Surface Process Hazards Unit 1: Slope failure and society – case studies from Peru and Italy

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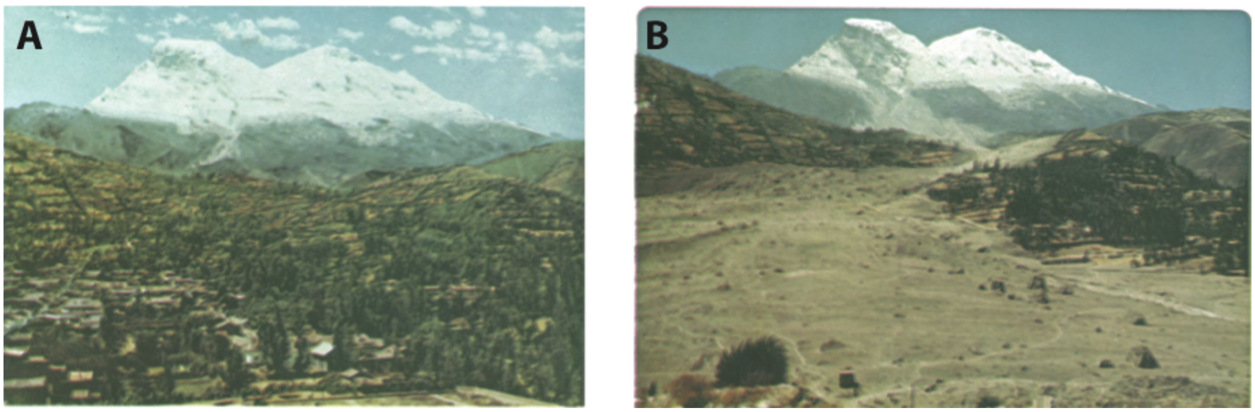
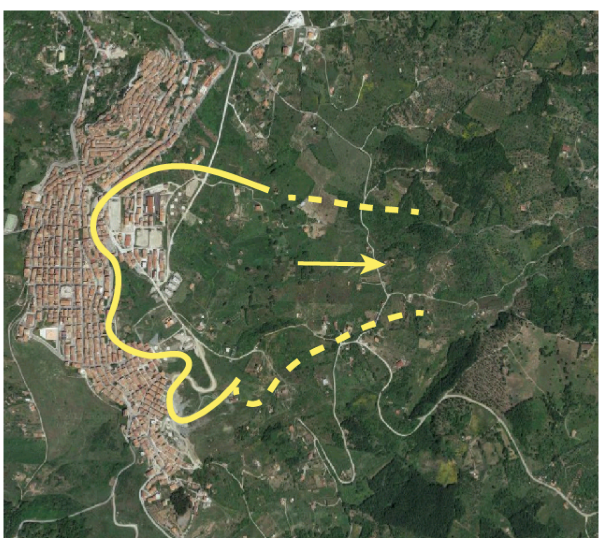
You have been provided with two case studies about the causes of and responses to major landslides that affected communities in South America and Europe. Read the case studies and study the corresponding images. When you are finished, you will be provided with some discussion questions based on what you learned and thought about as you read the articles.



The town of Yungay, Peru and surrounding rural area with Huascarán in the background before (A) and after (B) the May 31, 1970 debris flow. Courtesy of the National Information Service for Earthquake Engineering, University of California, Berkeley. http://nisee.berkeley.edu/elibrary/Image/S3809.*



Approximate area of mass movement in San Fratello, Italy in 2010. Base image from Google Earth. Figure after Figure 3 in http://sgi1.isprambiente.it/geoportalenews/sanfratello/Relazione_San_Fratello.pdf

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Case Study 1: Nevado Huascarán (Peru), May 31, 1970

Figure 1. Nevado Huascarán, the highest peak in Peru (elevation 6768 m). The scar of the ice/rock avalanche is evident on the north peak (arrow). Image S. Hall.

Summary and location of the event

Nevado Huascarán is the highest peak in Peru and second highest in all of the Andes Mountains (Figure 1). Rock and ice falls originating from Nevado Huascarán have occurred throughout history and will likely continue to occur with ongoing glacier melt and active seismicity in the area (Figure 2). Coincident with a magnitude 7.9 earthquake on May 31, 1970, a "rock avalanche" (rock and ice fall) from the west face of the north peak (primarily granodiorite with fractures and joints throughout) converted into a high-velocity debris flow (mud and sediments) which buried towns along the Rio Santa valley on its way to the Pacific Ocean, ~150km (~93 miles) away.

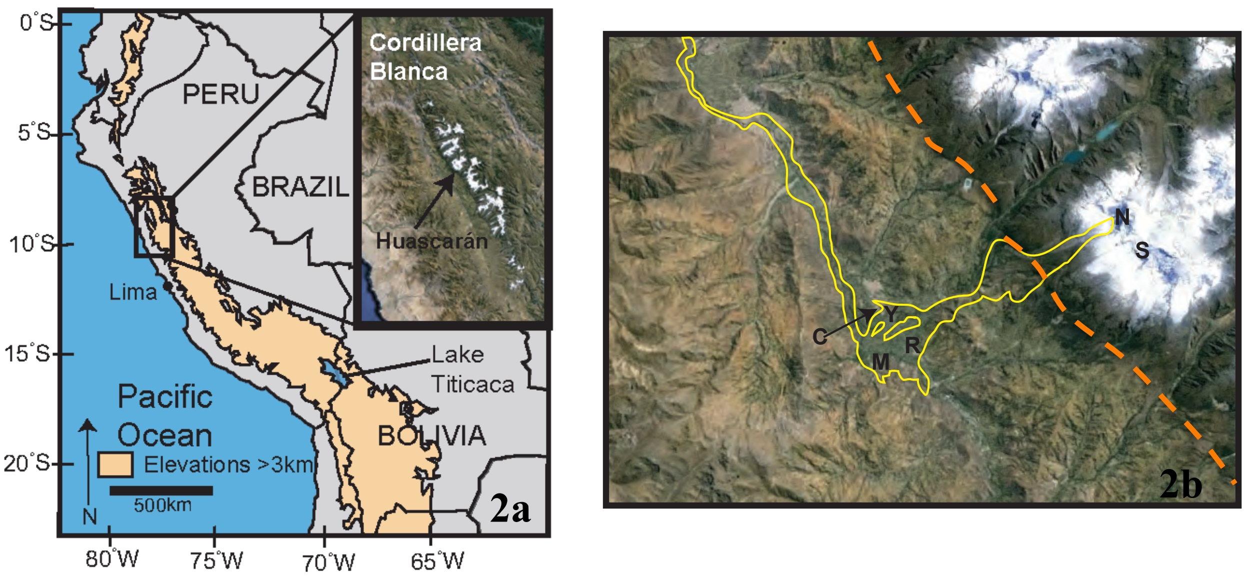

Figure 2. (a) Location map of the Cordillera Blanca in north-central Peru. **(b)** The central portion of the Cordillera Blanca containing the highest peaks in the range, the north (N) and south (S) peak of Nevado Huascarán. These peaks, as well as other nearby glaciated peaks, have sourced many rock avalanches during at least the Pleistocene. While there have been few seismic events along the active Cordillera Blanca Fault (orange line, 2b), seismicity related to subduction along the Peruvian coast triggered a rock avalanche from the north peak of Nevado Huascarán resulting in a debris flow (path shown in yellow.) The location of the buried towns are shown by letters: Y (Yungary), R (Ranrihirca), and M (Matacoto), and the location of Cemetery Hill is shown with the letter C. Modified after Evans et al., 2009; imagery from Google Earth.

Within 3-4 minutes from the start of the event, the valley towns of Yungay, Ranrihirca, and Matacoto were buried, killing an estimated 6,000-20,000 residents (Evans et al., 2009). The 1970 event was not the first time in recent history that a large rock avalanche/debris flow originated from this peak. Just 8 years earlier, a similar, although smaller, event buried part of the town of Ranrihirca. On this Sunday afternoon, many of the town residents were busy at the market or watching a football match on TV. When the earthquake began at ~3:23pm, the shaking and swaying made it difficult to walk, and the many adobe-style structures collapsed. The shaking stopped after ~45 seconds, and this is when a thunderous noise and cloud of dust was seen rising from the area near the base of Huascarán. Some say they saw the debris flow fly over a small ridge on the west side of town taking the form of a huge breaking wave. People in the town of Yungay ran towards Cemetery Hill, the high ground of town where a large statue of Jesus stands with outstretched arms (Figure 3). Many claimed to feel a very strong gust of wind just before the arrival of the debris flow. Some say the wind was so strong it stripped the trees of leaves. One account says ~90 people made it to the top of the hill in the ~3 minutes they had between when the strongest shaking stopped and when the debris flow buried the town (Cluff, 1971).

Figure 3. (a) Cemetery Hill (left) and memorial gardens built on top of the buried city of Yungay. **(b)** Yungay memorial site with partially buried remnants of the old church. Images S. Hall.

Geologic, hydrologic, and geomorphic setting

A variety of geologic, hydrologic, and landscape features make catastrophic mass wasting events somewhat common in this glaciated, seismically active, high-relief landscape. The Callejón de Huaylas Valley is covered by moraine material from past glaciations and debris flow deposits from previous mass wasting events. These glacial and debris flow deposits are exposed by the action of the north-flowing Rio Santa as it moves through the subsiding valley. Water from seasonal precipitation, rapidly melting glaciers, and periodic high-precipitation events associated with the El Nino phase of ENSO also enhance the threat of mass wasting events. Erosion by the Rio Santa has exposed debris flow deposits from events that have occurred in the area during the past ~2 million-10,000 years, allowing for scientific study of past events. Scientists have found evidence in these deposits for debris flows similar in style and scale to the 1970 debris flow (Figure 4).

Figure 4 1970 debris flow deposit at the based of Cemetery Hill in Yungay, Peru. Note the large angular clasts in a fine-grained matrix. Image S. Hall.

Tectonics also play a role in triggering mass wasting events in the area. The trigger for the 1970 event was a large (magnitude 7.9) subduction zone earthquake along the Peruvian coast where the Nazca Plate subducts beneath the South American Plate (Figure 5). In addition, the Cordillera Blanca Fault, located approximately 5 km (3 miles) from the peak of Nevado Huascarán on the western side of the Cordillera Blanca Range, poses a seismic threat to the region. Although very little historical seismicity has been recorded along this structure, scientists have identified fault scarps that offset ~16ka moraines, indicating that the fault has been active in the recent geologic past (Farber et al., 2005).

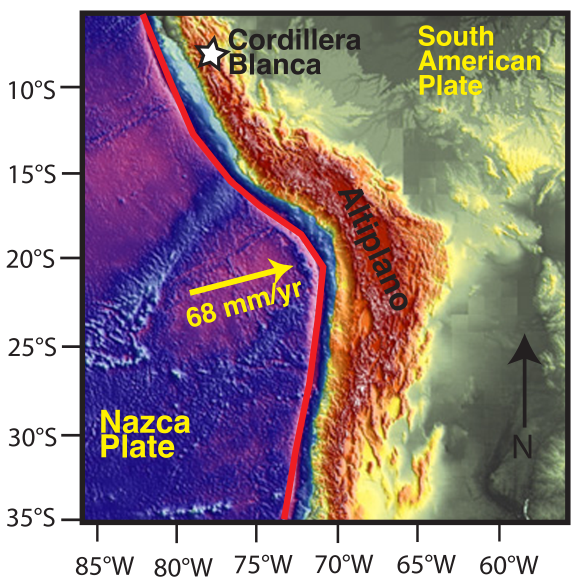

Figure 5. Physiographic map of western South America and the Pacific Ocean. The red line indicates the plate boundary between the Nazca and South American Plates. This subduction zone is capable of hosting magnitude earthquakes as large as magnitude 9! Shaking from a large earthquake at the coast, such as in 1970, can be felt well inland.

Consequences on the landscape and infrastructure

In the immediate aftermath of the debris flow, ~4 palm trees stood sticking out of the mud along with pieces of the town church and a regional bus, all of which still remain in the deposit today (Figure 3b). The town of Yungay is now a memorial site where thousands of Peruvian and international visitors come each year. The surrounding area is being resettled and the town of Nueva Yungay has been established nearby, yet away from the paths of the past flows (Figure 6).

Next steps: hazards and future planning

With climate change contributing to rapidly melting glaciers and more variable precipitation patterns (Urrutia and Viulle, 2009; Schauwecker et al., 2014), we can expect an elevated risk in the future for debris flows in this high-relief and seismically active region. In addition to the risk of rock avalanches like the 1970 event, debris flows have also been generated by the overtopping or bursting of lakes that are dammed by moraines.

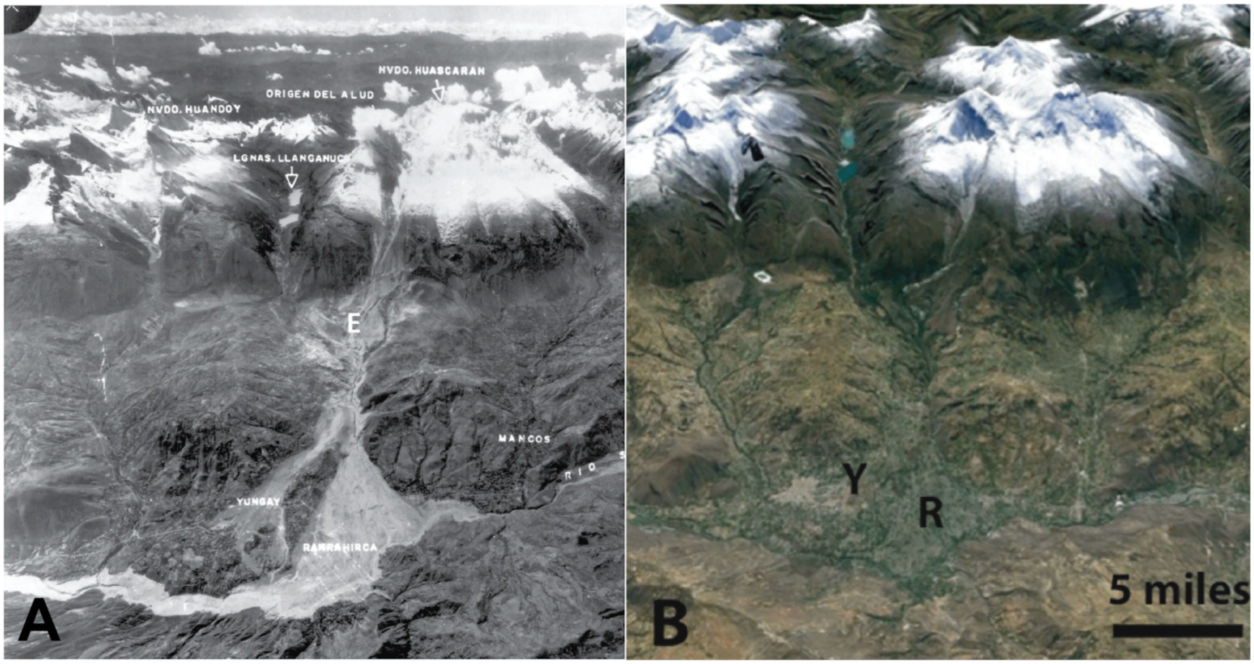

Figure 6. (a) Aerial imagery, oblique view to east, just after the debris flow. From Servicío Aerofotografíco Nacional de Perú; June 13, 1970. **(b)** Google Earth image from today, oblique view to east. Y = Yungay; R = Ranrihirca. While much of the surrounding area has been resettled and re-vegetated, the site of old Yungay remains as a memorial site.

Glacial landscapes are often full of loose sediment – moraine material, boulders, colluvium – and have lakes or bogs filling areas upstream of end moraines that cross the U-shaped valleys (Figure 7). If a mass, a block of ice, rock, landslide material, or merely a large amount of water falls into one of these moraine-dammed lakes and the lake level rises rapidly, the dam may fail or overflow, creating a flood and subsequent downstream debris flow. Many of these events historic and ancient events have been documented in this region (Carey, 2010; for more info, check this out: http://glaciers.uoregon.edu/hazards.html).

Figure 7. End moraines composed of till (a mix of clay, gravel, cobbles, and boulders) are left behind as glaciers melt and retreat up valley. Moraines such as these block the flow of water through the valley and host lakes that could burst through the moraines in an especially wet year or as result of shaking or ice/rock fall into the lake. Image S. Hall.

Following the 1970 event, geohazards assessments of several avalanches from the glaciated high peaks of the Cordillera Blanca Range were undertaken to understand the causes of the avalanches, come up with strategies for preventing avalanche-related loss of life in the future, and establish evacuation plans. In addition, extensive surveys in the region were conducted to describe and monitor all of the ~380 regional lakes and ~600 glaciers, especially when the feature is located upstream of a populated area, next to a melting glacier, or in steep terrain (most localities). In some cases, officials have lowered the lake levels as a preventative measure to alleviate some stress on the dam in the event of a water-raising event. One such monitored lake, Lake Palcacocha, is upstream of the city of Huaraz, the largest city in the Cordillera Blanca with a population of ~101,000 people. While quite rural, this region has a large population living both in the urban settings and spread out over the land farming and raising livestock. Further, the tourism industry in the region is of huge economic importance as this region is a world-class climbing destination as well as home to one of Peru's most visited national parks (Huascarán National Park) and multiple UNESCO world heritage sites.

Case Study 2: San Fratello (Sicily, Italy), February 13-15, 2010

Summary and location of the event

Figure 8. Maps showing the location of San Fratello within Italy (top left), the proximity to the Nebrodi Mountains (center), and the relationship of San Fratello with the rivers and topography of the region (top right). Imagery from Google Earth.

San Fratello is a hillside town of roughly 4500 residents in the Messina Province of NE Sicily (Figure 8). Lying on the northwest side of the Nebrodi Mountains (part of a larger range called the Apennines), San Fratello sits on a steep ridge with 2 river valleys on either side–Furiano Creek and Inganno Creek (Figure 8).

Figure 9. Infrastructure damage as a result of the 2010 landslide. ISPRA. http://sgi1.isprambiente.it/geoportalenews/Sanfratellodoc.html

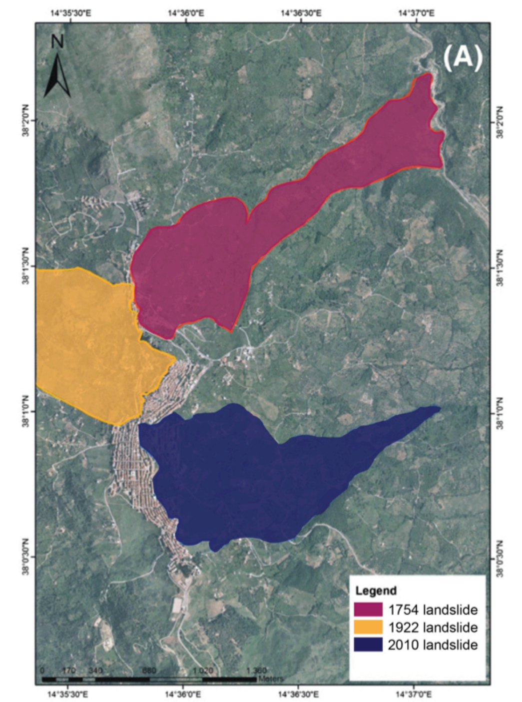

Figure 10. Area of the historical landslides in the region (1754, 1922, 2010). Modified from Bardi, et al., 2014.

On February 13, 2010, after a winter of higher than average precipitation and several days of persistent rain, ground motion began across a 1.2 mile wide area just east of town and continued moving for 2 days. The mayor reported that "they were watching the town disappear before their eyes." Ultimately, the landslide area covered approximately 250 acres. Roughly 90% of this slide area was outside of the town of San Fratello and the other 10% within a populated area including the San Benedetto, Riana, Porcaro, and Stazzone districts of town (Figure 8). Approximately 2000 people were evacuated from the area at the onset of ground motion, and although no fatalities were reported, dozens of historic and modern buildings were destroyed, and about 300 buildings sustained damage. Agricultural areas on the outskirts of town were also affected by the landslide, and much of the municipality's water, sewer, and drainage systems were destroyed. Despite the extensive property and infrastructure damage (Figure 9), residents still held their annual, pre-Easter Jewish celebration a month later. The 2010 event was not the first time that ground motion had impacted San Fratello; documented landslides in 1754 (during which the northeast portion of town was damaged); 1922 (when an area along the western hillside of the town was totally destroyed); and 2000 also caused considerable damage to the town and its infrastructure (Figure 10).

Geologic, hydrologic, and geomorphic setting

The Sicilian coastline is generally steep and dissected by river valleys. The San Fratello landslide was located in an area with a slope angle greater than 30° and has been characterized as a "complex slide" because of the geologic and hydrologic factors that contributed to the event. Geologically, the three principal bedrock lithologies in the area include, from oldest to youngest:

- Cretaceous Monte Soro Complex: quartz arenite sandstones and clays;
- Cretaceous Scaly Clays: marly claystones with decimeter-scale beds of limestone and limestone marl;
- Eocene Frazzano Complex: sandstones and clays with interbedded conglomerate, sandstone, and gneiss

Most of this bedrock geology is covered with thin (in most places, less than 10 m or 30 ft) deposits of unconsolidated clays and silty clays. The 2010 landslide occurred within this surficial layer.

Interestingly, studies of the 2010 event reveal that the slide area is not one coherent block but involved different types of movement at different depths. For example, the area that affected the San Benedetto district was characterized as a type of mass wasting event called a rotational slide with a curved slip surface located roughly 11.5 m (~38 ft) below the surface. In contrast, the area that damaged the Stazzone district had a flatter slip surface with a depth of roughly 30 feet. A slip surface was not identified for the slide area near Riana.

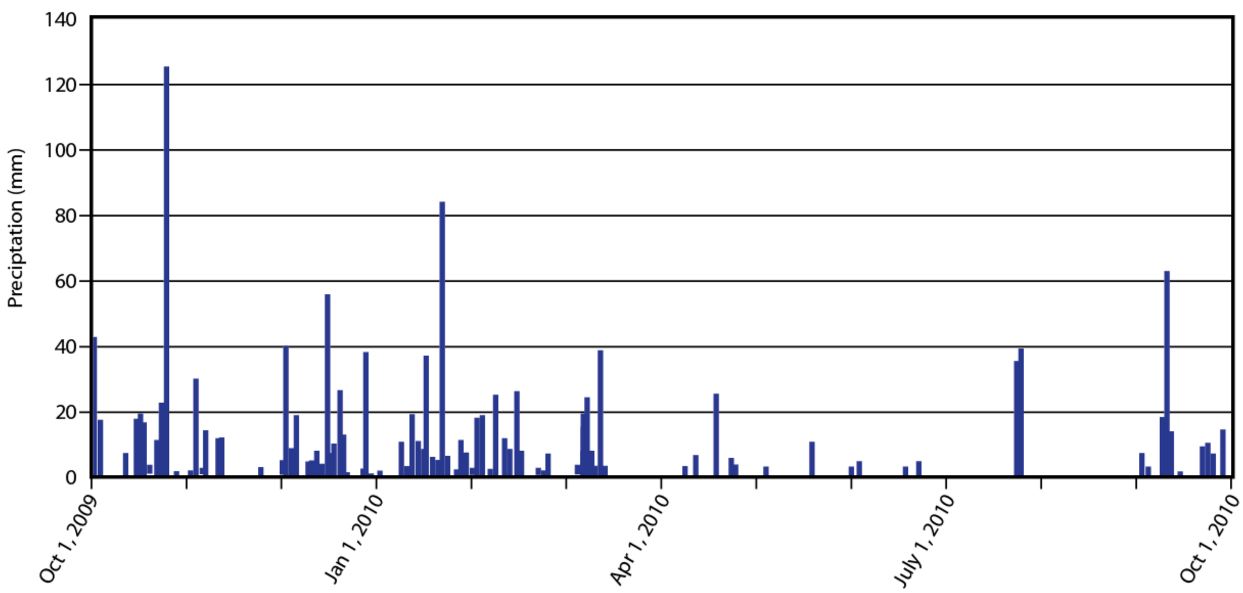

Figure 11. Precipitation data (in mm) recorded in the San Fratello area between October 2009-2010. Modified from Bardi et al., 2014.

Surface water and groundwater also played an important role in the generation of the 2010 event. The winter preceding the landslide brought approximately 35 inches of precipitation to the area from October 2009-January 2010 (Figure 11). In the 8 days prior to the initiation of the landslide, San Fratello received roughly 4 inches of rain. Scientists used borehole studies to measure the depth to the water table and found that the location of the water table corresponded closely to the location of the landslide slip surfaces.

Consequences on the landscape and infrastructure

Following the 2010 event, a variety of landslide-inducing surface features were observed in and near San Fratello, including traction cracks (the ground surface pulls away and creates a raised pattern) and extensional and compressive fractures (Figure 12). Observed landslide scarps (steep regions where the slip surface has reached the Earth's surface and caused a ground rupture–see figure 15) 5-10 m (~15-30 ft) high developed about 1/4 mile from the center of town. With the modification of the Earth's surface came rapid changes in surface water flow patterns and led to the creation of several small "landslide lakes"(Figure 13). An earth flow was generated in the lower portion of the landslide area and entered a tributary of Inganno Creek. Infrastructure damage was extensive. Water and sewer pipelines, schools, churches, and homes were damaged and in some cases, completely destroyed (Figure 9).

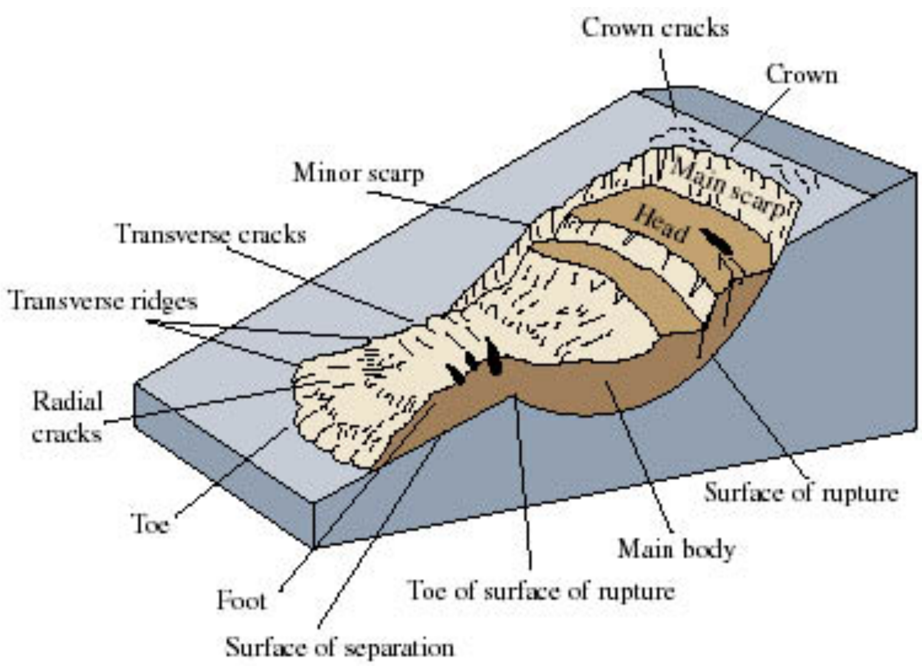

Figure 12. Diagram illustrating some of the main parts of a complex slide. Pay particular attention to the landslide crown and scarp, features mentioned in the article. From USGS.

Next steps: hazards and future planning

An important part of planning for future landslides involves understanding the causes and geographic extent of the landslides that have occurred in the area in the past. The ability to map a landslide allows scientists to identify areas of relatively low, medium, and high risk and use these hazard maps to make decisions about future land use and actions that should be taken to mitigate (decrease) the risk of life and property loss from future events. This is challenging in an area like San Fratello for several reasons. Multiple landslide events have resulted in the "overprinting" of older landslides by more recent deposits. In addition, the ground surface is partially obscured by vegetation and has been modified by environmental processes (example: erosion) and human activities (example: construction, agriculture.)

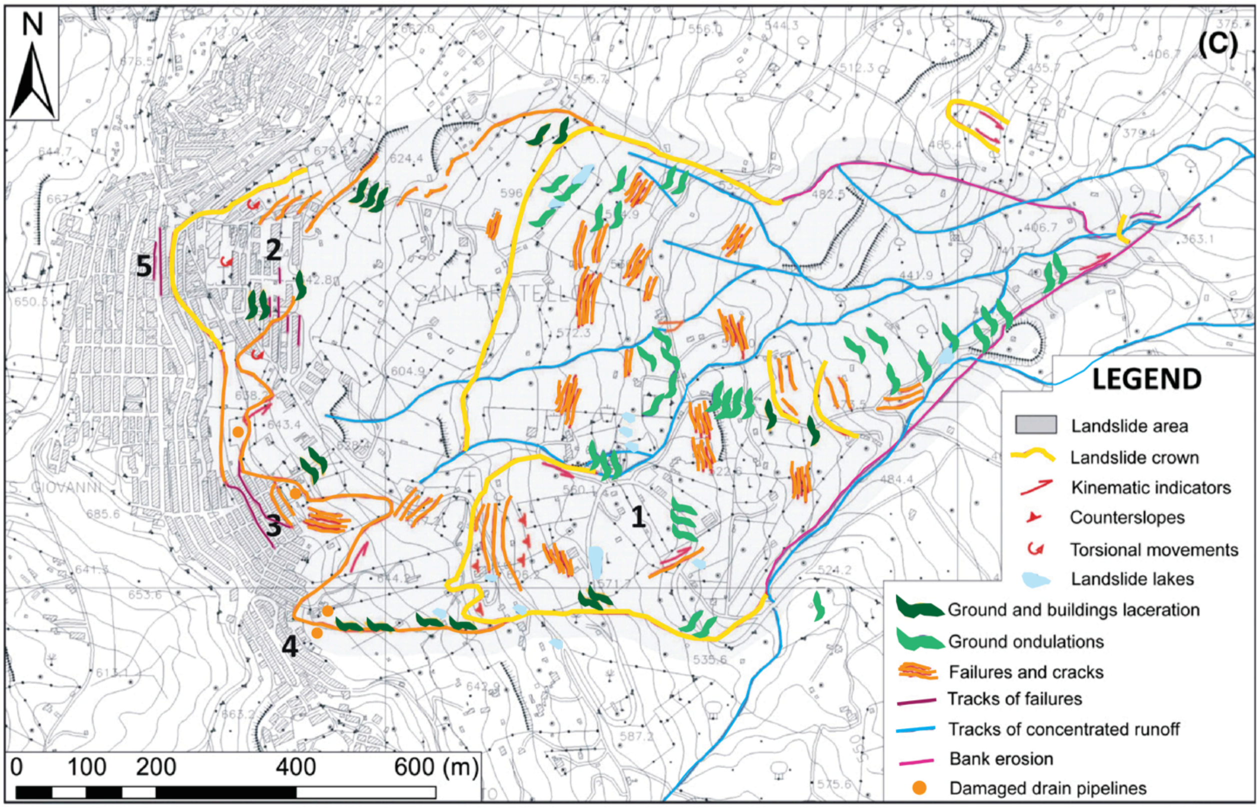

Figure 13. Map of the 2010 San Fratello landslide. Effects of the landslide, including counterslopes, torsional movements, landslide lakes, ground and building damage, erosion, and damaged pipelines are illustrated. Districts mentioned in the article are Porcaro (1); Stazzone (2); Riana (3); and San Benedetto (4). Modified from Bardi et al., 2014

A variety of strategies have been employed in San Fratello since the 2010 slide to attempt to stabilize the ground, and there are additional plans for hazard mitigation in the area. Concrete drains to collect surface water, adjacent drain pipes to transport the water, and perforated pipes to remove water from the subsurface have been installed in and around the landslide area. In 2012, several global positioning system (GPS) receivers were installed on buildings and drainage wells within the landslide area to monitor ground movement. Research using a geodetic technique called InSAR was also conducted in the area to measure the amount of ground displacement that occurred between 2010 and 2013. The study results provided valuable information related to understanding the extent of the landslide and documenting that slow ground deformation continued years after the onset of ground movement in 2010 (For more, see Bardi et al., 2014). In particular, the InSAR data suggest that the greatest amount of ground deformation within the study area occurred in the San Benedetto (2294 mm, or ~7.5 ft, of displacement!) and Porcaro (2178 mm, or ~7.1 ft) districts. In contrast, the Stazzone and Riana quarters experienced 604 mm (~2 feet) and 545 mm (~1.8 ft) of displacement, respectively, during the study period.