The fate of sediment after a large earthquake

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The 2008 Wenchuan Earthquake

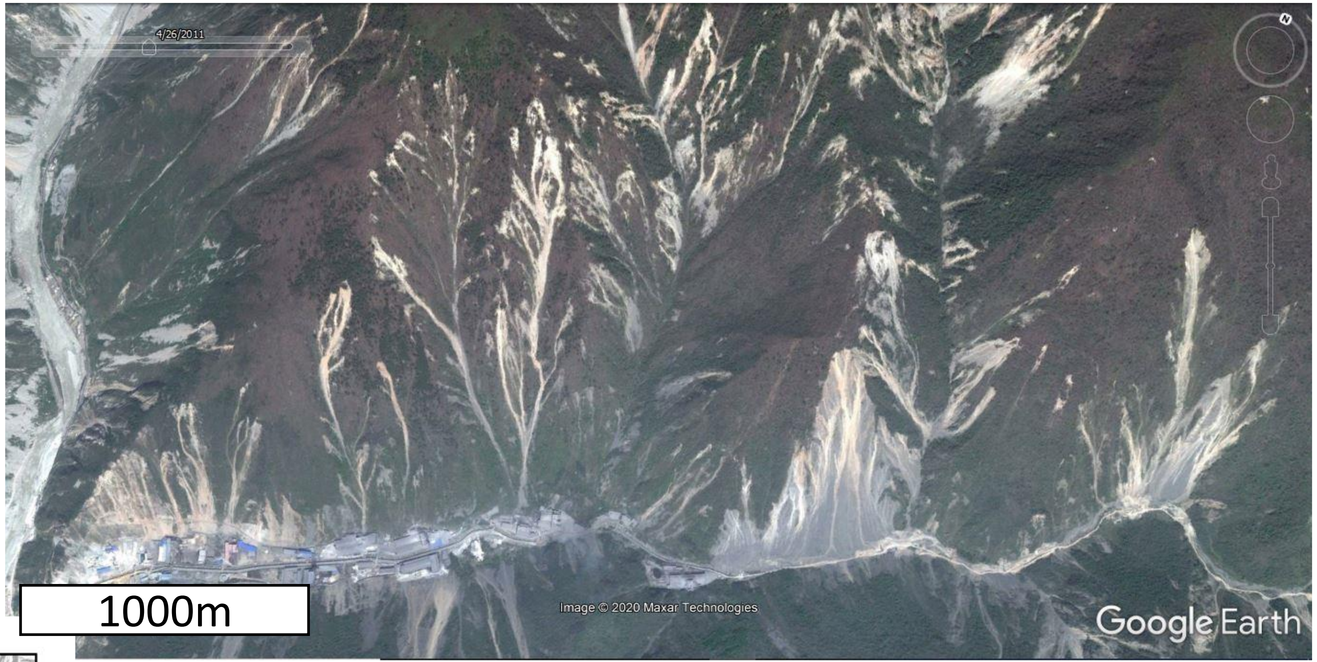
- The M_w7.8 Wenchuan earthquake in the Chinese Province of Sichuan caused over **60,000 landslides** on the steep slopes of the Longmen Shan. These landslides have a combined **volume of close to 3km^3**
- The earthquake is followed by an increase in sediment flux in rivers and landsliding and debris flow activity. However it is unclear how much sediment is removed from the mountain range.

Sediment budgets and cascades

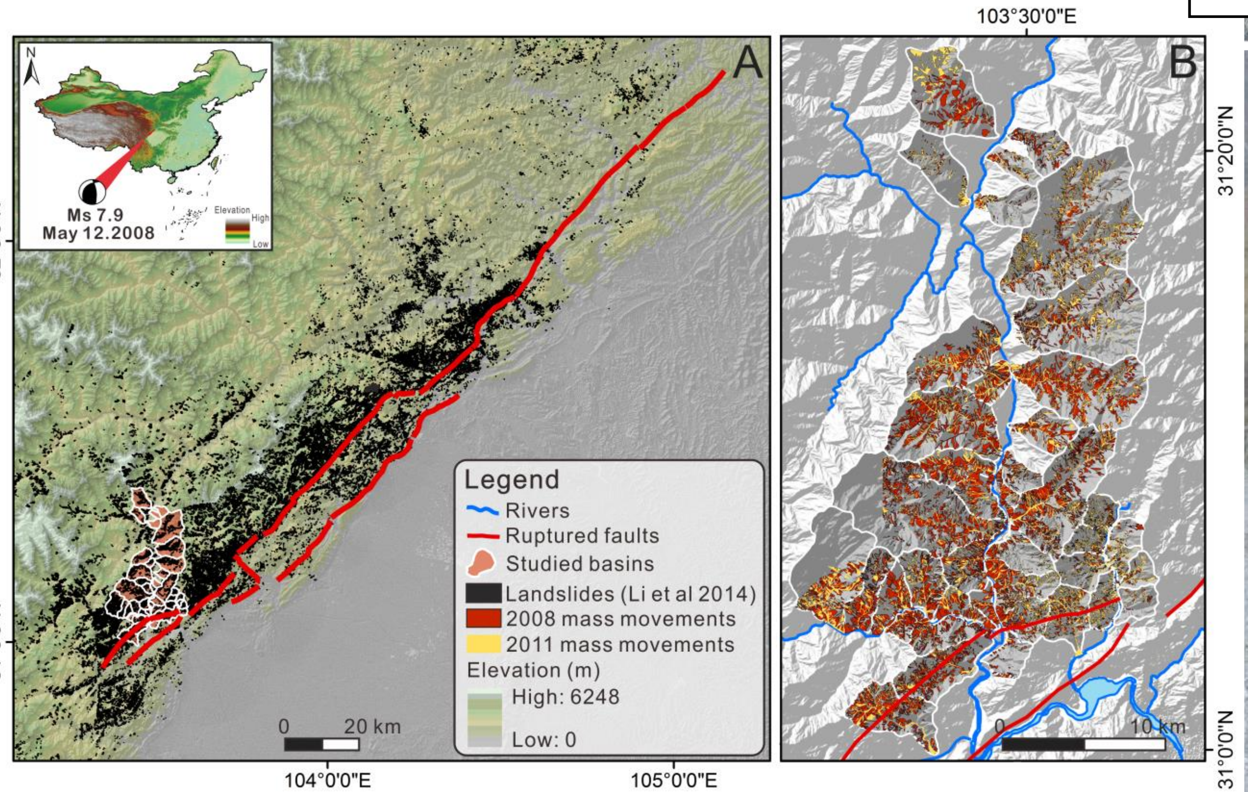
- Sediment leaves mountain ranges in a cascading fashion via a series of temporary stores.
- Using a multitemporal landslide inventory and literature derived sediment transport rates **we have identified the stores and transport processes** exporting the sediment produced by the Wenchuan earthquake
- Using this framework **we have estimated the volume of sediment which remains in catchments 10 years after the Wenchuan earthquake**

Constructing the sediment budget

We have mapped mass movements following the earthquake in **42 catchments between 2008 and 2018**. These catchments contain **1km^3** of sediment.

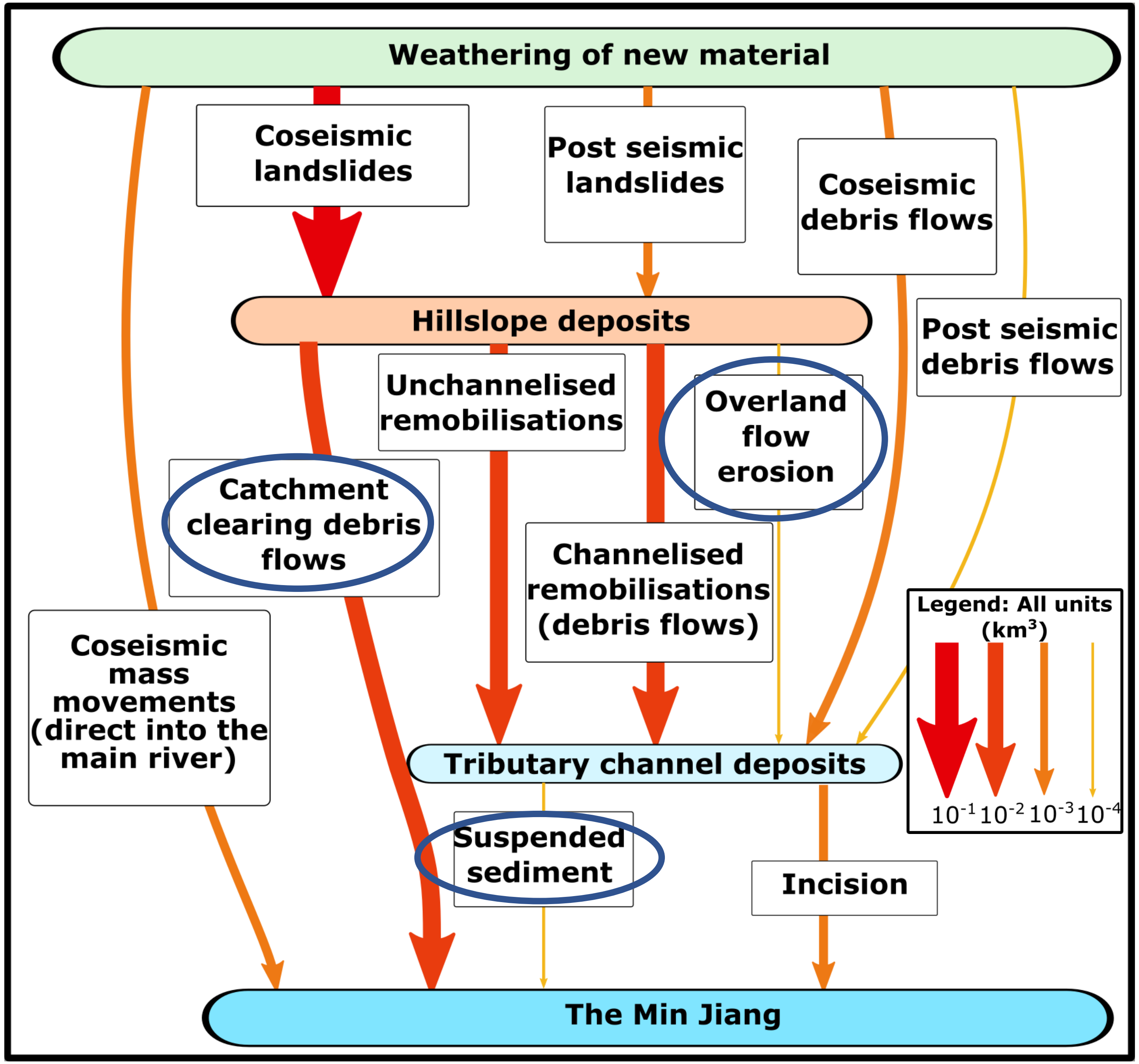


Using the inventory we were able to identify and quantify **2 temporary sediment stores** and **8 sediment transport** processes. We combined these with a further **3 processes** with estimates from the literature to complete the sediment budget



Sediment transport processes

- We identify **11 different fluxes of sediment,** shown in the flow chart to the right, which mobilise sediment between the 2 temporary stores, **3 coseismic, as named, and 8 post seismic** We use our multitemporal landslide inventory to record and estimate the volume eroded by each process. **However 3 (marked in blue) have to be estimated from the literature**.
- Remobilisation recorded in the landside inventory is separated by the presence of clear channelisation. Any movement without channels is assumed to be a shallow landslide (unchannelised remobilisation) while channelised remoblisation is likely to be a debris flow.



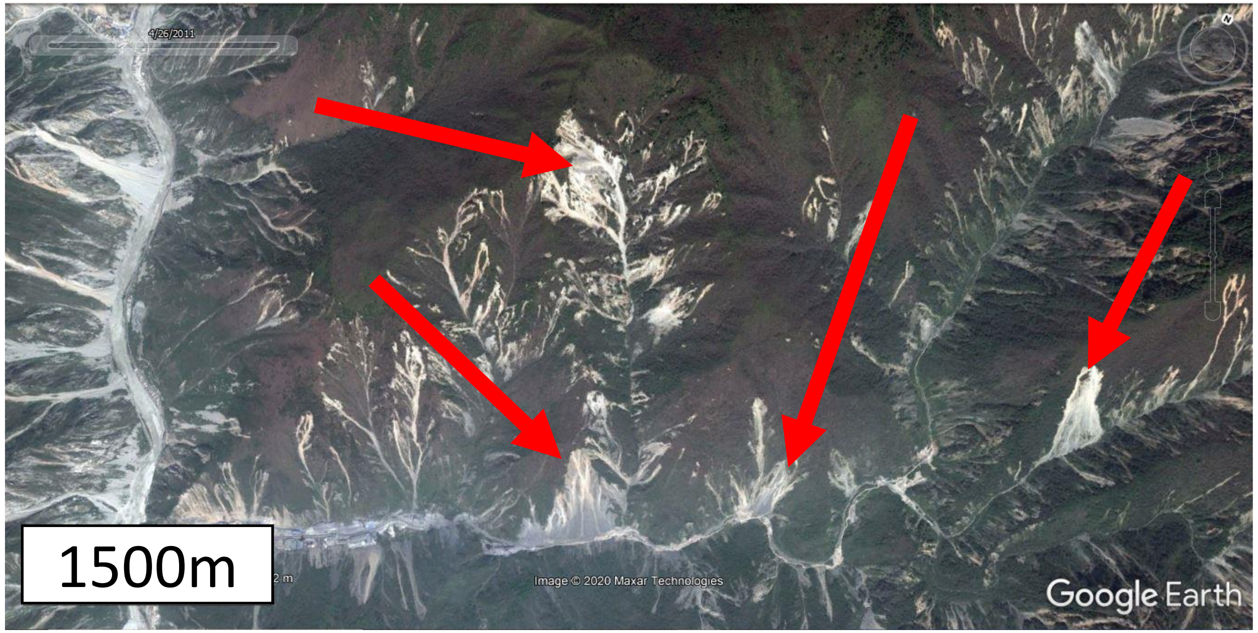
Sediment stores

Tributary channel deposits

These are deposits which are **entirely within the channel network**. Tributary channels in the Longmen Shan are steep but small with low stream orders (3-4) compared to the Min Jiang (7) which results in alluviation of the channel beds. The deposits are formed **of reworked hillslope and debris flow deposits**

Hillslope deposits

These are deposits which **require further remobilisation before fully entering the channel network**. These are typically landslide deposits which do not enter the channel network or are not being actively reworked by the Min Jiang



Sediment transport - Debris flows

- Hillslope deposits are remobilised by 2 types of debris flows; **catchment clearing debris flows and channelised remobilisations.**
- Channelised remobilisations are identified **as long fresh reactivations of landslide deposits**. They enter the channels if their deposit has a drainage area greater than the average drainage area of channel heads

- Catchment clearing debris flows are the very largest debris flows which deposit material directly into the Min Jiang. **They entrain sediment from both hillslope and tributary channel deposits**.

The 2010 Qingping debris flow deposited an estimated 5×10^{-2} km^3 into the Min Jiang, (Tang et al 2012)

Tributary channel deposits

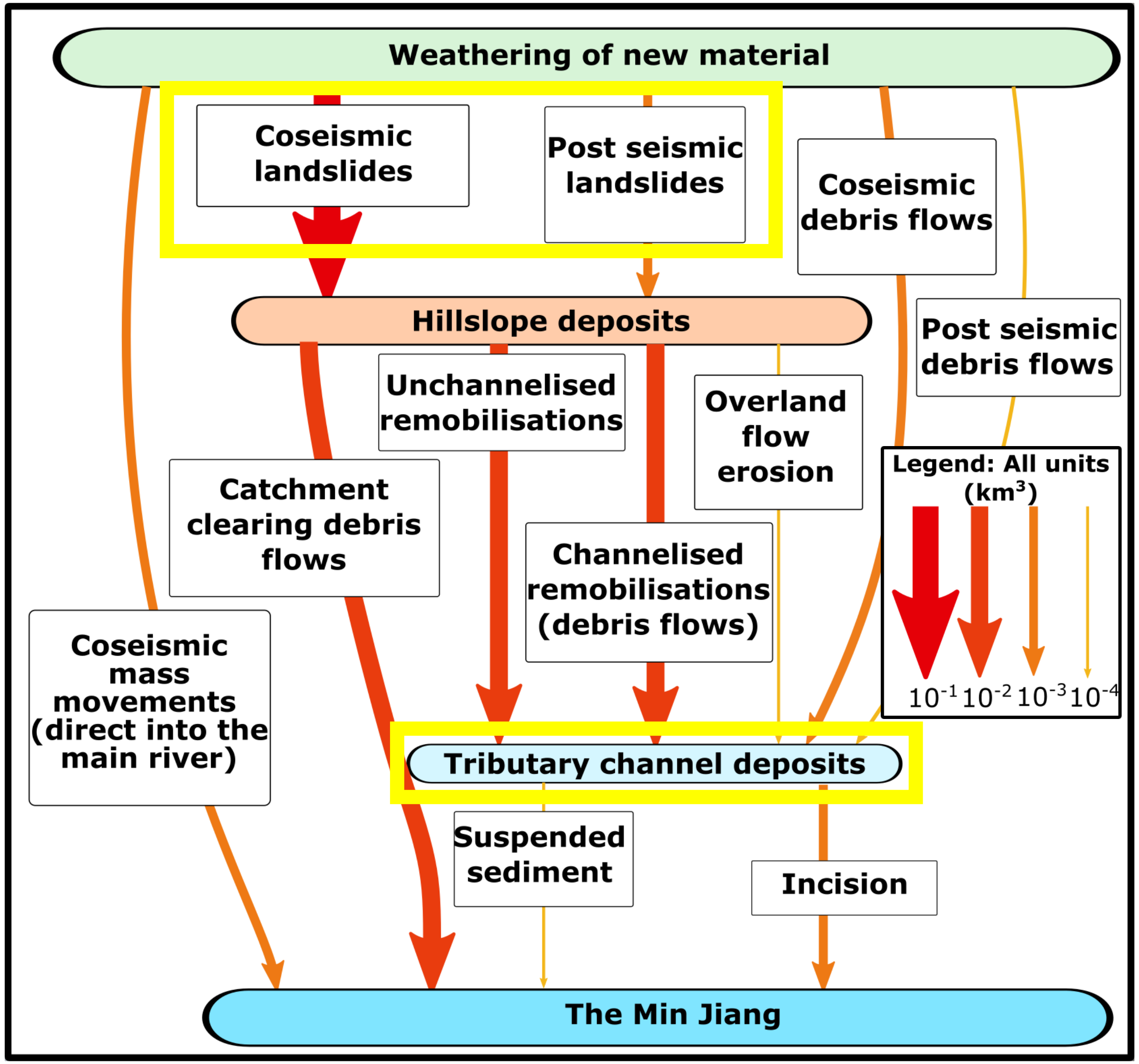
Tributary channel deposits are eroded by channel clearing debris flows, suspended sediment in streams and **incision by a combination of fluvial and debris flow processes**

We estimate the deposition and erosion of the deposits by tracking the width of the active channel. Yellow lines indicate **widening (deposition) of channel deposits since 2011**

Vegetation growth over the channel deposits **and narrowing of active channel indicates incision** into and erosion of the channel deposits

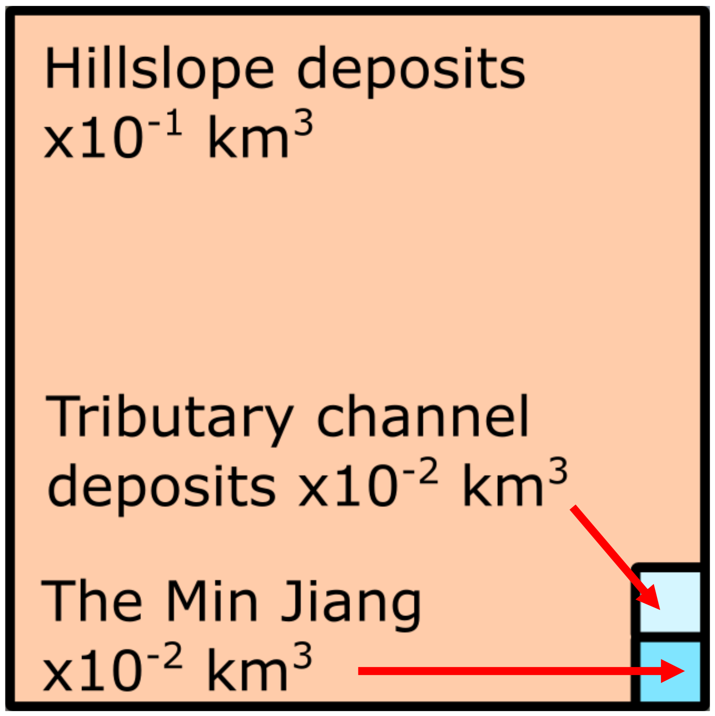
Quantifying the sediment cascade

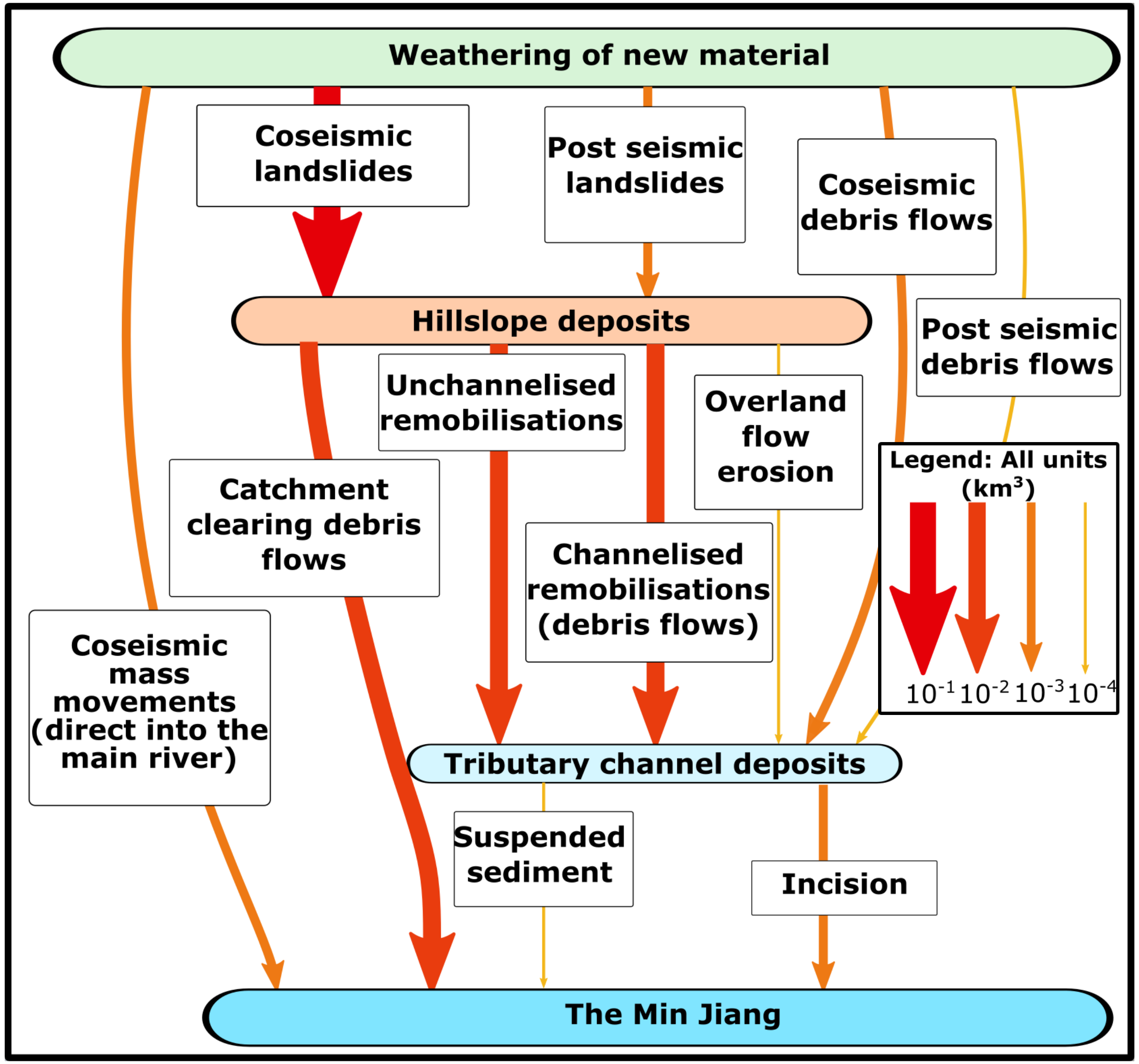
- We quantify the initial volume of the sediment produced by the earthquake by using **empirical area – volume scaling relationships on our mapped landslide areas**.
- We also use our observations of channel widths widening and narrowing and our literature derived values to estimate the volume of sediment in the tributary channel and the Min Jiang
- Simply removing the estimated input into the channel network from the initial sediment volume gives the volume remaining in hillslope deposits.
- We use the estimate of hillslope deposit volume to constrain the previously unknown area – volume relationships of the remobilisation processes



The sediment budget of an earthquake

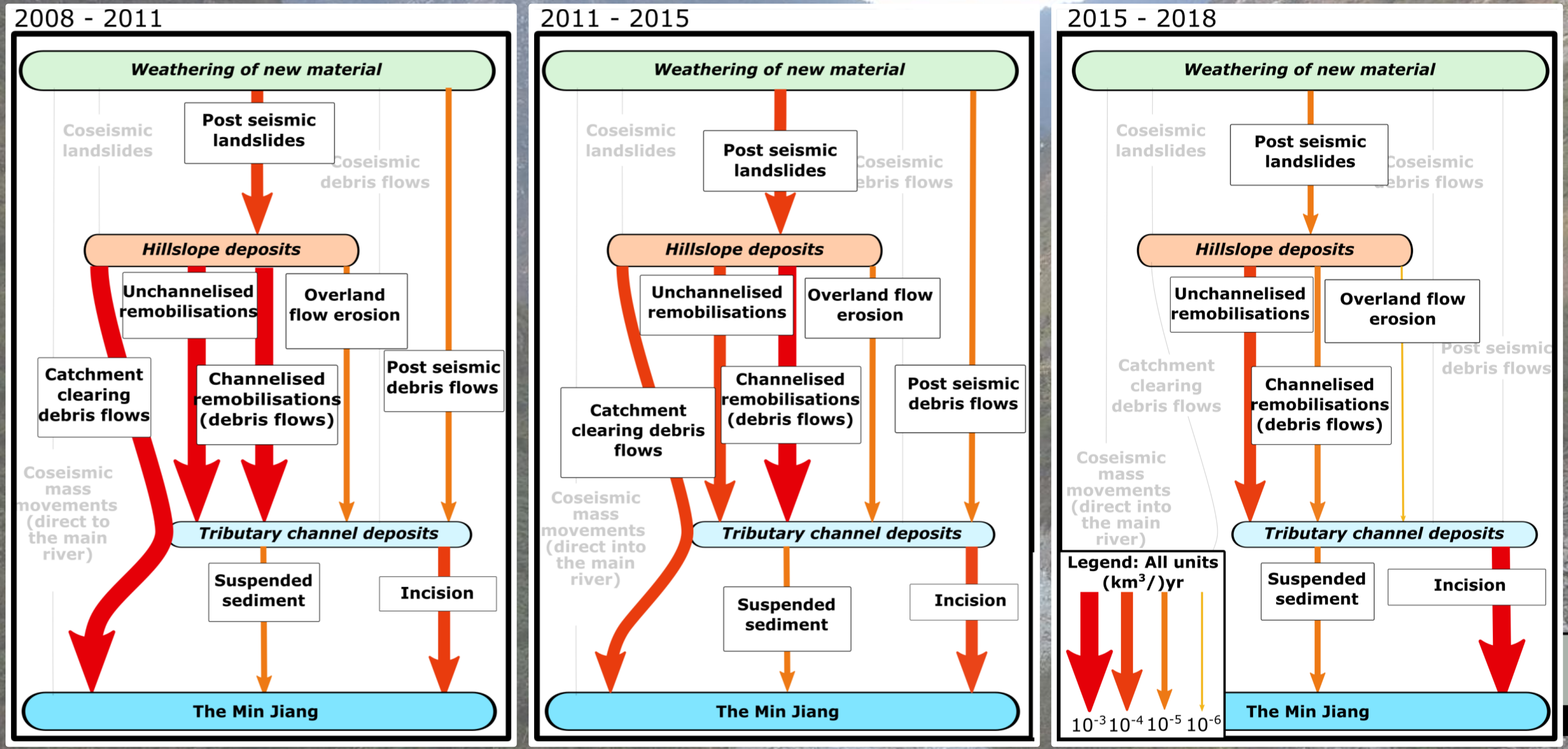
- After 10 years, **more than 80%** of the sediment produced by the earthquake remains on the hillslope.
- **Over 50%** of the sediment mobilised after the earthquake occurs **by debris flows**





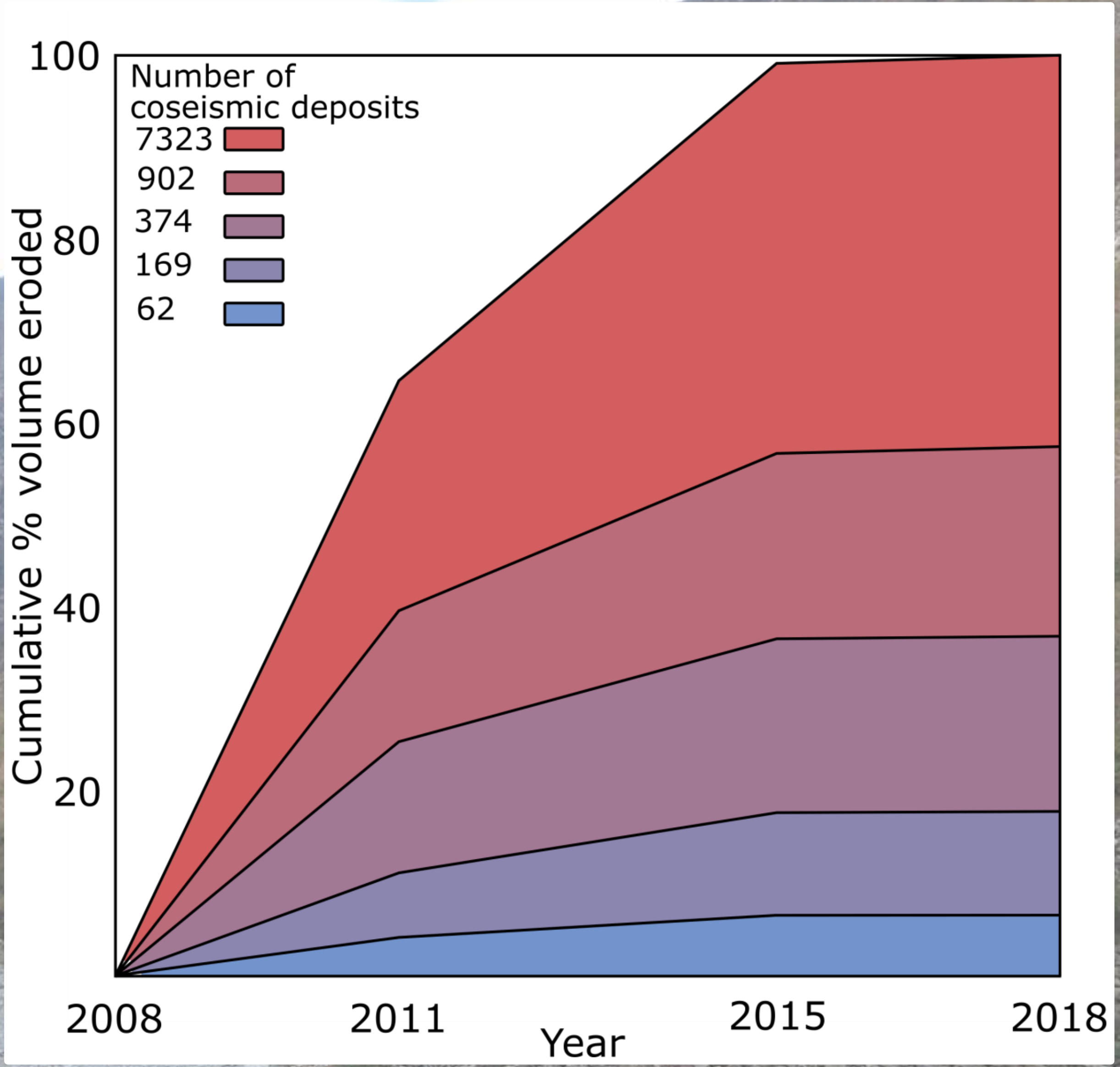
The sediment cascade through time

- Separating the sediment budget into timesteps reveals that ~67% of the sediment remobilisation occurs in the first 3 years and **95% in the first 7**
- Incision becomes the dominant process as the flux from the hillslope decreases



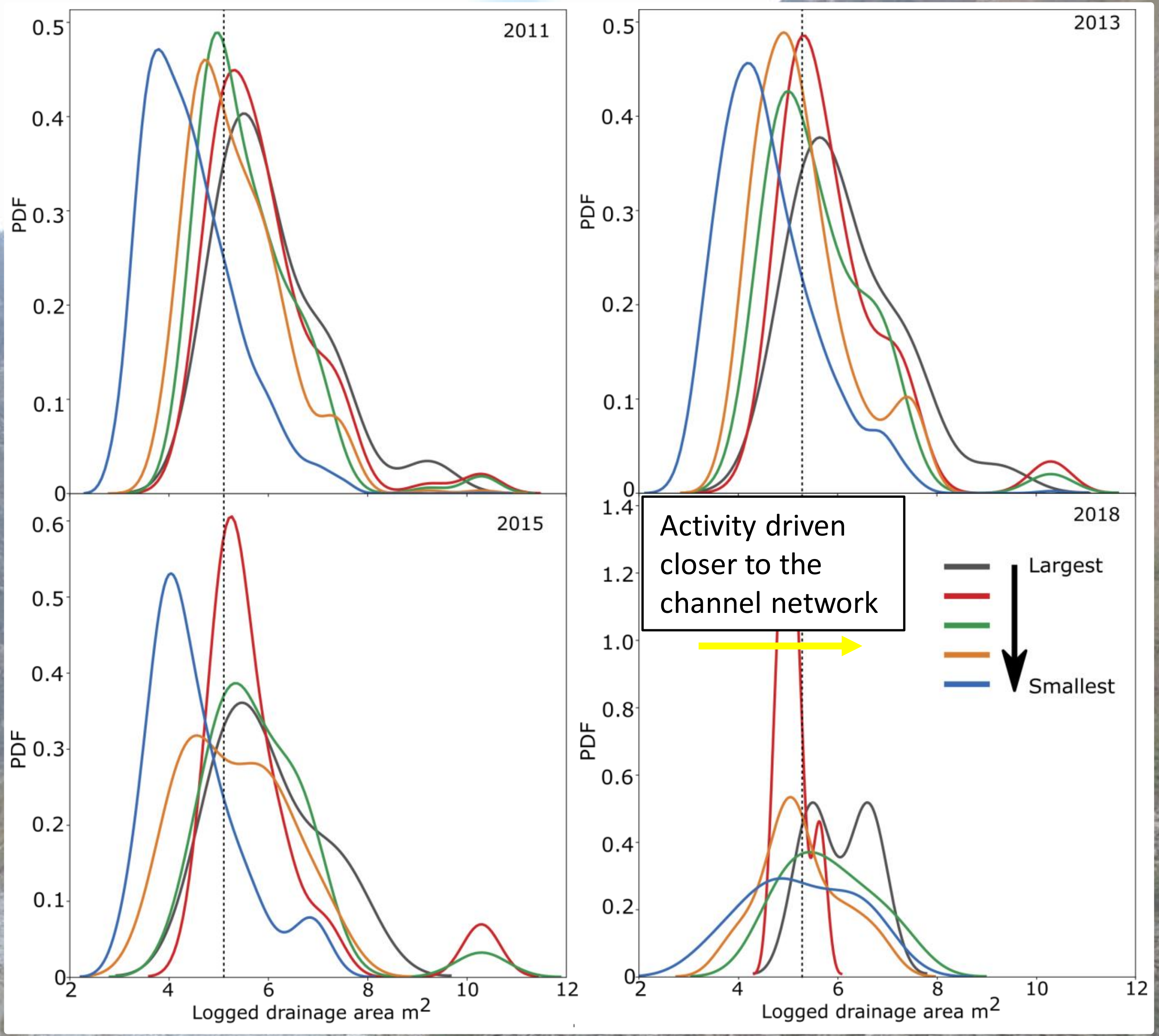
Debris flow sources

Ordering the landslide deposits and separating them into bins of equal volume reveals that **the smallest landslide deposits (red, highest) are eroded the fastest** by debris flows following the earthquake. The largest landslide deposits (blue, lowest), **despite being the most connected to the channel network, contribute the least**.



Debris flow sources

- In 2011 **the small active landslide deposits (blue) are significantly closer to the ridges than the largest deposits** (grey).
- Initially the **deposits closest to the ridge line are the most active**, however these **stabilise the quickest** driving debris flow triggering closer to the hillslope/channel threshold (dotted line).
- Through **time hydrologic drivers of slope stability become more important**



Conclusions

Any questions? Contact me (Oliver Francis) at;
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- We have quantified the sediment cascade for 10 years following the 2008 Wenchuan earthquake
- Over 80% of the sediment is left on the hillslope despite the orders of magnitude increase in sediment flux.
- Debris flows from the smallest landslide deposits close to ridges are the dominant process in depositing sediment into the channel network.
- These small deposits stabilise the quickest despite being on the steepest slopes rapidly decreasing the sediment flux from the hillslope
- We have recently submitted a paper entitled "The fate of sediment after a large earthquake" with further details and analysis of this work.
- I am currently finishing my PhD and looking for post doc opportunities

References and copyright

- Tang, C. *et al.* Catastrophic debris flows triggered by a 14 August 2010 rainfall at the epicenter of the Wenchuan earthquake. *Landslides* **8**, 485–497 (2011).