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Challenges for selecting earthquake ground motion estimates for rock slopes stability

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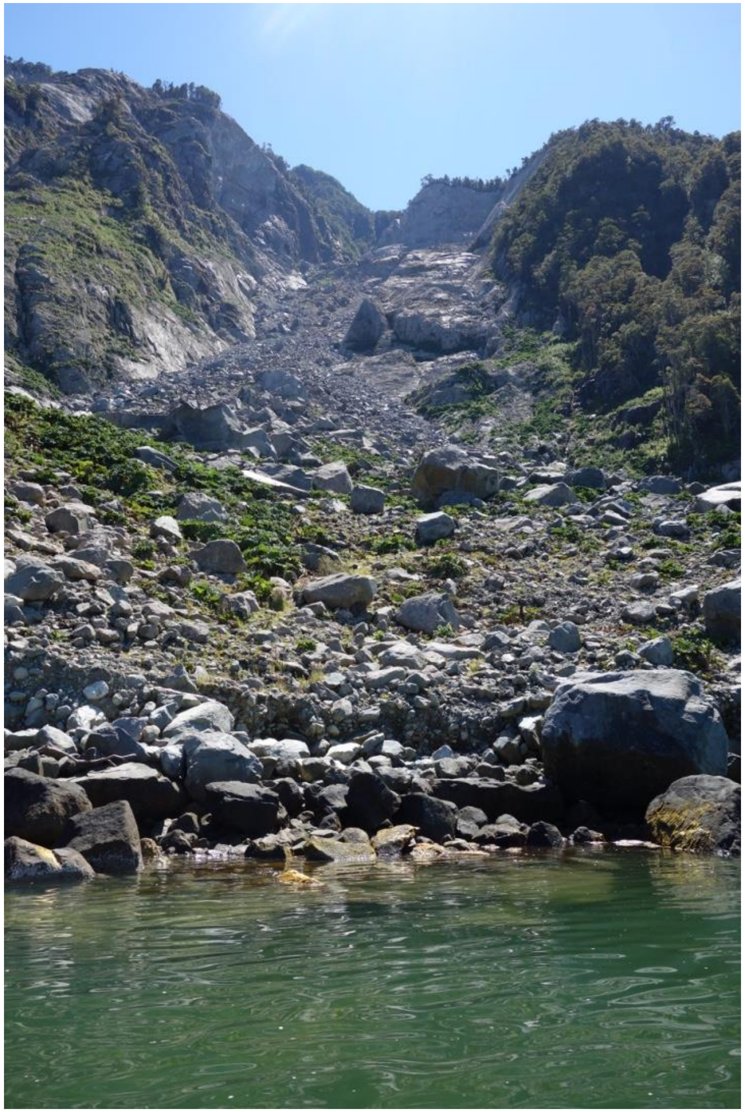
- Landslides caused by earthquakes
- Shaking of slopes and topographic response
- Approaches to assessing stability
- Summary – but not conclusions
- Questions



Newton Fund Award (NE/N000315/1) is acknowledged for project funding

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Landslides caused by earthquakes

Below top: Earthquake induced landslide in Baltistan, Pakistan, April 2016. Below bottom: earthquake induced landslide from the Kumamoto Earthquake Japan, April 2016.

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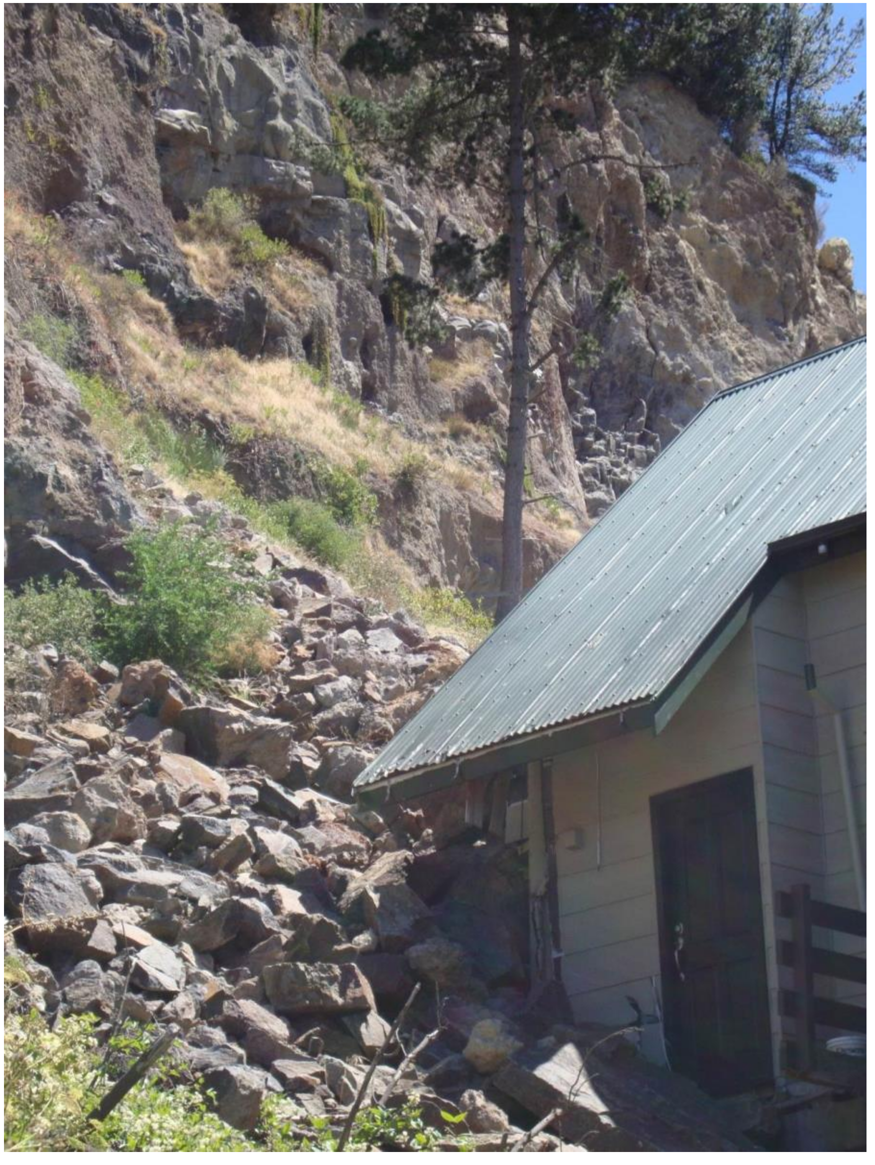
- Earthquake triggered landslides show nonlinear behaviour – in most cases a softening model
- The most common analytical method assumes bi-linear conditions.
- Landslides accumulate strain which may allow them to progress towards failure under ambient stress



Landslides are a common secondary effect of strong shaking. In order of frequency of occurrence:

1. Rock fall / rock topple (M>4.0)

2. Rock slides / debris slides (M>5.0)

3. Debris avalanches (M > 6)

4. Rock Avalanches (M > 6.5)

Multiple block rock fall in Taroko Gorge, Taiwan, triggered by the M_W=6.8 Hualien Earthquake in 2002. Note the landslide scar on the slope to the right (north) of the dust cloud (epicentral distance c. 30 km)

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The Chuifenershan Landslide, a dip slope failure sliding on a bedding plane triggered by the 1999 M_W=7.6 Chi Chi earthquake.

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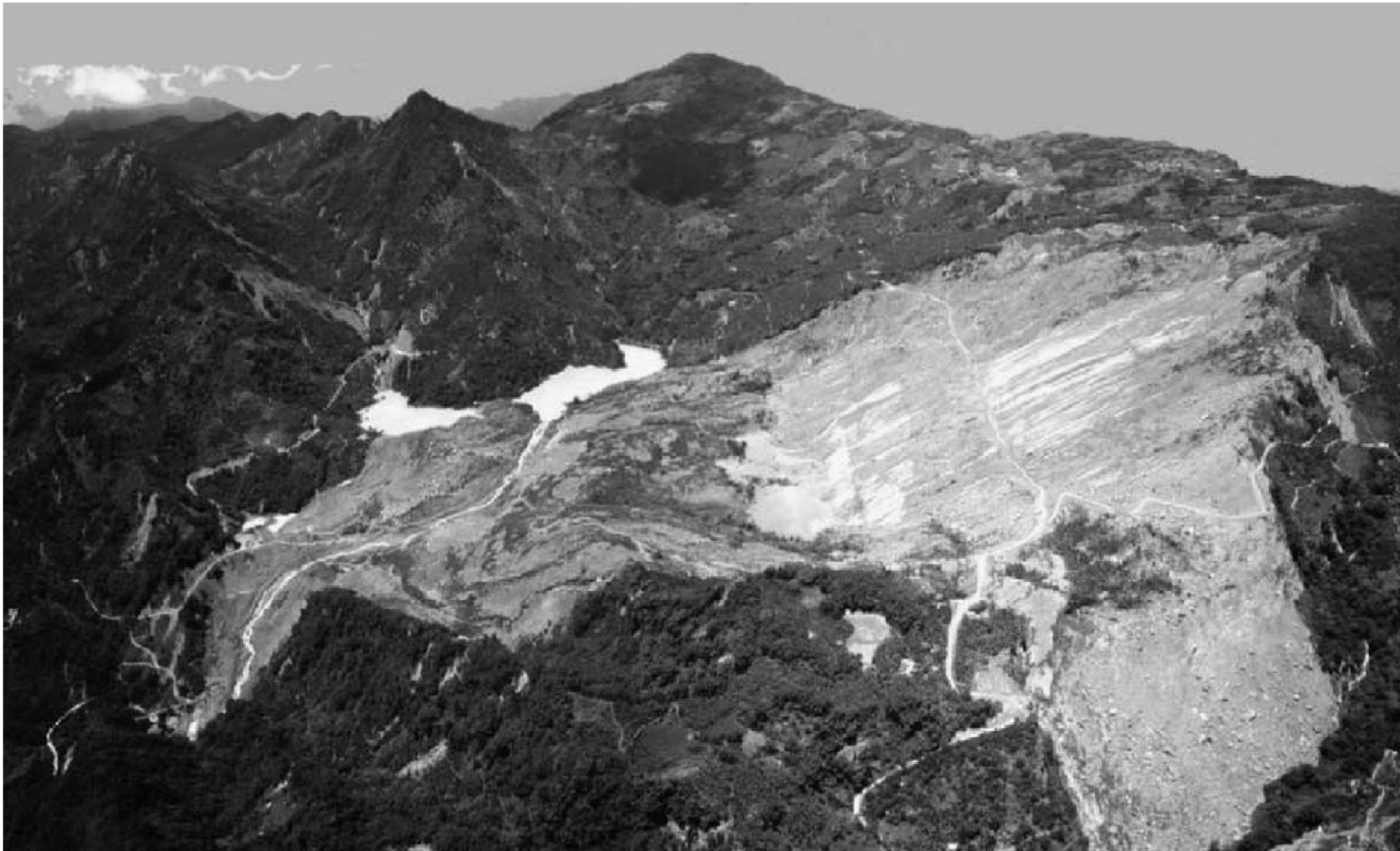

A simple model

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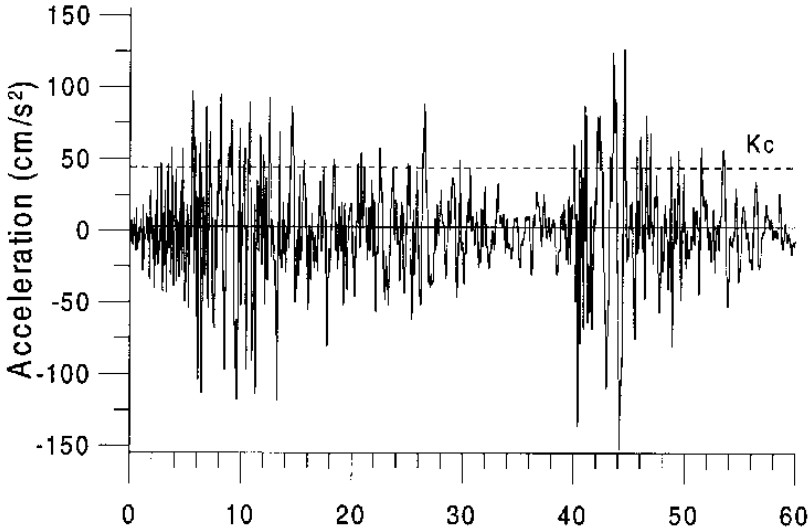

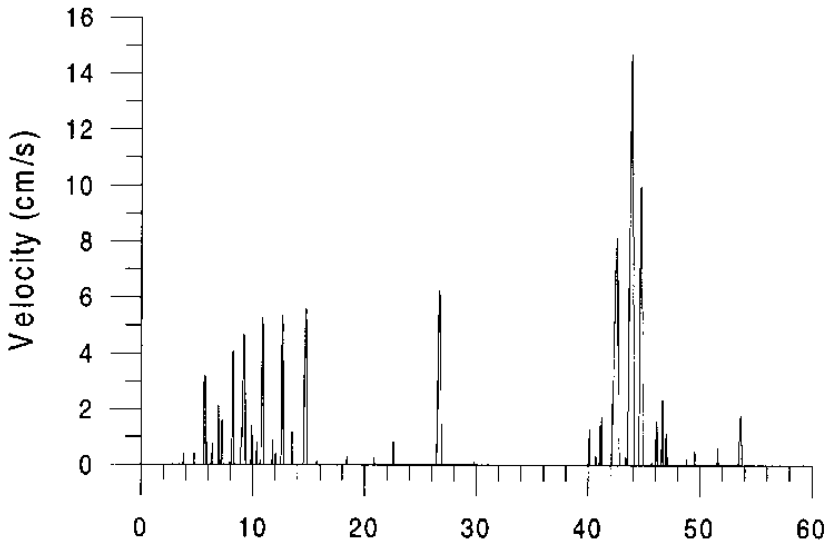

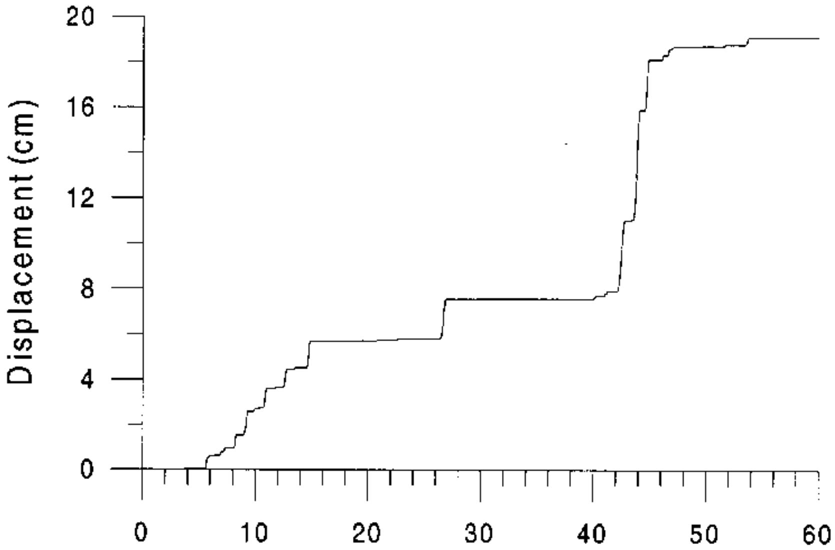

Real conditions vs design conditions

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- Design PGAs are based on freefield motions
- Slide geometry is governed by ambient effective stress state
- Slide material properties are static during the shaking.

- Accelerations on slopes are different from freefield motions.
- The geometry of earthquake induced landslides do not match "critical slip surfaces" from slope stability analysis.
- Stiffness degradation is well established

From: Massey et al (2018). Landslides Triggered by the 14 November 2016 M_w 7.8 Kaikōura Earthquake, New Zealand, Bulletin of the Seismological Society of America, Vol. 108, No. 3B, pp. 1630–1648, July 2018, doi: 10.1785/0120170305

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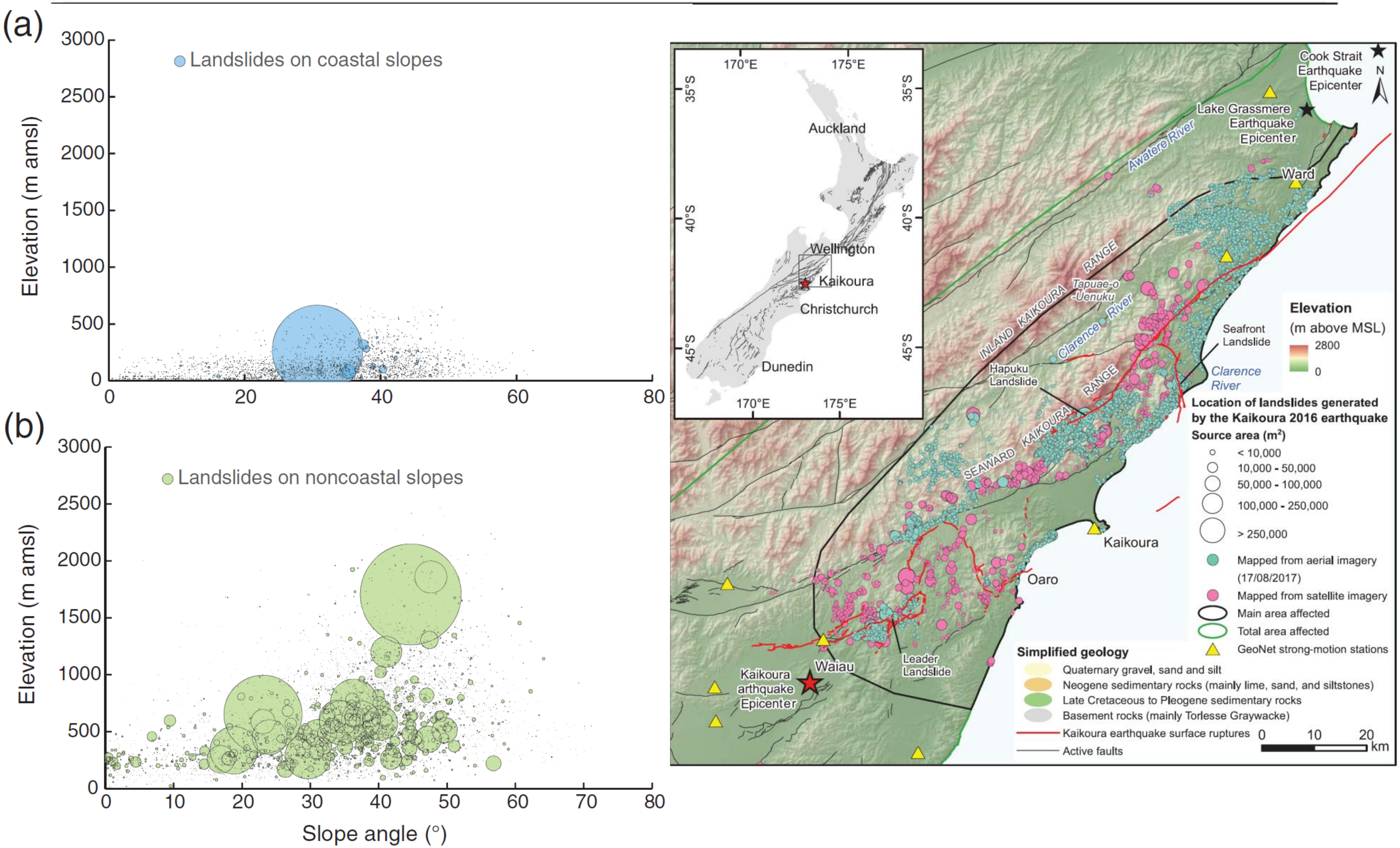

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Shaking on slopes and topographic response

The Aysen Fjord Earthquake

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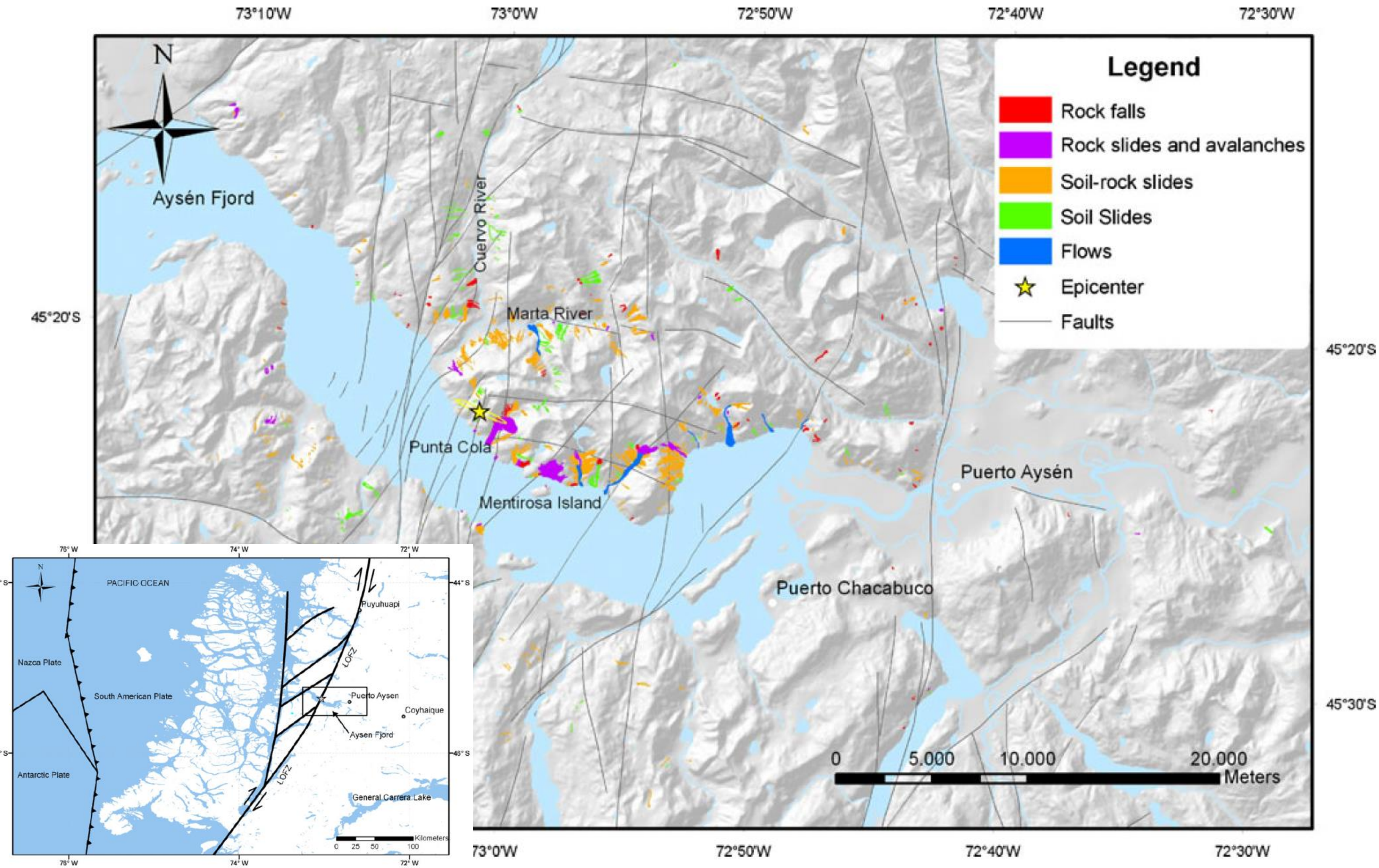
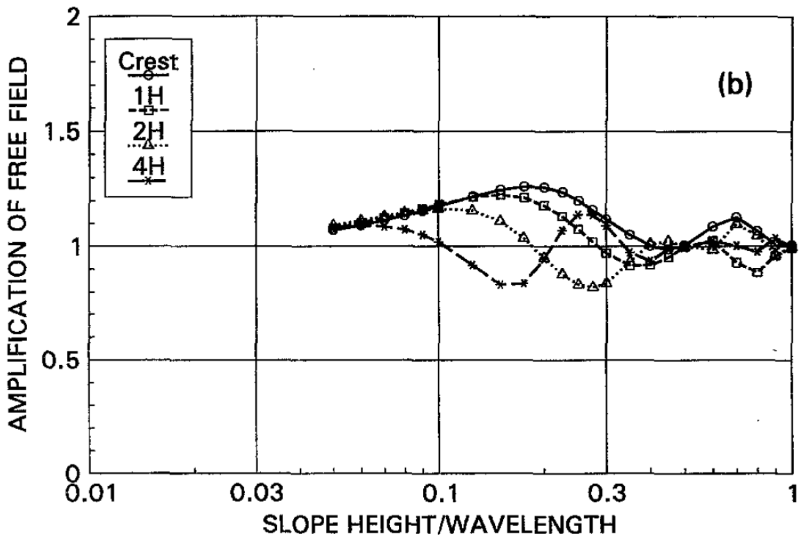
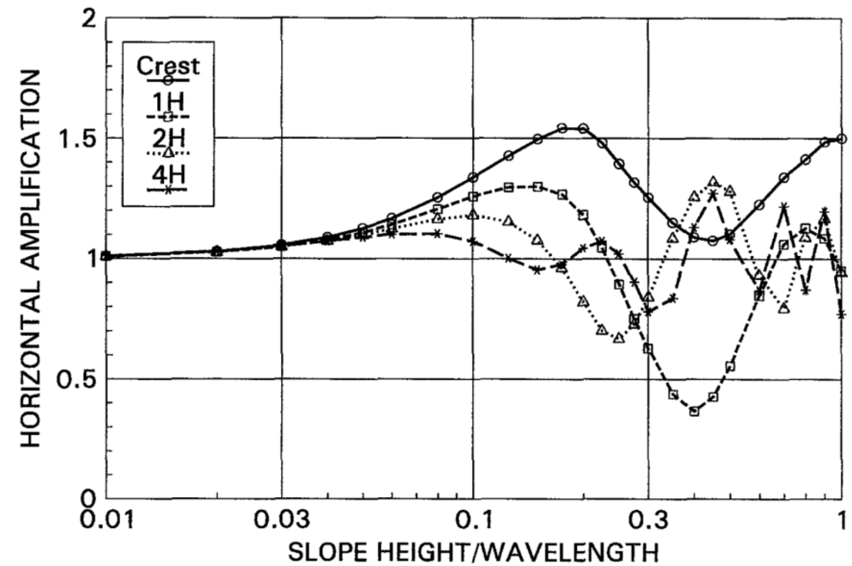
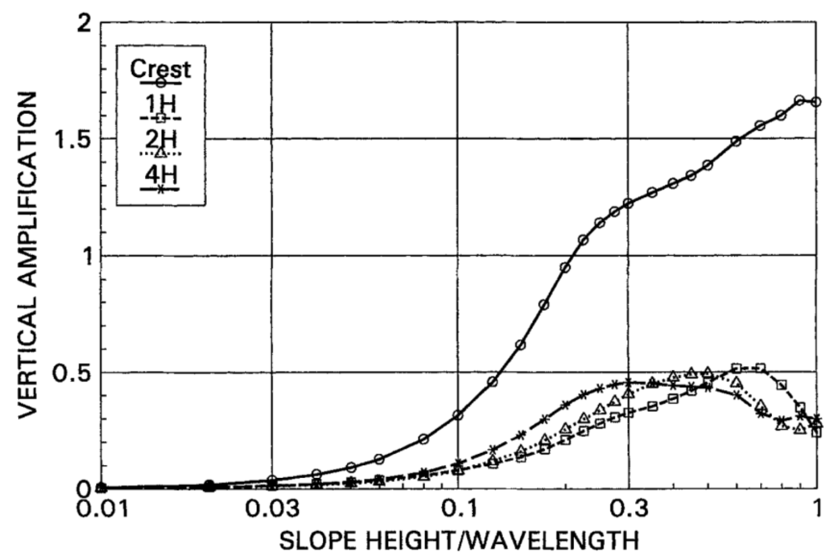






Amplifications behind the crest for vertically incident SH waves (top left), vertically incident SV waves (top right) and vertical ground motions from a SV wave (bottom right).

From Ashford et al (1997). Topographic Effects on the Seismic Response of Steep Slopes. Bulletin of the Seismological Society of America, Vol. 87, No. 3, pp. 701-709.



Key observations:

- Crest accelerations are a function of:
  - Wave type
  - Wave polarisation
  - Wave frequency / wavelength
  - Slope height / angle.
- A de-amplification effect occurs at the foot of a slope
- There is a decrease in amplification patterns behind the crest.

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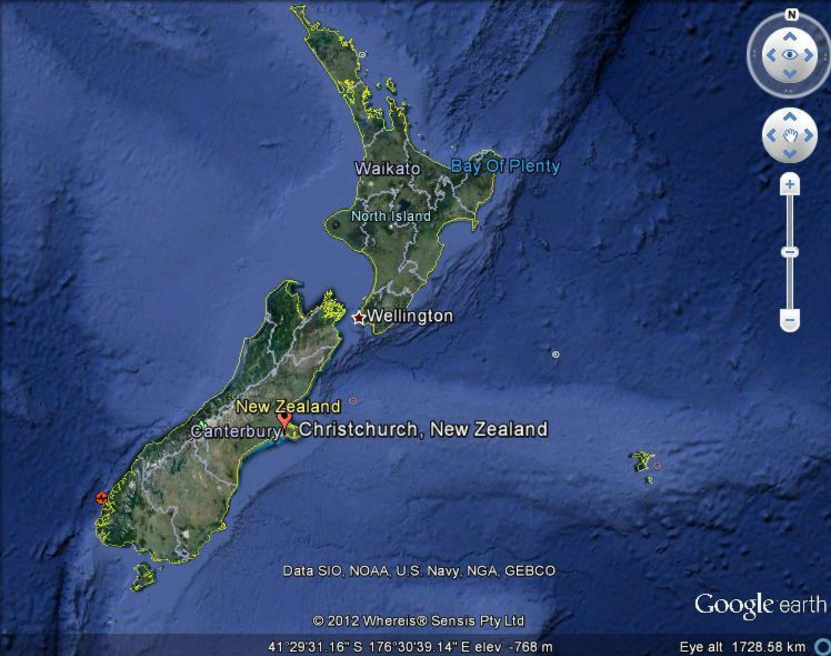

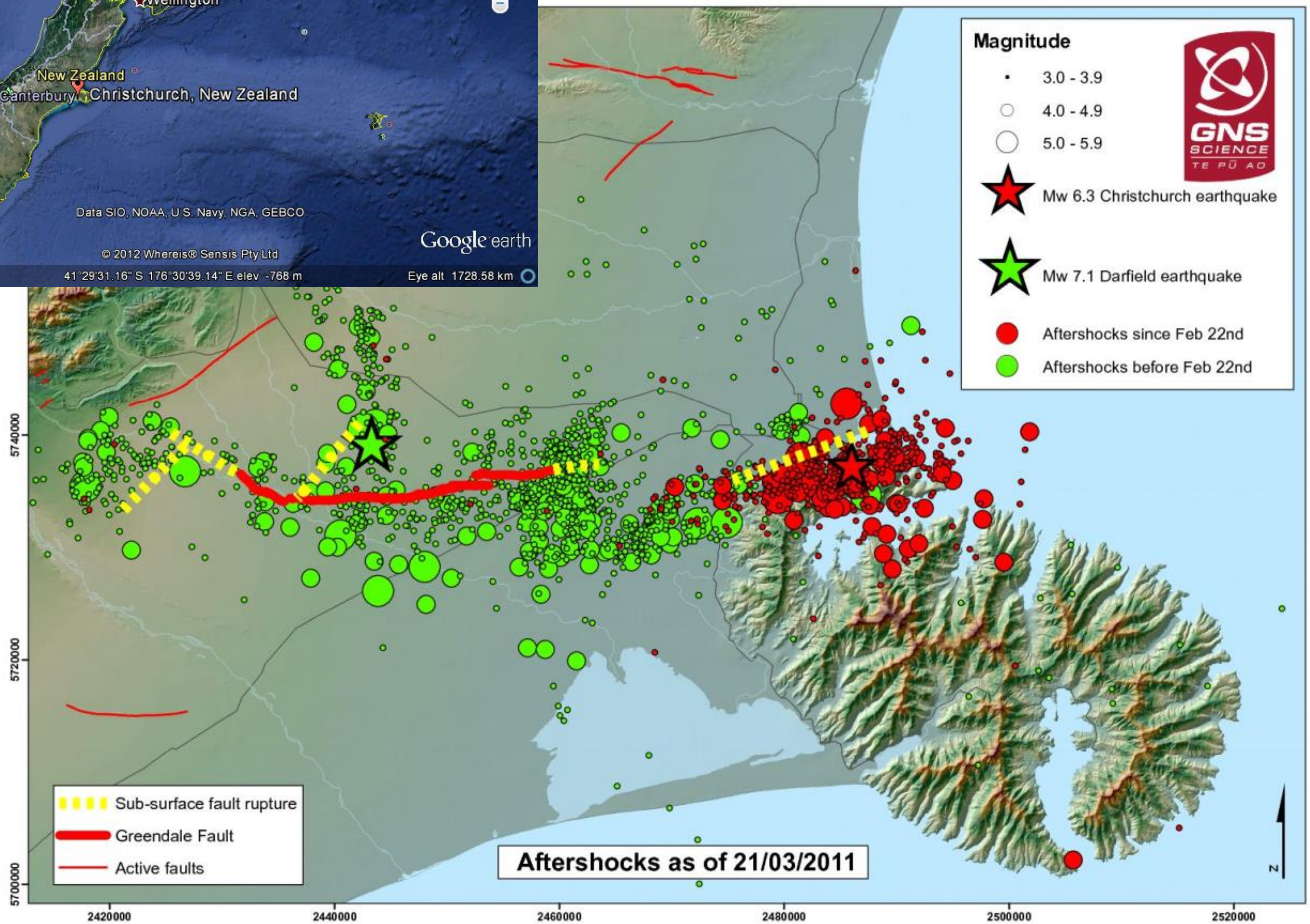

Ground shaking

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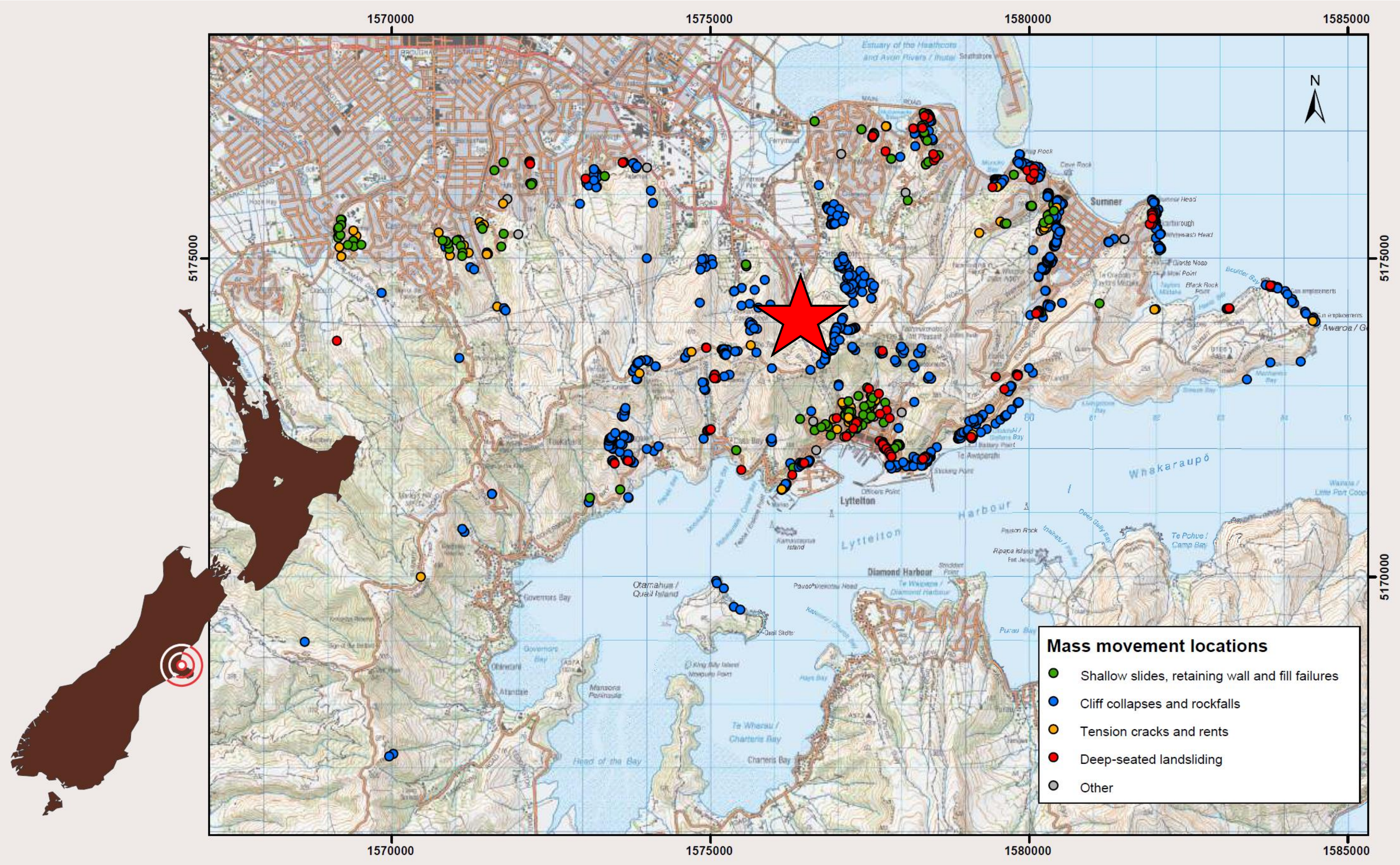

How is shaking measured?

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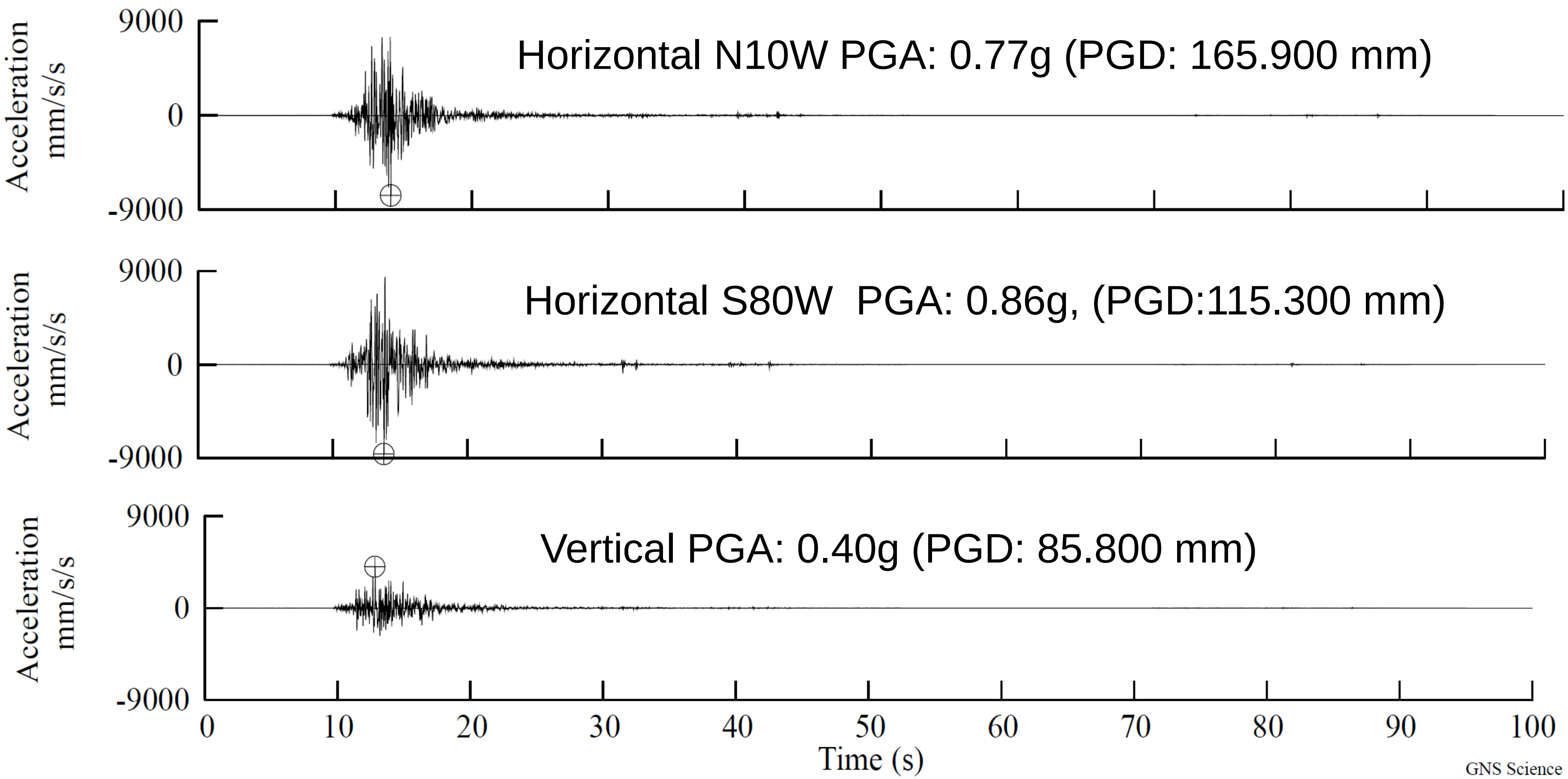
Accelerograms recorded on rock from the 22nd February 2011 earthquake in Christchurch.



GNS Science

Conceptual model of slopes in the Port Hills: topographic amplification in creating spatial variations in ground shaking away from a rock slope.

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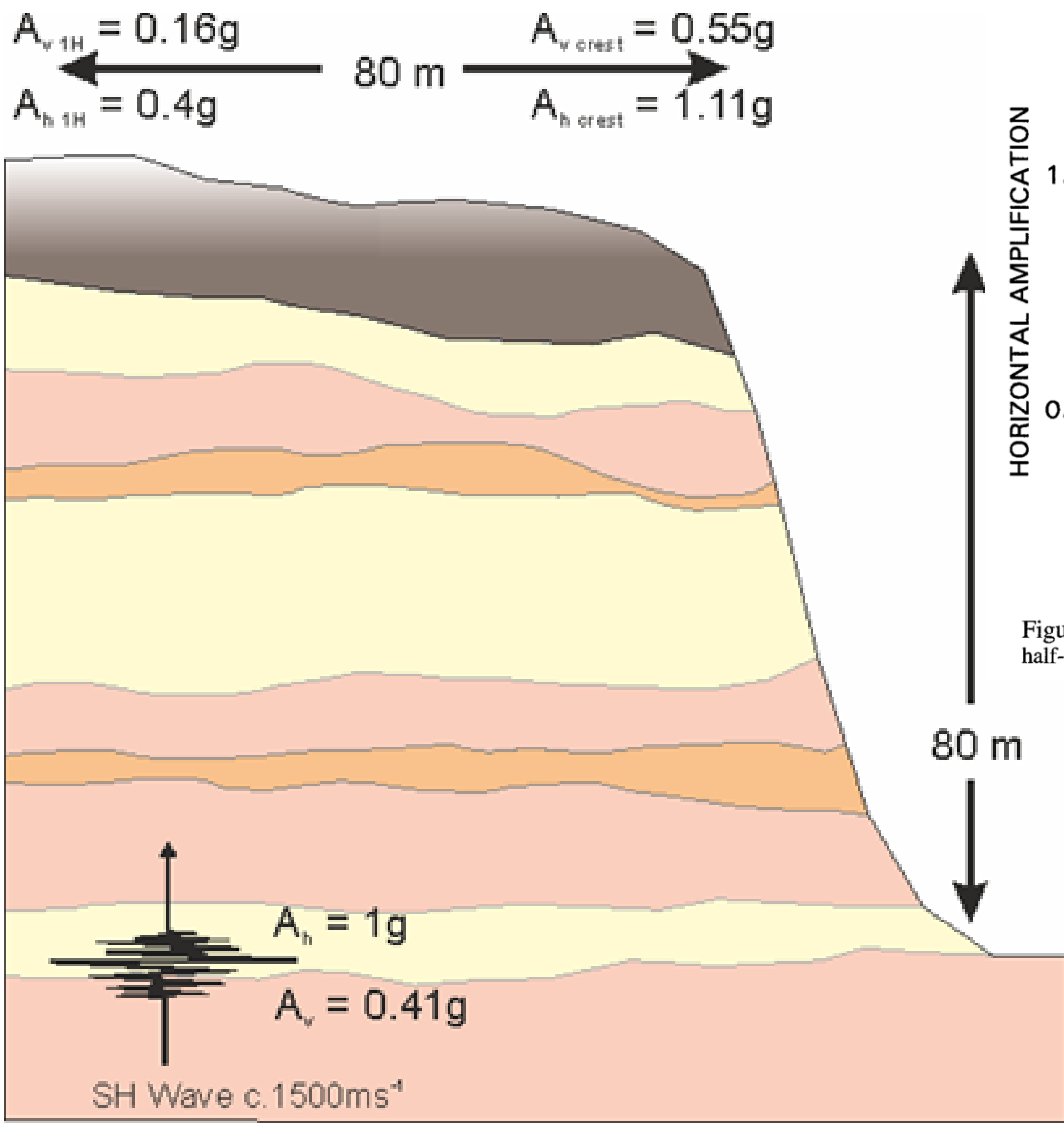


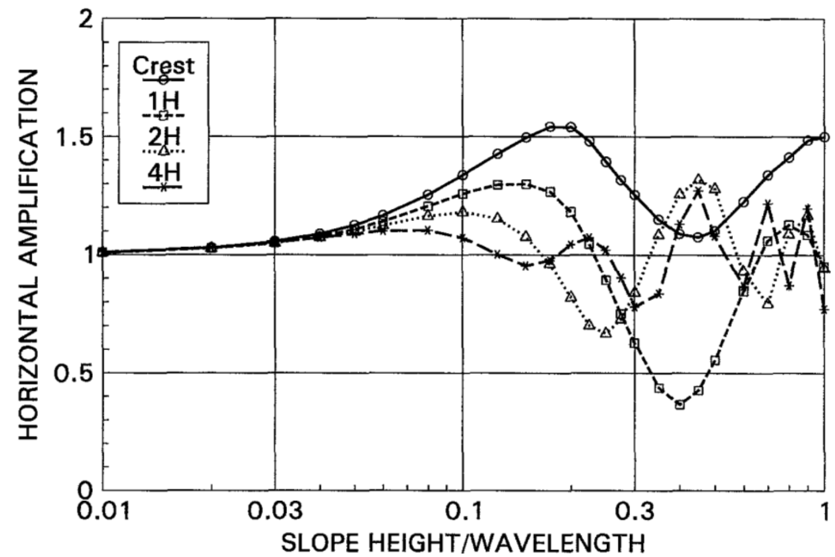
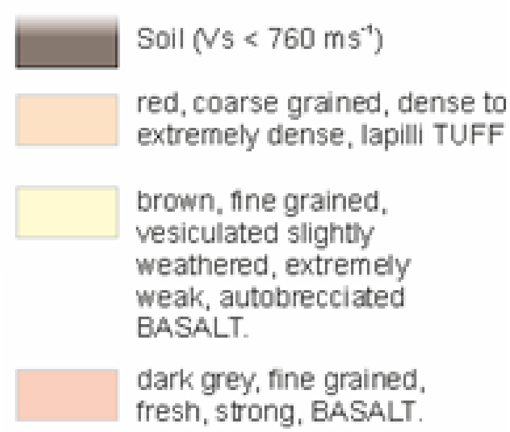


Figure 4. Horizontal amplifications for vertically incident *SV* wave on a stepped half-space for various distances behind crest, $\beta = 1\%$.



Slopes, ground motion and topographic amplification

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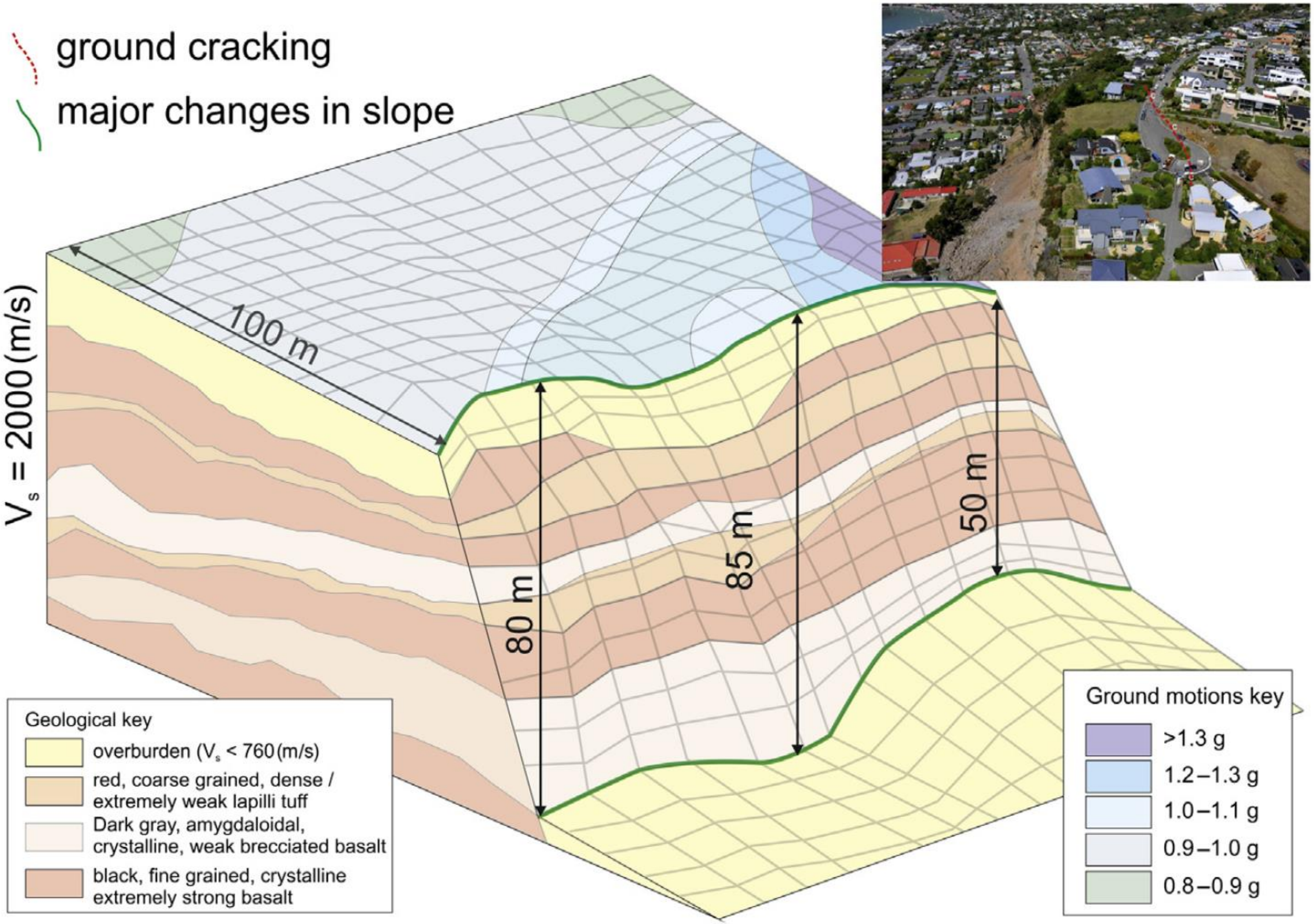

(Glendevere Terrace above Redcliffs School, Redcliffs: photo by G. Hancox)

(Photo courtesy Graham Hancox GNS Science)

(Searidge Road, Scarborough: photo by G. Hancox)

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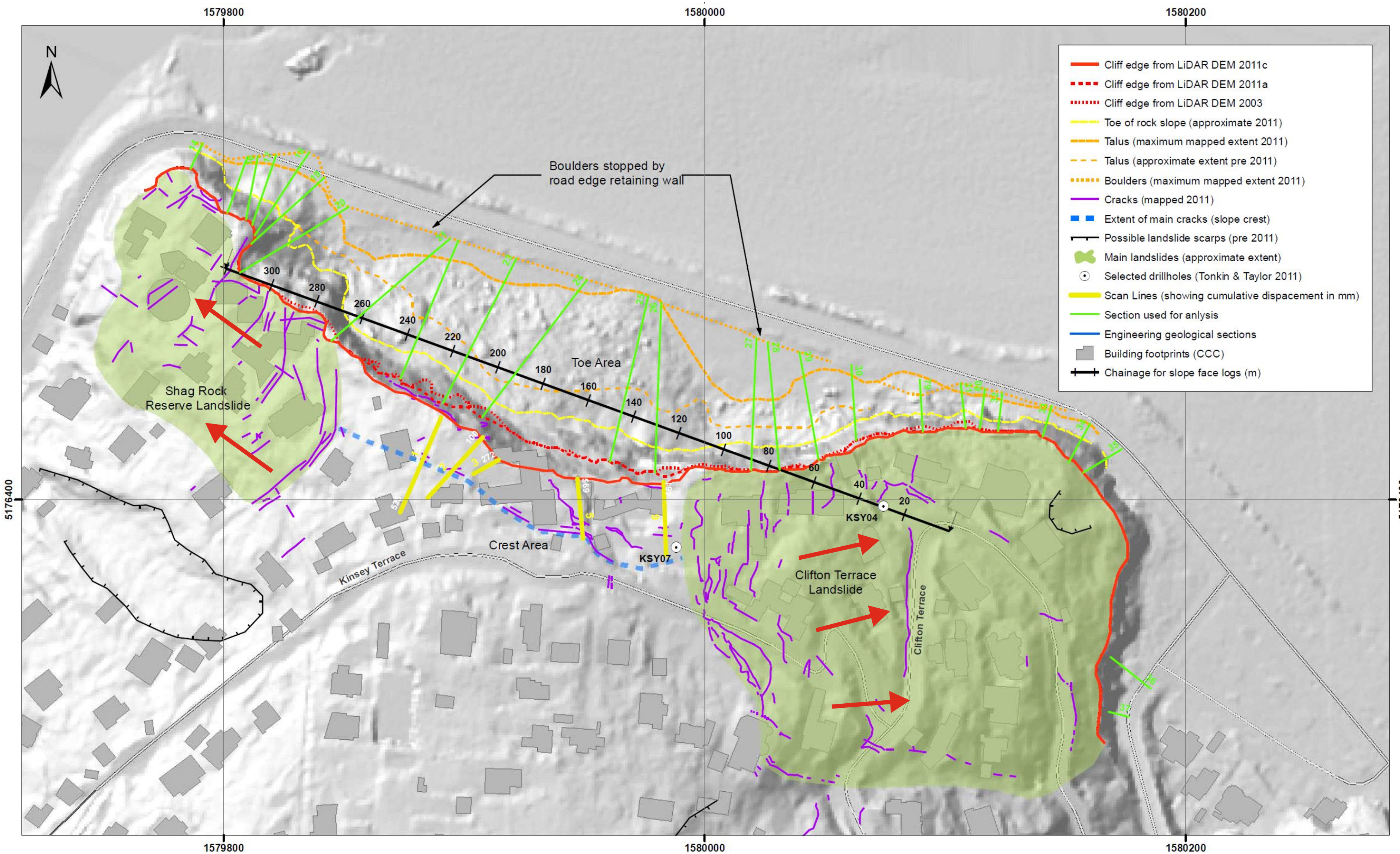

From Stolte et al (2017). An Experimental Topographic Amplification Study at Los Alamos National Laboratory Using Ambient Vibrations. Bulletin of the Seismological Society of America, Vol. 107, No. 3, pp. 1386–1401, doi: 10.1785/0120160269

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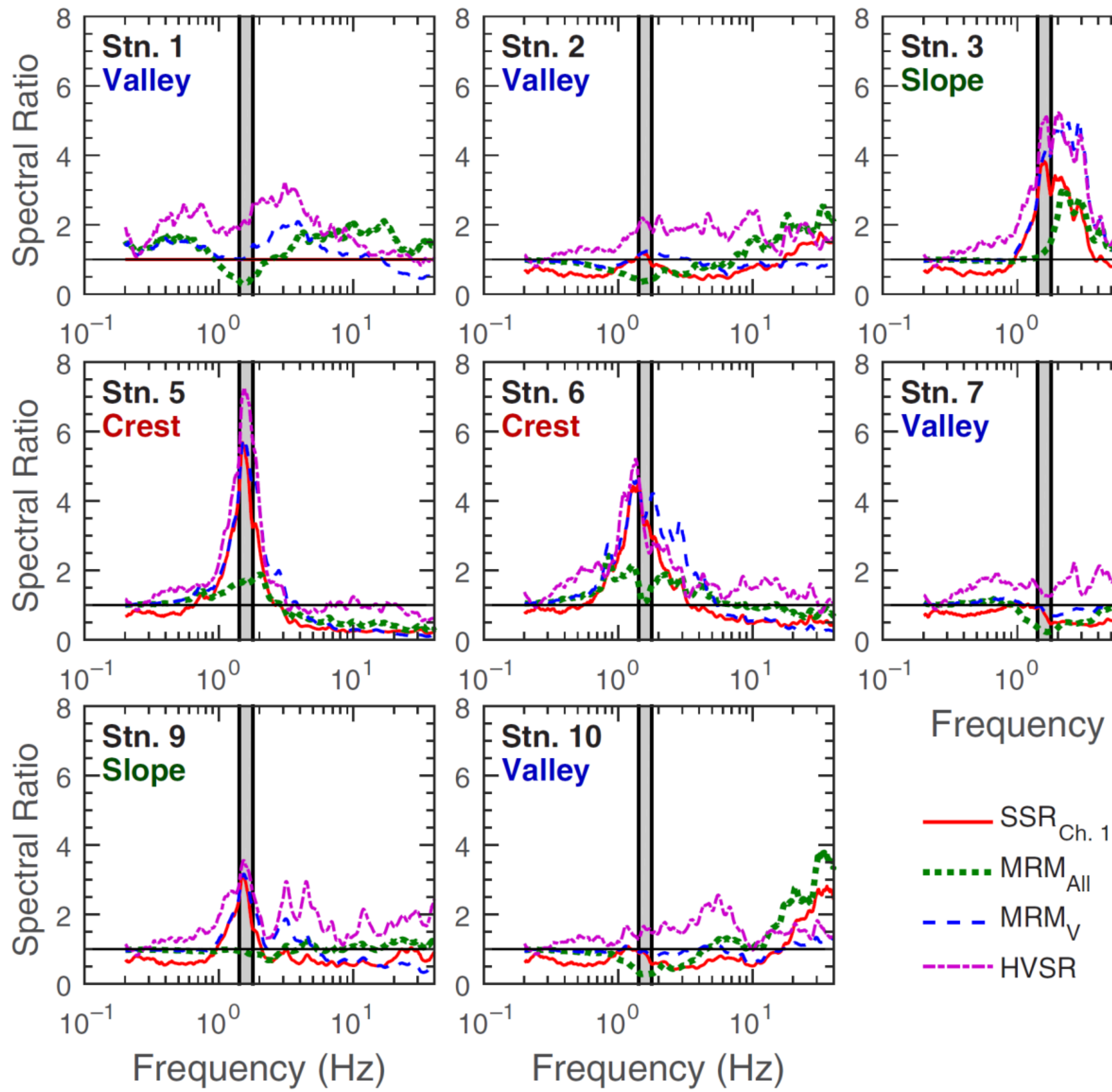

Spectral ratios computed from horizontal motions recorded in an orientation perpendicular to the ridge.

Landslides in rock

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Assessing the stability of slopes

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Hazard Identification

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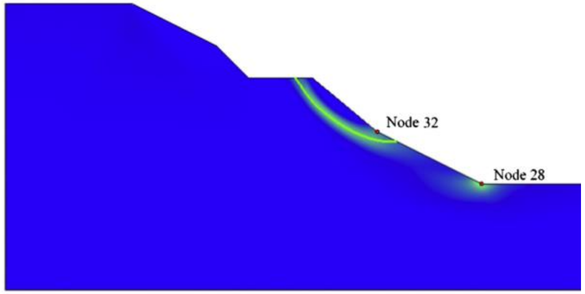
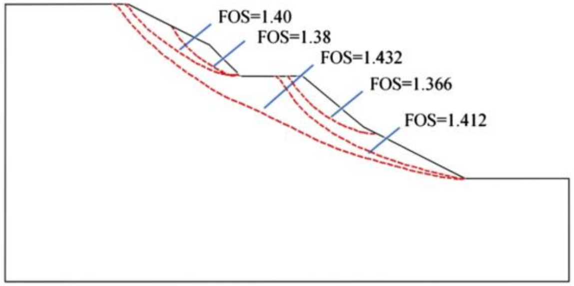
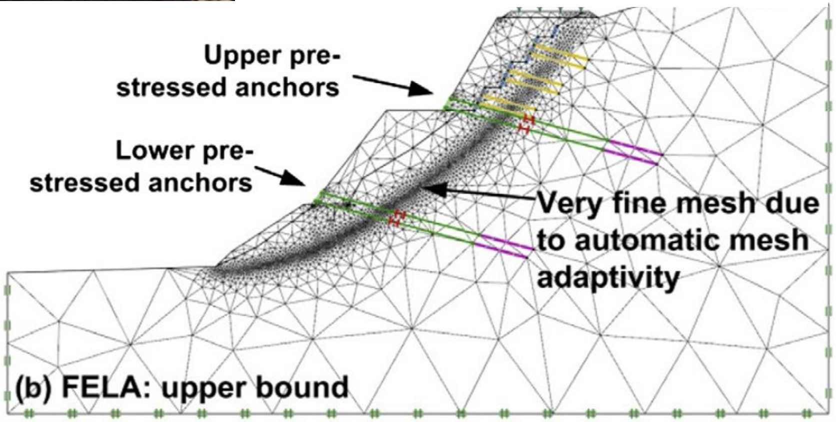
- Field survey and mapping:
  - Geomorphological mapping.
  - Conceptual models
  - Hazard mapping.
- Calculations:
  - Limit state calculations
  - Probabilistic & reliability methods.
  - Design charts
- Numerical models:
  - Finite and distinct element codes
  - Particle flow codes







Top left: field survey of landslides in North Yorkshire. **Top right**: comparison of limit state models from Liu et al (2015) *Computers and Geotechnics* 63, 291–298. **Bottom**: example of finite element model from Tschuchnigg et al (2015) *Computers and Geotechnics* 70, 178–189

The Meson Alto Landslide, Chile

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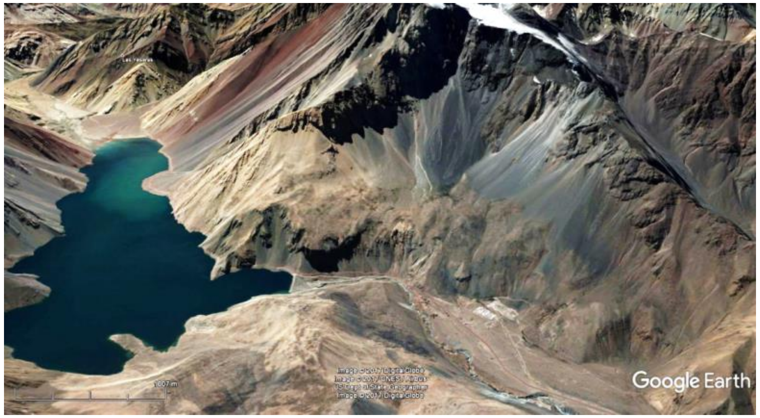

A large rock slide/avalanche

- Geomorphologically it has a minimum of 2 phases of movement
- C. 4.7 km^3.
- Using a limit state model F > 2.5, using an anisotropic conditions from autobrecciated layers F > 1.7.
- Smaller blocks F varies from 1.1 to 1.6

Rockslide / wedge at Zuma Beach in Malibu, California at Point Dume 25, March 2018 filmed by Lloyd Eric Cotsen

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Time dependent processes

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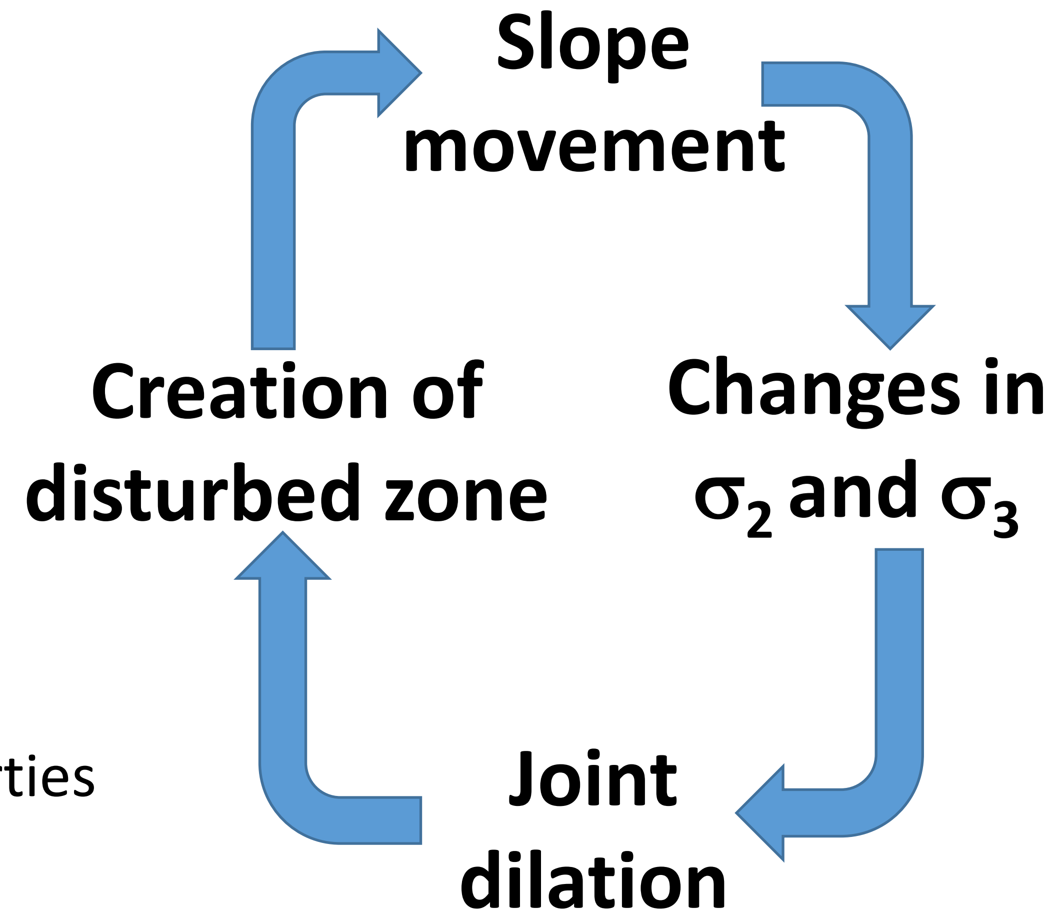
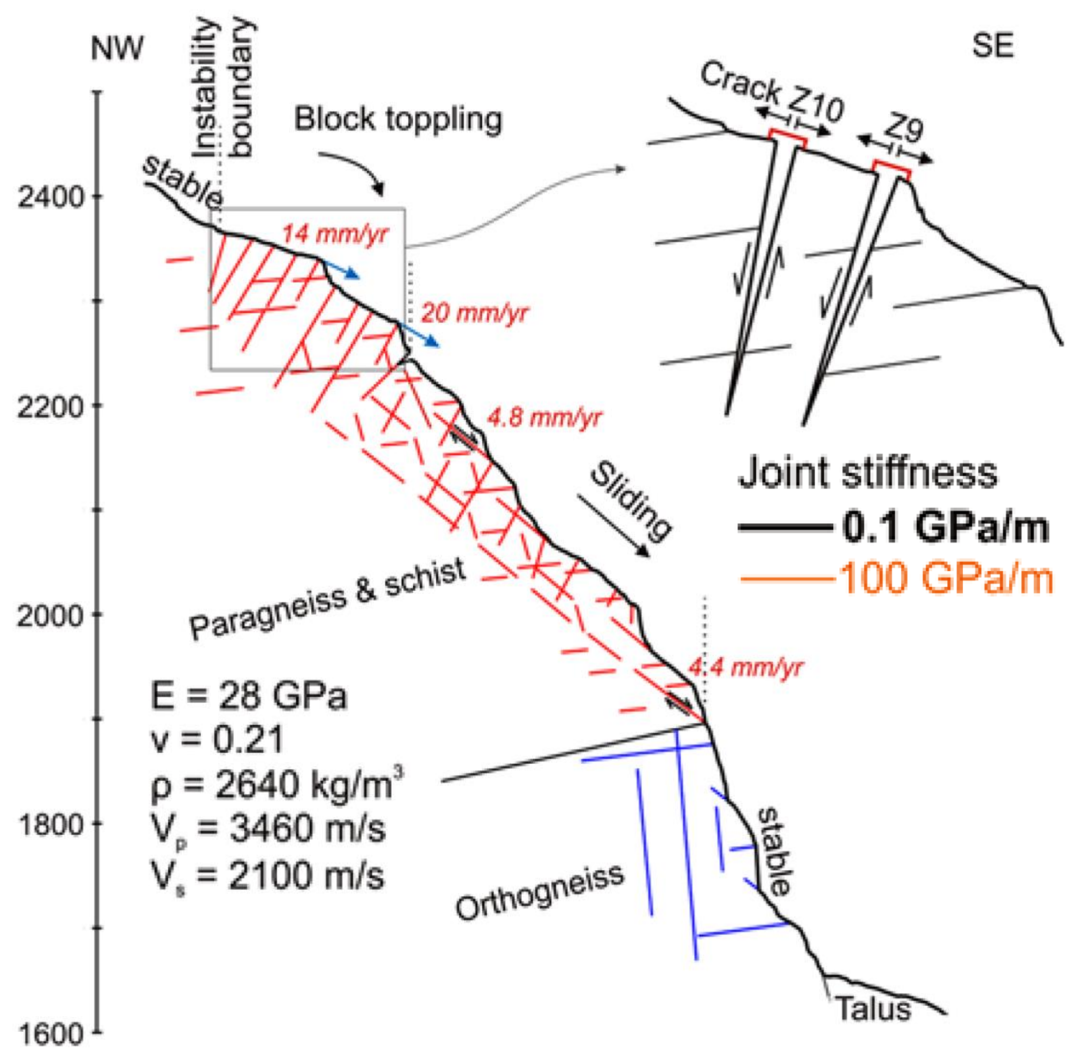
- Events causing disturbance in slopes
  - Erosion – especially deglaciation
  - weathering
  - **Landslide activity**
  - **earthquake**
- Elastic response
  - Joint dilation and loss of frictional strength
  - Changed dynamic properties
- **Disturbance zones**



From: Moore et al (2011) Site Effects in Unstable Rock Slopes: Dynamic Behaviour of the Randa Instability (Switzerland). Bulletin of the Seismological Society of America, Vol. 101, No. 6, pp. 3110–3116, doi: 10.1785/0120110127



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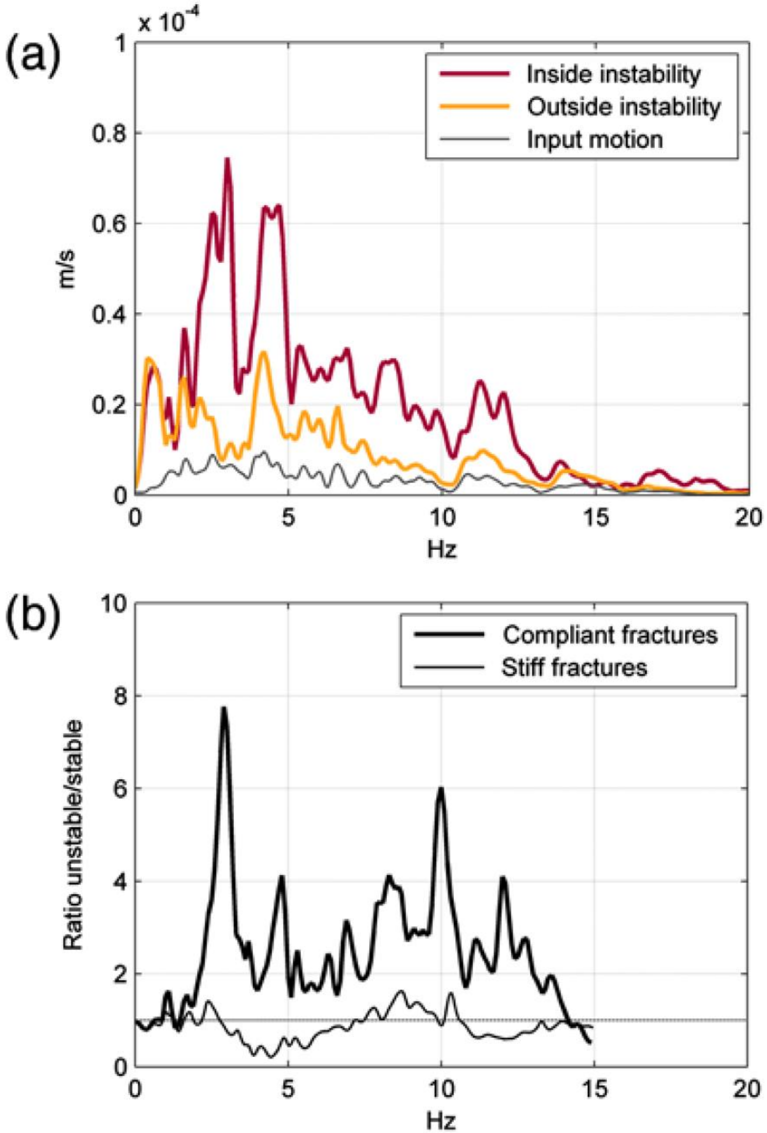

Top left: Computed response spectra for the Randa Landslide from inside and outside the area of instability.

- Higher ground velocities showing the response to the rock mass in the area around the zone of instability
- The increased strain within the slide mass due shows even higher seismic response.

Bottom left: calculated responses represented as instability ratios for stiff (rough, closed) vs seismically compliant (smooth, open) joints.

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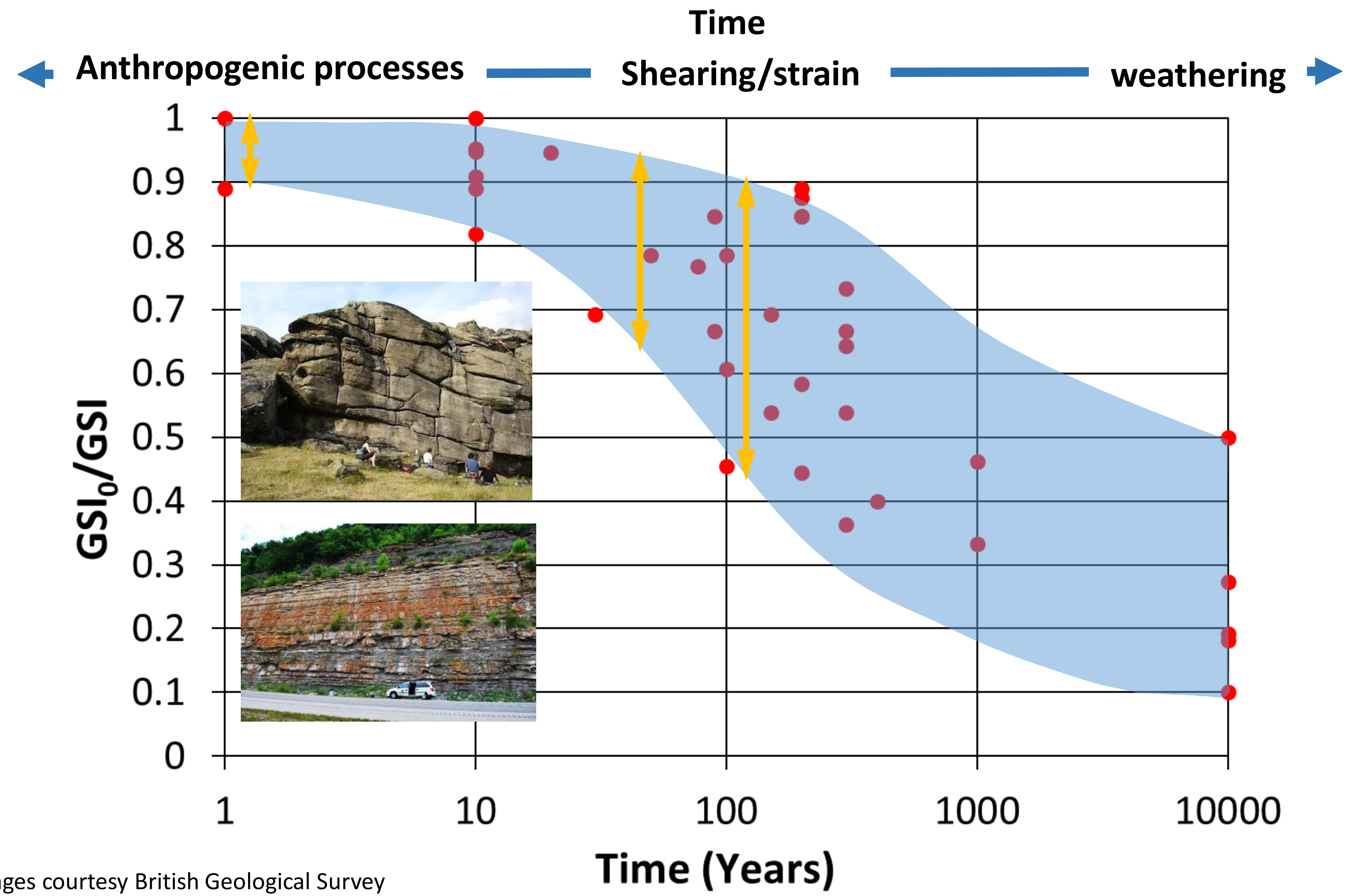
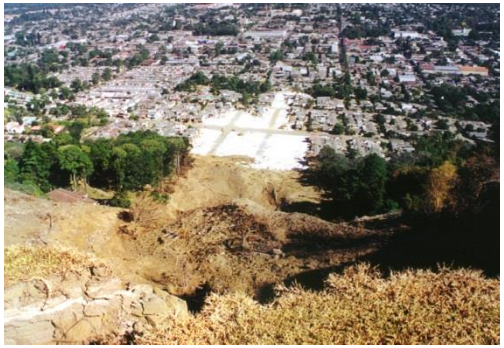
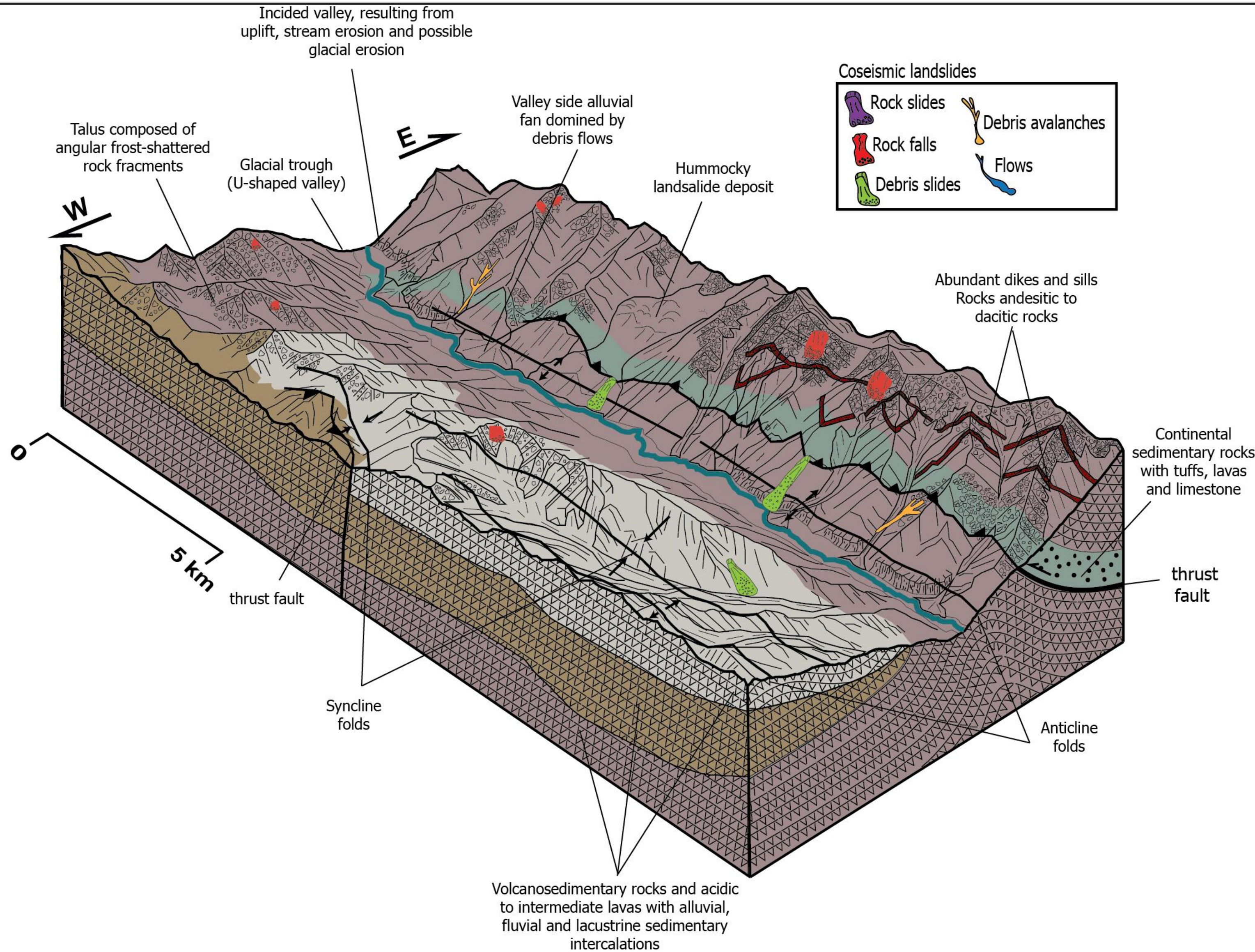


Images courtesy British Geological Survey

Right: From: Crosta, Imposimato, Roddeman, Chiesa, Moia (2005) Small fast-moving flow-like landslides in volcanic deposits: The 2001 Las Colinas Landslide (El Salvador). *Engineering Geology.*



(above) The landslide at Las Colinas and Las Barioleras were caused by the differences in seismic properties between the underlying Balsamo Formation and the overlying Tierra Blanca.


Incided valley, resulting from uplift, stream erosion and possible glacial erosion
Talus composed of angular frost-shattered rock fracments
Glacial trough (U-shaped valley)
Valley side alluvial fan domined by debris flows
Hummocky landsalide deposit
Coseismic landslides
Rock slides
Rock falls
Debris slides
Debris avalanches
Flows
Abundant dikes and sills Rocks andesitic to dacitic rocks
E
W
0
5 km
thrust fault
Continental sedimentary rocks with tuffs, lavas and limestone
thrust fault
Syncline folds
Anticline folds
Volcanosedimentary rocks and acidic to intermediate lavas with alluvial, fluvial and lacustrine sedimentary intercalations

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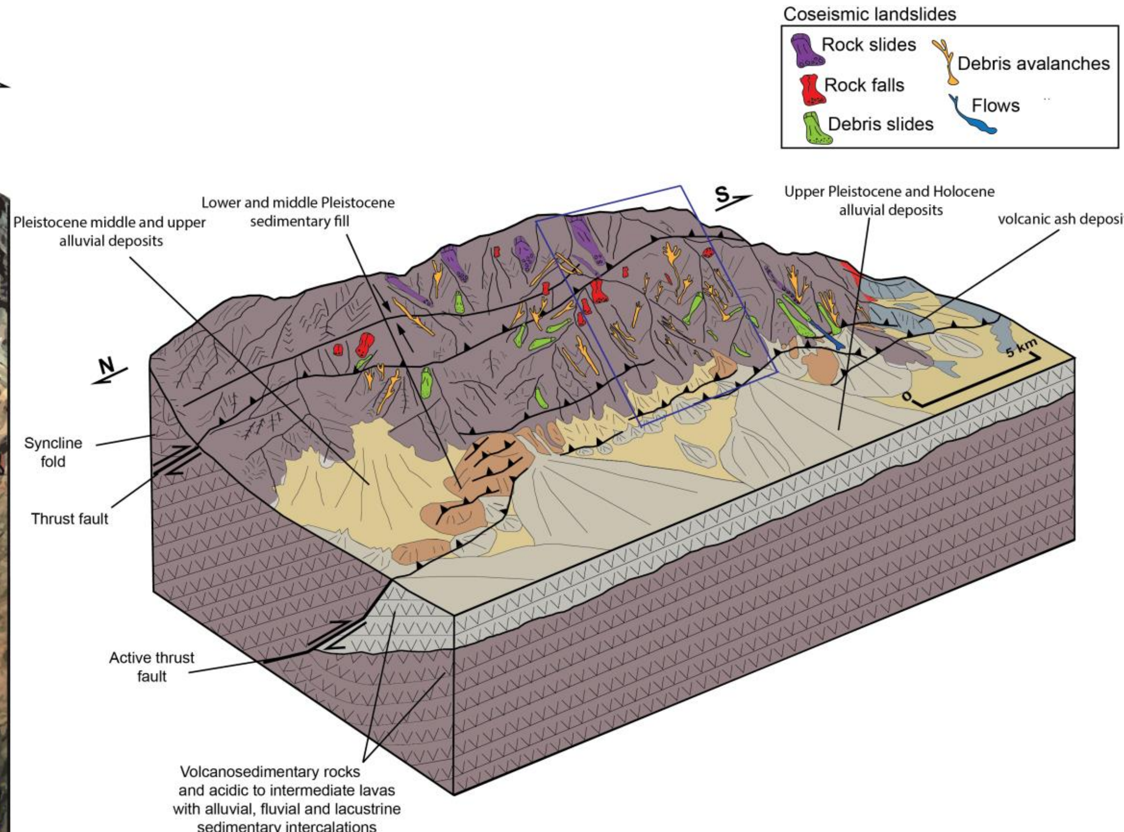

Conceptual model of mountain thrust belt terrain and associated landslides for shallow crustal or ocean margin events, Chile.

General observations

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- We have a vastly better understanding earthquake induced landslides
- Topographic amplification is better understood - how that can be used is less clear.
- Seismic response of rock masses varies with joint dilation / rock mass disturbance
- With so many uncertainties are we any closer to having a reliable predictive tool?

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Questions