledge can lead to better preparedness for the next big event.

THANK YOU FOR YOUR ATTENTION !

Acknowledgement:

Prof. Xuanmei Fan, Prof. Qiang Xu; Prof. Xiangjun Pei,, Prof.Chuan Tang, Prof. Yunsheng Wang, Prof. Bin Yu, Prof. Wei Hu, Prof. Huan Huang, Dr. Gianvito Scaringi; Dr. Guillem Domenech, Dr. Yonghong Luo, Dr.Jian Huang,

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