# Geohazards explained 2

## Collapsing volcanoes: the sleeping giants' threat

**Dormant volcanoes are typically thought of as relatively safe environments to live around. However, under certain geological conditions, such volcanoes can be prone to collapse and may generate massive rockslide avalanches reaching tens of kilometres from the volcano.**

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On Earth and other planets, volcanoes are extremely dynamic systems within fairly short geological timescales. Erupted lava and pyroclastic debris build up volcanic landforms, and the threat the associated processes cause to surrounding populations are one of the central focuses of volcanology. Through observation of eruptions at the surface, measurements of gas and seismicity, or through the study of the products they generate, we have made substantial progress towards understanding and reducing hazards associated with volcanoes. Less well documented are destructive events triggered by volcanic flank collapses that produce massive and extremely destructive rockslide avalanches. Rockslide avalanches are huge masses of rock sliding down at velocities exceeding 250 km/h, often travelling tens of kilometres and covering areas of up to hundreds of square kilometres. The devastation they may cause is particularly significant when considering their capacity to transform into secondary lahars (i.e. volcanic mudflows) provided that sufficient water is present within the moving rockmass, or their ability to enter lakes or oceans and produce large-scale tsunamis. Mount St Helens erupted in 1980 and gave a glimpse of how huge flank collapses can be: the summit elevation was reduced by about 500 m and the volcanic edifice lost approximately one third of its total volume. More recently, a much smaller portion of Volcán Casita, in Nicaragua, failed as a consequence of heavy rainfalls associated with the passing of Hurricane Mitch in 1998; however, because such large amounts of water were involved in the collapse, the rockslide quickly turned into a mudflow that almost instantly took the lives of 2500 Nicaraguans.

In terms of hazard mitigation, volcanic eruptions often grant windows of opportunity prior to their climax through precursory signals such as changes in emitted gas volumes and compositions at the surface, abrupt transitions in underground seismicity or ground deformation accompanying the rise of magma towards the surface. Unfortunately, when flank collapses are not associated with eruptions, precursory indications are mostly absent, and hence pose a bigger threat to unprepared human populations living around volcanoes. This threat becomes more and more of a reality as field scientists are finding that almost every volcano on Earth has undergone one or more flank failures. To better understand and find ways to anticipate flank collapses, there is a growing need to investigate the processes that lead to mechanical failure, and the differences these will make in terms of avalanche size and transport capacities. Volcán Mombacho, in Nicaragua, is a perfect field laboratory to pursue these investigations.

### The puzzling transport properties of rockslide avalanches

Large-scale mass movements involving rock material possess several intriguing properties, the most peculiar of all probably being the distance travelled horizontally in comparison with the height from which the rockmass fell. Under Coulomb friction laws, granular materials should stop moving horizontally at about 1.6 times the collapse height. Remarkably, collapses of over 1 $km^3$ will typically reach distances 10–15 times larger than their fall height. Possible explanations for this include the presence of air trapped under the bulk of the mass, basal fluidization or lubrication by air or water, energy released by progressive material fragmentation, or vibrational energy produced by solid particle interactions. To date, however, no model is widely received and as a result, the transport properties of such rockslides are still poorly understood. In order to derive a robust emplacement model, a certain amount of information must be known on the kinematics and dynamics of transport. Fortunately for us, almost every well-preserved rockslide avalanche deposit possesses a detailed record of the deformation suffered during transport. While the base of rockslide avalanches is stipulated to be the agent reducing frictions during transport, the bulk of the mass behaves as granular material in the frictional regime; as a result, deformation is preserved in the form of surface faults that extend into the interior of the deposit. Recent studies have shown that fault structures can truly be considered fingerprints, unique to each avalanche, which, when deciphered, yield invaluable information about the type of deformation suffered (extension/compression), its location in space (rockslide front/back, centre or sides), and in time (chronology of fault formation). Figure 1 shows two deposits displaying the two main surface morphologies encountered on rockslide avalanches: one is full of individual hummocks with circular to elliptical bases (Tata Sabaya, Bolivia), and the other is covered by ridges that are fault structures (Socompa, Chili/Argentina). Within the interior of most avalanches, three types of fault structures are detected: normal (extension), thrust (compression) and strike-slip (transform) faults. Simple laboratory analogue experiments involving the slide of stratified sand on a low friction ramp are able to physically replicate the two structural types (hummocky vs. ridged) as well as the distribution of surface features. Much like in nature, the bulk of the sand mass deforms in the frictional regime and responds to deformation by faulting. When the material is homogenous in size and mostly non-cohesive, analogue rockslides are always ridged, and when more cohesive materials (plaster or humid sand) are sandwiched in between non-cohesive sand, hummocks dominate the surface (Fig. 2). Because these experiments are filmed, details on the chronology of deformation (i.e. kinematics) provide the missing link between deposits seen in nature and their transport mode: extension dominates the first stages of collapse and normal faults affect the whole mass; then, as the slide travels further and reaches gentler slopes, compression is active at the avalanche front and thrust structures develop. From initiation to emplacement, systems of strike-slip faults observed on both sides serve to accommodate differences in velocity within the moving mass. These various structures are all observed in nature at the same locations (thrust structures are more typically at the front and normal faults at the back) although their respective proportions may vary. Experimentally, variations in normal versus thrust fault densities have been obtained by simply changing the initiation and deposition slopes (i.e. ramp curvature). Four rockslide avalanche poles were derived from slope and material homogeneity variations: dominantly extensional (normal faults cover most of the surface), dominantly compressive (thrust faults cover most of the surface), hummocky (materials are very heterogeneous) and ridged (homogenous materials). These laboratory analogues may provide key information on how transport and emplacement occur in nature. Such structures seem to only form under certain conditions: the base of the rockslide has to experience low-friction (lubrication or fluidization) while the bulk of the mass forms a brittle, deforming carapace, much like in a plug-flow model. The following sections offer superb examples of two such rockslide avalanches in a single volcanic environment, and illustrate how field observations can be directly linked to initiation, transport and emplacement properties.


**Fig. 1.** Satellite images of small areas of the Andean Tata Sabaya (left) and Socompa (right) rockslide avalanche deposits. Note the contrasting surface morphologies: hummocky (left) and ridged (right).

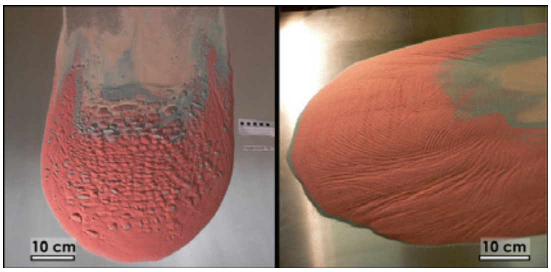


**Fig. 2.** Laboratory analogue models of rockslide avalanche deposits. Hummocky topographies (left) are reproduced using layered materials with different cohesions while ridged topographies (right) are best replicated using sands with homogeneous size and cohesion. Note the lobate deposit shapes in both, and the complex surface structure relationships on the ridged deposit.

## Mombacho: a collapsing volcano

Volcan Mombacho, Nicaragua, forms part of Central American volcanic front (CAVF, Fig. 3), a volcanic arc created by subduction of the Cocos Plate under the Carribean Plate. It is a fairly typical basaltic–andesitic stratovolcano composed of alternating lava flows and tephra layers. The early Mombacho was most likely built prior to a huge ignimbritic eruption 23 000 years ago involving a large volume of pumice that mantled surrounding topographies creating deposits several metres thick (Fig. 4), and during which emptying of the magma chamber resulted in the collapse and formation of the nearby Apoyo Caldera (~5 km wide, see Fig. 3 for location). Hence, most of the current Mombacho edifice was constructed subsequently, and the presence of a soft, easily compressible pumice layer underneath substantially affected its structure as it was being built. Indeed, as magma is erupted/intruded, weight is added onto volcanic flanks, and the edifice base tends to radially move outwards through

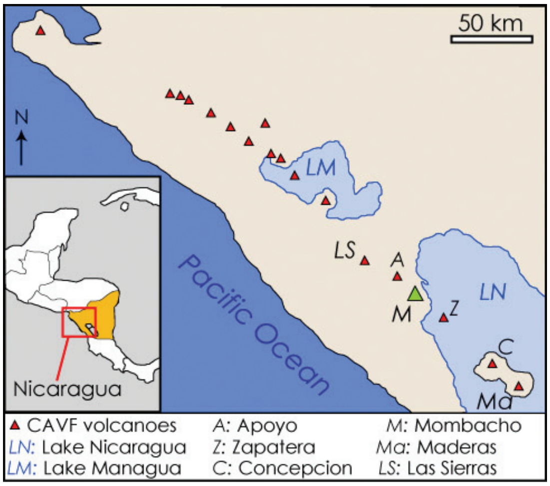


**Fig. 3.** Map of western Nicaragua and of the Central American Volcanic Front (CAVF).

**Fig. 4.** The thick ignimbrite deposited during the 23 000 BP eruption of Apoyo forms most of Volcán Mombacho's soft substratum.

systems of thrust faults, while its centre sags downwards via normal faults. When soft substrate present underneath is pushed outwards, anticlinal folds often rise around the volcano's base (Fig. 5).

Currently considered dormant, Volcan Mombacho presents some fundamental morphological differences with nearby Volcan Concepcion, 200 km south-east or Momotombo, 200 km north-east (Fig. 3): the latter two have the near-perfect conical shape of typical stratovolcanoes, while Mombacho's topography appears irregular and lacks a clear summit crater (Fig. 6). From aerial or satellite view (Fig. 5), the reason for these differences becomes obvious: two large amphitheatres are carved within the north-eastern and southern flanks. The north-eastern amphitheatre is U-shaped, represents a volume of 1.1 km$^3$, is 200 m at its deepest and amputates the edifice down to its base. In contrast, the southern amphitheatre is bowl-shaped, has a volume of 1.6 km$^3$, measures 500 m at its deepest and carves out most of the volcano core. The missing portions of the edifice are now found as two giant >10 km-long rockslide avalanche deposits (RADs), namely 'Las Isletas' in the north-eastern sector, and 'El Crater' in the southern sector. Amazingly, yet another RAD deposit crops out in the south-east sector, partially buried by the eastern margin of El

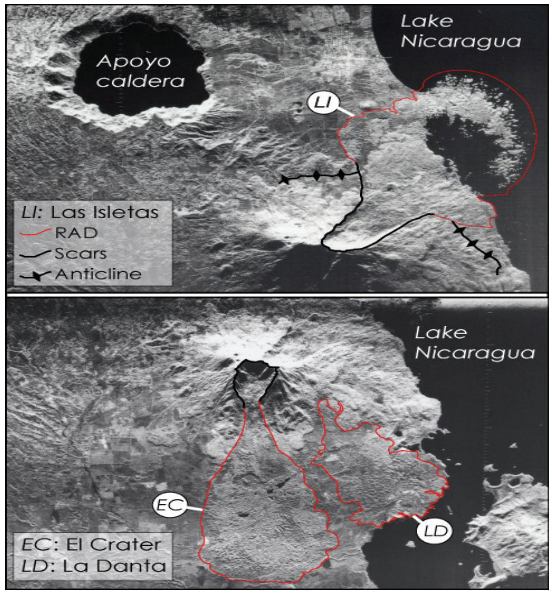


**Fig. 5.** Radar image of Mombacho and its three rockslide avalanche deposits. Top image shows Las Isletas RAD and collapse amphitheatre. Note the discontinued anticline fold structure on both sides of the scar. Bottom image shows El Crater (N–S oriented) and La Danta (NW–SE oriented) RADs. The Island on the right is the Zapatera volcano. In both images, hummocky topographies are well marked by radar illumination angle.

Crater RAD, and covered by several monogenic cinder cones (La Danta RAD, Fig. 6). All three RADs are easily detectable within the landscape because their surface is peppered with hundreds of conical hummocks generally tens of metres in diameter (Fig. 7). These morphological features form during avalanche transport as lithologies of varying mechanical behaviour are spread out and torn apart, forming intricate systems of graben and horsts within the resulting

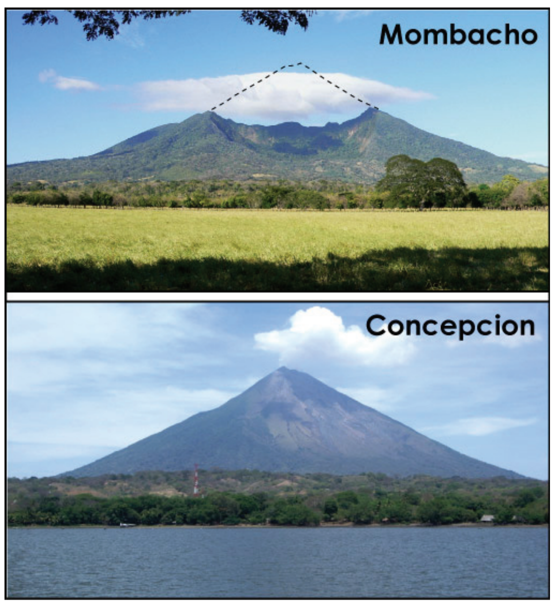


**Fig. 6.** Contrasting edifice shapes at Nicaraguan volcanoes Mombacho (top) and Concepcion (bottom).

**Fig. 7.** Hummock overgrown by an opportunistic tree at Las Isletas. The bulk of the hummock is made up of decimetre to metre-sized blocks with a small amount of matrix.

**Fig. 8.** Road cut through a hummock at El Crater. The top yellowish layer is the altered block and matrix unit (particularly matrix-rich here), and the underlying brick red unit is the basal extremely altered unit. This cross-section illustrates well how systems of grabens and horst resulting from extension within the spreading rockslide may generate hummocks.

deposit (Fig. 8). Because only Las Isletas and El Crater are preserved in their entirety, they are the only two described below.

**Las Isletas RAD** The fan-shaped deposit of this rockslide avalanche is located right by the city of Granada (population: 100 000) covers over 56 km$^2$, reached ~12 km in distance, has an average thickness of 22 m and shows interesting geomorphological features such as lateral depositional wings, normal and strike-slip faults, and hummocky topography. It is composed of six main lithologies (Fig. 9); from top to bottom: a block-rich unit observed on the surface of most of the deposit, which grades into a block/matrix unit (Fig. 10), a hydrothermally altered unit present only inside the amphitheatre area towards the Mombacho summit (not shown in Fig. 9 log), and a basal unit mostly made of a pumice-rich layer, frequently mingled with a lapilli-rich unit towards the east of the deposit (Fig. 11). While hummocks are observed in both side-wings, most are found within the Las Isletas Peninsula, a crescent-shaped feature that delimitates the distal portion of Las Isletas RAD (Fig. 5). Internally broken blocks having preserved their original shapes ('Jigsaw puzzle structures') are frequently found within the block and matrix-rich unit and suggest that the bulk of the moving mass avoided significant shearing. In contrast, the pumice-rich base of Las Isletas RAD most likely accommodated stress by intense shearing; the latter unit is full of rounded clasts testifying to rolling and abrasion during transport, a feature which is not observed in the original Apoyo ignimbrite underlying Mombacho.

No ash was observed in any of the deposit units, which discards the possibility of an eruptive event accompanying the Las Isletas collapse. No post-Colombian historic records relate such a large-scale event within the archives of the city of Granada, founded in 1524 AD; hence we do not possess direct evidence for the timing of this catastrophic flank collapse. We did, nonetheless, find some evidence relating this event to historical periods after 1000 AD; fragmented and dispersed human bones were found within the matrix/block unit along with burial urns and pottery that were typical of populations linked to the Mayas, who populated this region of Central America after 1000 AD (e.g. Fig. 11). Altogether, this suggests that the Las Isletas rockslide avalanche occurred between 1000 and 1524 AD. Until carbon dating is carried out on these bone samples, no absolute age can be determined.

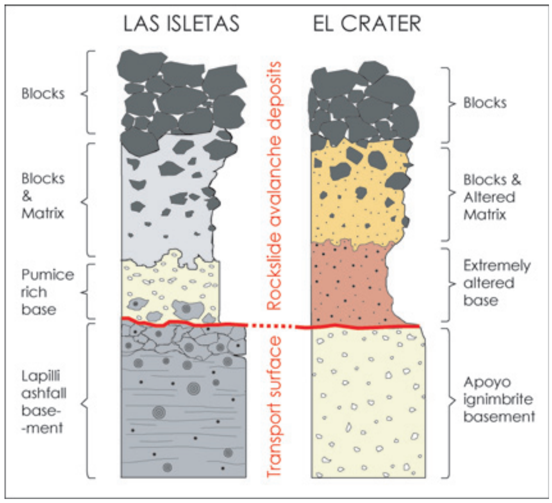


**Fig. 9.** Stratigraphic logs of both rockslide avalanche deposits. Thickness not to scale.

**El Crater RAD** El Crater deposit is spoon-shaped, extends to about 12 to 12.5 km from the summit, covers an area of approximately 50 km$^2$, and has an average thickness of 38 m. Comparatively, the El Crater RAD is covered by a greater number of hummocks than Las Isletas, they are however generally smaller in diameter. Lithologies observed in the field are also fairly different, particularly at the base. The same block-rich unit forms the carapace of the deposit, the supporting matrix/block unit is composed of more hydrothermally altered materials (Fig. 12), and the basal layer is made of rather fine grained material in an extreme alteration state (Fig. 13). Much as is found at Las Isletas, the surface is intersected by a series of normal faults that usually delimitate hummocky domains (see Fig. 8). Jigsaw-puzzle block breakage is also observed in a few locations throughout the avalanche deposit, and most rounded altered clasts are found within the basal layer. Here again, no co-eruptive ash has been found within the deposits suggesting that no magmatic explosion was

Fig. 10. Block/matrix unit within Las Isletas RAD, and jigsaw-puzzle fracturing. Note how brecciation tends to increase from core to border.

associated with the collapse event.

For El Crater rockslide avalanche, we do possess historical evidence dating from the Spanish conquest. Juan Lopez de Velasco from 1571–1574 AD writes 'Four leagues away from the city there was an Indian village named Mombacho, close to a smaller volcano, which one night collapsed during a big water and wind storm in the year 70 [note: 1570], and a whole side fell onto this village'. In turn, Juan de Guzman in his 'Georgicas' (1586) gives the following description 'One morning, two hours before sunrise, the summit of the mount was torn and fell onto the village, and consequently destroyed and covered it with so much soil and rocks, that it is today invisible'. Finally, Antonio de Ciudad Real, also in 1586, wrote: 'the Mombacho volcano, which, in the past years, collapsed in the region of the southern sea, and expelled so many rock mounds that a village of four-hundred Indian neighbours was devastated, with only one person escaping. This person, having seen the big preceding earthquakes, and not knowing what they meant, went to inform the Spanish in Granada, and, meanwhile, the collapse occurred.'. These texts provide us with some valuable information: first, it seems the collapse occurred in 1570 before dawn and devastated an Indian village with around 400 inhabitants. Second, large earthquakes preceded the flank collapse, and the avalanche was accompanied by a big storm.

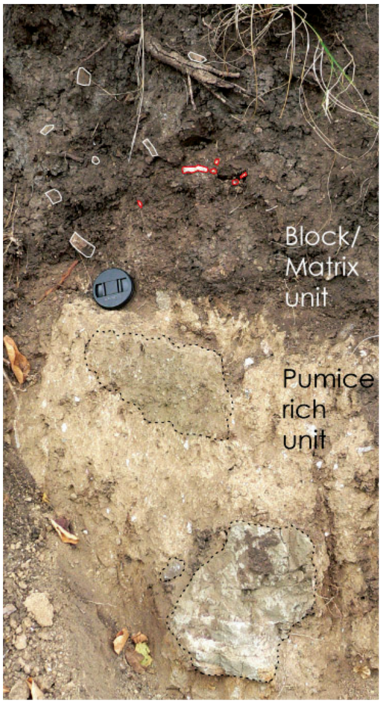


Fig. 11. Contact between the Las Isletas rockslide base (bottom) and block/matrix unit (top). A couple of blocks of the lapilli-rich unit (outlined in dotted black) are enclosed within the pumice-rich base. Pre-Colombian ceramic (outlined in white) and bones (outlined in red) are found in this particular area or the deposit.

## Why dormant volcanoes collapse…

The Las Isletas and El Crater rockslide avalanches share a certain number of similarities. Both have lobed, spoon-like shapes that are characteristic of unrestricted spreading of the rock mass. They reached nearly the same distance, which is not too surprising considering both collapsed from similar heights. The presence of countless hummocks on their surface illustrates not only that the bulk of the mass deformed in the frictional regime (i.e. fault-forming regime), but also that extension dominated during transport. These observations coupled with the fact that both show evidence of intense shearing at the base (rounding and abrasion of clasts) and brittle deformation (jigsaw-puzzle structures) within the overlying units, altogether support a plug-flow model where a carapace rides an intensely deformed lubricating layer. Lastly, and possibly most interestingly, it appears that no eruption was associated with either collapse. This has strong implications for hazard assessment around volcanic regions: inactive volcanoes may possess as much destructive potential as active ones under certain circumstances. In order to better understand how Mombacho came to collapse twice without erupting needs to be further explored; this is achieved by ex-

Fig. 12. The altered block/matrix unit in El Crater deposit with a large block that has undergone jigsaw fracturing. Here again, the outermost layer of the block suffered most brecciation. Most of the clays forming the matrix are hydrothermal clays originating from the Mombacho core.



 

**Fig. 13.** Contact between the basal extremely altered unit of El Crater deposit with the block/matrix unit. At this particular location, the block/matrix unit encloses much less altered clays compared to Fig. 12.

amining differences between the two events. When looking at Mombacho from above, the most obvious difference lies within the geometry of the amphitheatres left by both flank collapses (Fig. 14). The north-eastern scar is U-shaped close to the summit and diverges outwards, cutting the flanks down to their base. Not by coincidence, at this location, the base of the volcano is surrounded by the anticline fold that was most likely constructed as Mombacho was slowly spreading outwards. Another interesting feature of the Las Isletas collapse not observed at El Crater is the involvement of pumice-rich substrate at the base of the slide. The latter unit originates from the Apoyo ignimbrite and only crops out at locations further than the initial anticline location. These observations all suggest a mode of collapse already observed at other volcanoes (e.g. Socompa, Chile/Argentina): initially, the substrate is being folded and pushed upwards, and serves as a buttress that reinforces the volcano structure. As more and more load is added to the flanks, and as the edifice pursues its outward movement, the fold structure eventually fails, cutting through the extruded substrate and producing a rather shallow but long collapse. In contrast, at El Crater, no substrate was involved in the rockslide, and there is a gross grading from materials in their most extreme hydrothermal alteration state at the base to less altered

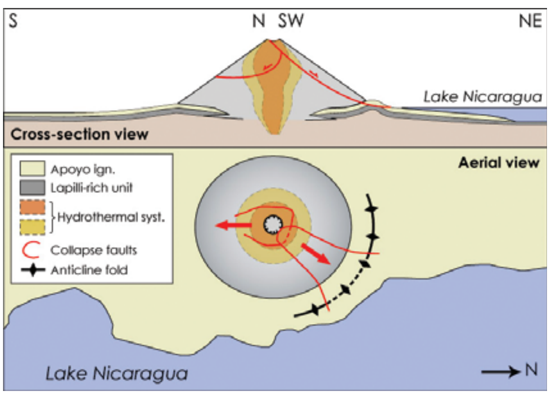


**Fig. 14.** Interpretative sketch of the structural configuration responsible for collapse of both sides of Mombacho. The north-eastern sector collapsed due to extrusion and destabilization of the underlying Apoyo ignimbrite substrate while the southern flank collapsed due to extreme hydrothermal alteration and edifice core weakening. Hydrothermal alteration within the volcano core is shown according to the different lithologies observed within deposits as moderately altered (yellow) to extremely altered (orange).

rock towards the upper units. The scar corresponding to the collapse is horseshoe-shaped and incises the edifice much deeper than its north-eastern equivalent (Fig. 14). This suggests that the El Crater side failed due to intense hydrothermal activity and edifice core weakening, and that the lowermost, clay-rich altered base served as a lubricating layer much like the pumice-rich unit at Las Isletas.

There are several lessons that can be learned from studying such massive destructive events within the life of a volcano: first, volcanoes having shown no signs of activity for a long period of time are still a threat to surrounding populations. In particular, edifices built dominantly on soft substrates are more prone to be weakened by outward spreading, which in turn may allow a vigorous hydrothermal system to develop, further destabilizing their structure. Spreading also causes anticlinal systems to appear at the base of the flanks, which may in turn facilitate mass failure. Second, investigating surface and internal structures provides invaluable information on avalanche transport mode: through the sliding of a brittle-like carapace over a ductile lubricating layer it becomes possible to reconcile the observation that both extension (hummocks) and moderate deformation (jigsaw-structures) occurs within the bulk of the rock mass, and extreme deformation and shearing at the base. Lastly, it seems that in order to generate rockslide avalanches, two main ingredients are required: a slow weakening process (hydrothermal alteration or spreading and folding), and a quasi-instantaneous trigger (such as an earthquake).

## Suggestions for further reading

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