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Analyzing the evolution of the Tessina landslide using aerial photographs and digital elevation models

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Abstract

Evolution of the Tessina landslide near Belluno, Italy, from 1954 to the present situation has been documented using multitemporal landslide maps. The maps were produced through the interpretation of sequential aerial photographs and direct field-mapping of the landslide in 1998 and 1999. The interpretations were converted to large-scale multitemporal topographical maps and digitized, resulting in detailed geomorphological maps of the Tessina landslide for the following periods: 1954, 1961, 1969, 1980, 1991, 1993, 1998 and 1999. A quantitative volumetric analysis was also carried out using a series of digital elevation models derived from the available 1:5000 scale digital contour maps with 5-m contour interval for 1948, 1964, 1980, 1991 and 1993. The total volume of material removed and accumulated was calculated for the entire Tessina landslide for the different time steps available. Results indicate that the Tessina landslide existed prior to its main reactivation in 1960, after which the landslide reduced in activity. From 1991, however, very large reactivations have taken place, and the landslide continues to be active. Although the landslide has reached the lateral boundaries of the old pre-1960 landslide, it is now expanding upslope where it may still mobilize large amounts of material.

Keywords: Sequential analysis; Landslides; Digital elevation models; Geographic information systems; Airphoto interpretation

1. Introduction

The Tessina landslide, located in the Alpago area near the city of Belluno in Northeastern Italy (Fig. 1), was triggered on 30 October 1960 by a rotational slide following a period with heavy rainfall (Mantovani et al., 2000). In the following 4 years, several reactivations took place leading to the formation of a mudflow in the downstream section, which eventually came to a standstill 600 m from the village of Lamosano (Avolio et al., 2000).

In April 1992, the villages of Funes and Lamosano, located in the downstream part of the Tessina landslide, were threatened to be inundated by the reactivated mudflow, resulting in the temporary evacuation of these villages (Pasuto et al., 1992). After the event, a monitoring and warning system for the Tessina landslide was implemented, with a measuring hut along the left lateral scarp and a number of measuring points located across the upper landslide area, using an automatic theodolite, wire extensometers, directional bars, echometers, piezometers, flow sensors and video cameras (Angeli et al., 1994). A concrete channel was constructed in Lamosano, equipped with a series of nozzles, through which water can be sprayed under

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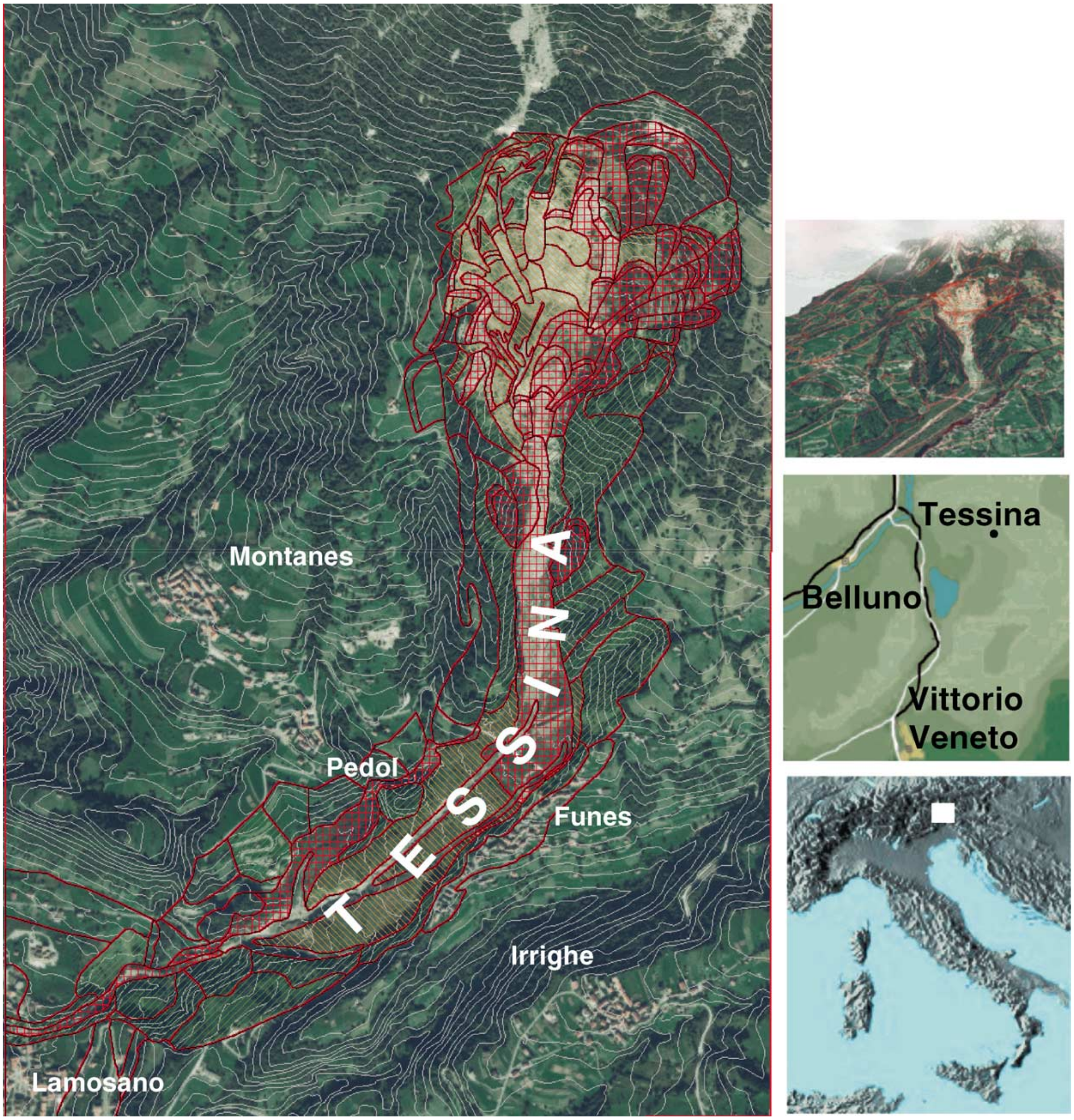

Fig. 1. Location map of Tessina landslide (bottom and middle right). Overview of the landslide area (left) and three-dimensional view of the Tessina landslide (upper right).

pressure in order to fluidize and mobilize a mudflow reaching the area and prevent it from overflowing the channel and endangering the town. In the area above the landslide, a drainage tunnel has been constructed to reduce the inflow of water. These measures did not succeed in reducing the activity of the landslide.

To further understand the origin of the landslide and its possible future development, more attention

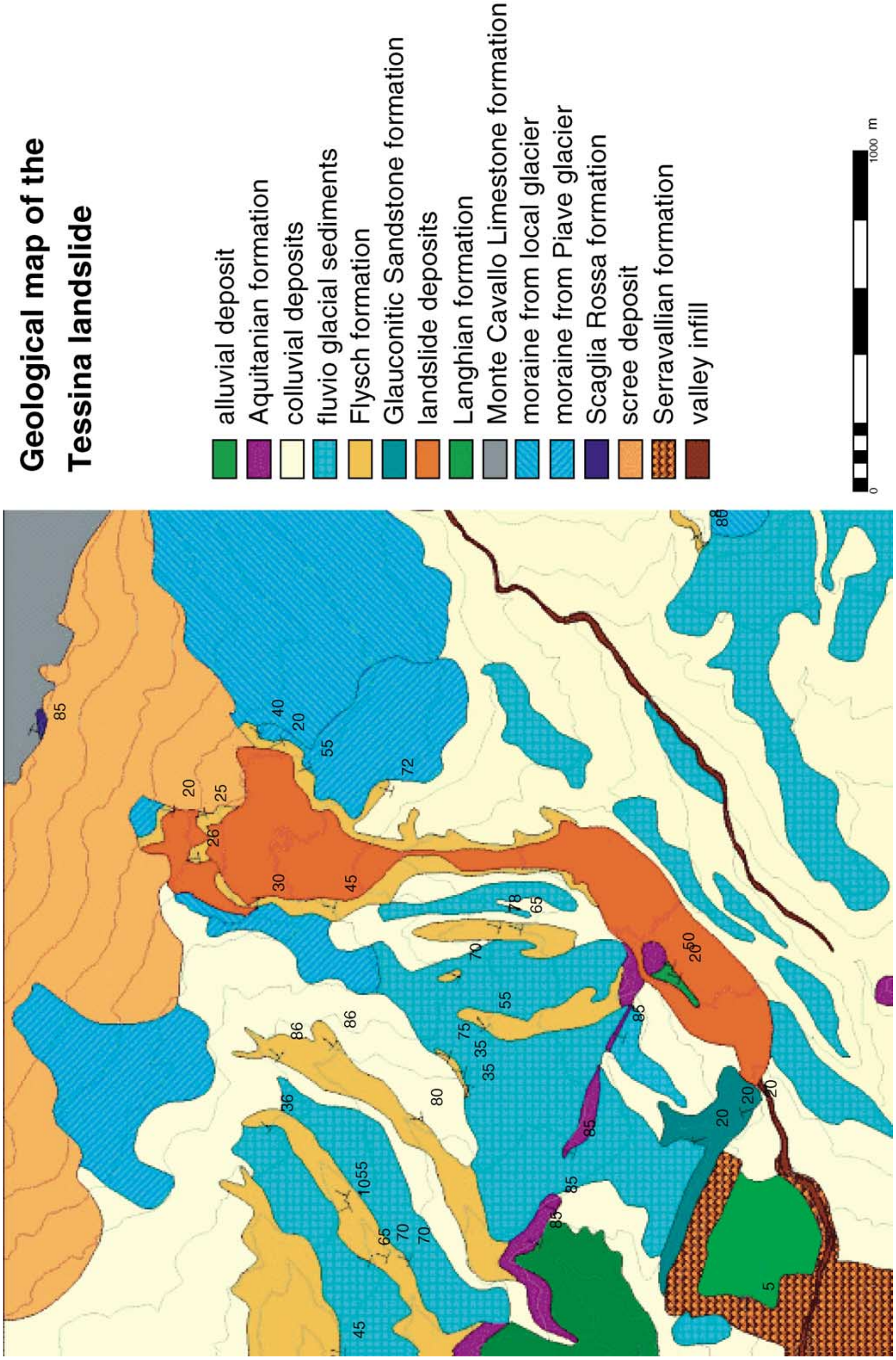

Fig. 2. Geological map of the Tessina landslide area, with dip-strike measurements.

needs to be given to geomorphological investigations. This research uses both qualitative as well as quantitative multitemporal analysis to extend the previous work on this topic carried out by Dall'Olio (1985), and includes the use of a geographic information system (GIS).

1.1. Geology and geomorphology

The slope affected by the landslide belongs to the northern flank of the asymmetrical brachysyncline of the Alpago catchment basin (Mantovani et al., 1976). The oldest rocks outcrop in the steep cliffs of Mount

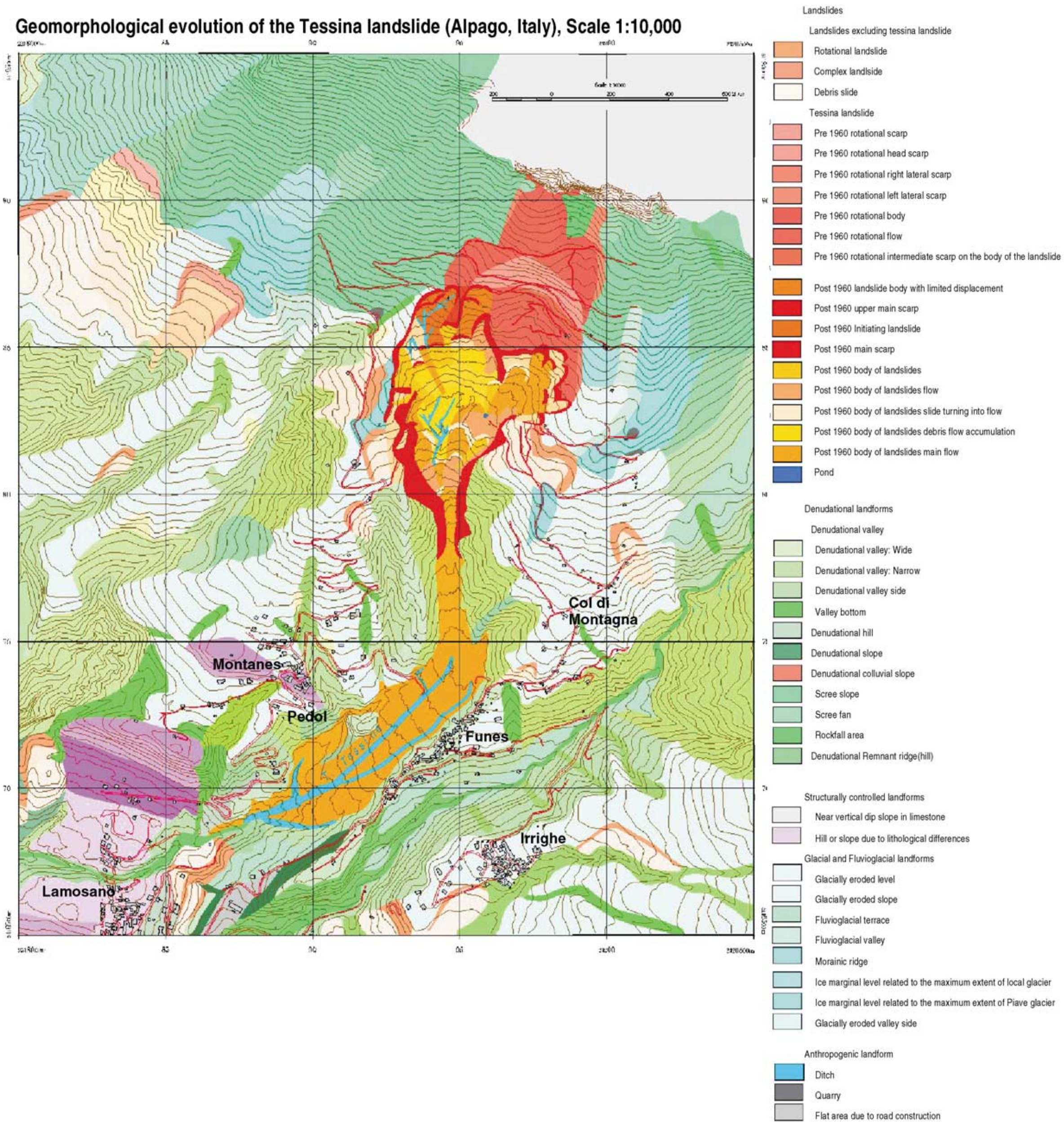

Fig. 3. Geomorphological map of the Tessina landslide area.

Teverone. They belong to the Jurassic–Cretaceous calcareous formation of Monte Cavallo (Fig. 2) and consist of bioclastic limestones (Mantovani et al., 1976). The stratigraphic sequence continues with marly and marly–limestone of the Cretaceous–Paleocene Scaglia Formations (Scaglia Grigia Formation and Scaglia Rossa Formation). Middle Eocene Flysch, a rhythmic sequence of marlstones, clay shales and calcarenitic layers up to 1 m thick, outcrops in most of the area below 1100 m. Quaternary materials are locally very thick, and cover more than 75% of the area. Ablation moraine deposits of Würm and Early Holocene age, partly of local provenance and partly derived from outside the basin, are found at an altitude around 1100 m, representing the maximum extent of the last glaciation. Large areas below 1100 m are covered by subglacial till deposits and fluvioglacial deposits. Slope deposits derived from old landslides and scree material are found extensively as well. In the NE of the study area, the scree, derived from limestone, is partly cemented. In the upper part of the Tessina landslide, geophysical surveys and boreholes have revealed one or two inverse faults, running parallel to the limestone cliffs (Mantovani, personal communication).

The geomorphological setting of the landslide (Fig. 3) is rather complex, and is partly related to the structural geology of the area and its deglaciation history (Van Westen et al., 2000). During the maximum extension of the last ice age, the main Piave glacier covered nearly the entire study area up to an elevation of approximately 1100 m, as evidenced by a series of ice-marginal complexes. A large part of the ice-marginal materials was later covered by scree. Simultaneously with the main Piave glacier, a smaller and local glacier existed East of the Tessina landslide in the valley of the Torrente Funesia. The smaller glacier did not have the opportunity to advance very far against the large Piave glacier during the maximum glaciation period. A contact zone of the two glaciers is found in the area of Col di Montagna (Figs. 2 and 3).

After the maximum phase, the regional Piave glacier, with its source area located far to the North, retreated and allowed the local Funesia glacier, with its source area directly Northeast of the study area, to advance. Intercalations of Piave and local glacier moraines have been found in the upper part of the Tessina landslide, and a large medial moraine was formed in the area of Col di Montagna. Some fluvioglacial levels were also formed during that period, partly covering the subglacial till material.

At the end of the last glaciation, the main Piave glacier retreated, leaving a series of ice-marginal levels (Fig. 3). The Funesia glacier still remained, and may have extended as far as the village of Funes, where deep drillholes revealed that the village is constructed on thick, local morainic material (Mantovani, personal communication). Due to glacial erosion and the periglacial environment, the limestone cliffs in the North of the area started to produce enormous quantities of scree, covering the Flysch and the morainic cover. Loading of the Flysch rocks by scree, together with permeability differences and the presence of a fault, created the old Tessina landslide. The landslide occurred as a series of rotational slide-blocks, with a relatively small displacement, due to the funnel shape of the landslide, causing obstruction of the blocks in the funnel outlet. Since the materials within the landslide blocks remained more or less intact, the old Tessina landslide did not develop into a flow, but remained dormant for a long period till the reactivation in 1960.

2. Qualitative multitemporal analysis

A qualitative analysis of the evolution of the Tessina landslide from 1954 to 1999 was carried out using a sequence of multitemporal maps interpreted from aerial photographs as well as direct field-mapping in 1998 and 1999. Aerial photographs were available from the following years: 1954, 1961, 1969, 1980 and 1991. Most of the aerial photographs were at a scale between 1:15,000 and 1:25,000, except for the oldest photos, which were at 1:66,000. Topographical maps were available for the following years: 1948, 1964, 1980, 1992 and 1993. Apart from the oldest map, which is at 1:50,000 scale, and with 50-m contour interval, all other maps were at scale 1:5000 with 5-m contour interval. After digitizing the contour lines were used to generate a series of digital elevation models (DEMs) with a pixel size of 2 m. The aerial photographs were scanned and orthorectified using the DEMs and a set of ground control points. For each of the available photo pairs, the geomorphological situation of the Tessina landslide was interpreted using stereo interpretation, and the interpretations were converted to the orthoimages and digitized. Each of these polygon maps had its own attribute table, with data related to the landslide type and activity. The reclassification of the polygon maps resulted in detailed landslide activity maps of the Tessina landslide for the following periods: 1954, 1961, 1969, 1980, 1991, 1993, 1998 and 1999. In this study, the ILWIS package (ILWIS, 2000) was used for all the GIS operations.

2.1. Interpretation of the aerial photographs from 1954

Since there are no aerial photographs prior to 1954, analysis of the Tessina landslide starts with them. The 1954 photographs reveal that prior to the main reactivation of 1960, most of the old Tessina landslide was stable, although some small landslide activity is developing in the centre of the present landslide body, previously a shallow narrow valley (Fig. 4A). The small landslides visible on the 1954 photos were interpreted as being of the ‘‘complex’’ type, the slide started as rotational movement on the scarp and further downslope changed into a flow that went a relatively short distance down the valley.

Apart from the few small active new landslides, many old landslide masses are observed in the 1954 airphotos, but their age could not be established. A number of rotational slide masses extend upslope to the vertical limestone cliffs. The scree slope beneath shows a slight inclination toward the cliffs, opposite to what would be expected from a normal screeslope, which is an evidence for back-tilting (Fig. 4B). On the Eastern part of the landslide, a clear scarp extends from the scree slope to the upper right sector of the present landslide. From this evidence, we concluded that the old Tessina landslide had extended all the way up to the limestone cliffs, considerably larger than in 1999. The western part of the old landslide is now buried underneath a large scree fan, which does not show clear evidence of displacements. From this, we conclude that the pre-1954 Tessina landslide is probably quite old, from early Holocene, before the main production of scree deposits covered it.

2.2. Interpretation of the aerial photographs from 1961

The most important reactivation of the old Tessina landslide, which started on October 30, 1960, can be observed on the 1961 airphotos (Fig. 4B). The activity, visible in its initial stage on the photos from 1954, started in the lower part of the landslide and advanced toward the present left lateral scarps. The multiple rotational landslides changed into a large mudflow that extended down to the village of Funes, filling-up the preexisting fluvial valley to a considerable height. The reactivated Tessina landslide (post 1960) had a different movement mechanism than the old one, which was estimated to be of early Holocene age, and which failed as a number of clearly recognizable slump blocks, without transforming into flows as did the recent reactivations. This is probably due to the fact the old landslide occurred in less-weathered Flysch deposits overlain by scree and moraine. As a result of the mechanical disintegration caused by the old landslide, the weathering of the Flysch materials in the old landslide masses was high, also because it is located in an area of abundant ground water, from the karstified limestone masses upslope. The reactivation took place in highly weathered landslide materials with low residual strength. The left lateral active scarp follows exactly the road, which was damaged during the 1960 event, which might be an indication that improper drainage from the road contributed to the 1960 reactivation.

2.3. Interpretation of the aerial photographs from 1969

A large new landslide area in the 1969 airphotos is almost double that of the 1961 photos. In its lower reaches, the Tessina landslide had reactivated to the limit of the old complex (Fig. 4C). In the years 1961–1965, several reactivations took place with nearly similar magnitudes as the initial one from 1960 (Mantovani et al., 2000). Although the region was struck by disastrous flooding in 1966, the landslide did not show any significant activity, and up to 1987, no major movement was reported. The head, right lateral and left lateral scarps in the 1969 photos are generally characterized by multiple rotational and complex landslide types. The mudflow in the downslope part of the Tessina landslide had increased in size, and passed along both sides of a higher part of the valley, leaving this area standing as an island within the mudflow masses (Fig. 4C). The mudflow was sufficiently high to endanger the village of Funes. The road, which con-

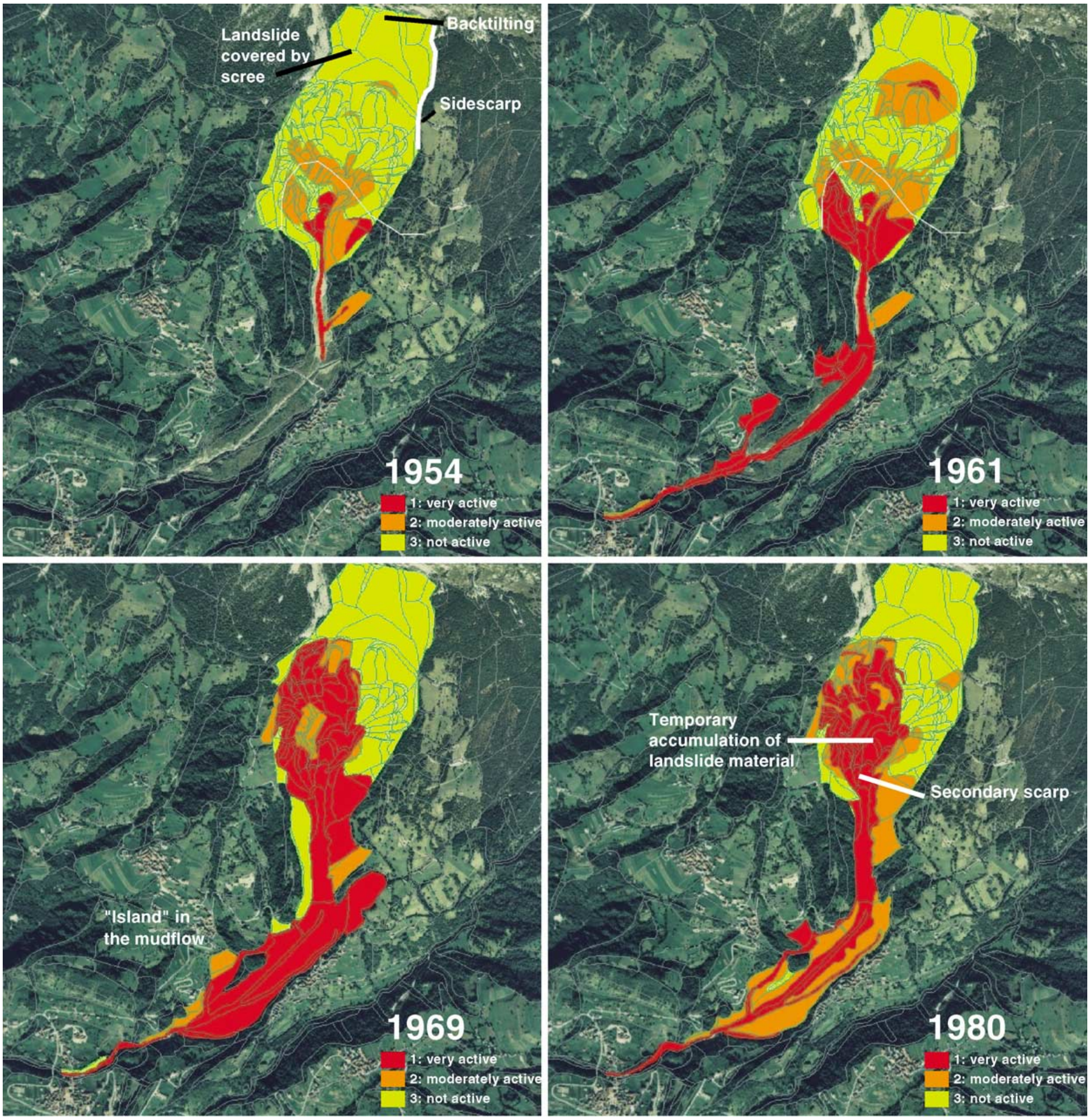

Fig. 4. Tessina landslide activity as mapped from aerial photographs. (A) Upper left, 1954. (B) Upper right, 1961. (C) Lower left, 1969. (D) Lower right, 1980.

nects the villages of Pedol and Funes, was totally destroyed. Further downstream, the mudflow narrowed near the town of Lamosano towards the mouth of the Tessina valley. Not only a large part of the old Tessina landslide reactivated in the period before 1969, but also many small landslide events are visible along the right side of the mudflow filled valley near Funes. Unlike the 1960 event which nearly only involved weathered Flysch, moraine and scree deposits were also involved in the landslides visible on the photos from 1969.

2.4. Interpretation of the aerial photographs from 1980

From the 1980 photos, no major morphological differences from 1969 could be observed, except for a general decrease in activity (Fig. 4D). The active rotational landslides visible in the 1969 photos were still active in 1980, as evidenced by the lack of vegetation and the existence of open cracks. The right lateral, left lateral and head scarps of the Tessina landslide had been reactivated slightly. But no large volume of materials was removed. In the center of the landslide, a large volume of material coming form the slide masses above was present in a temporary accumulation area, bounded downslope by a secondary scarp from which the various flows merged into the main mudflow in the valley downstream. Due to the funnel shape of the depletion area, most of the landslide materials coming from the rotational landslide upslope are concentrated temporarily before they are removed through a narrow channel and contribute to the mudflow downslope. Prior to 1980, a number of artificial drainage channels were constructed on the main flowmass to drain surficial runoff in an attempt to dry out the flow. The main flow extended down to the reconstructed road, connecting Funes and Pedol and caused relatively minor damage to it, whereas the old flow between this road and Lamosano showed no signs of activity.

2.5. Interpretation of the aerial photographs from 1991

The 1991 airphotos were taken before the main reactivation of December. In August 1990, there was a fresh movement of the upper part of the landslide's eastern sector. Following this event, a flow was active during 10 days moving some 200 m in the lower accumulation area (Pasuto et al., 1992). From these photos, only a slight reactivation of the previous landslides can be interpreted, and the rest of the area was changed little (Fig. 5A). The landslide accumulation was reactivated as a flowslide, and the new flow stopped before the Funes–Pedol road. Both depletion and accumulation zones are relatively more vegetated than in the 1980 photos. The valley sides of the Tessina landslide also are more vegetated by grasses and shrubs.

2.6. Interpretation of the main reactivation in the period 1991–1993

Although no new aerial photographs were available after 1991, the Tessina landslide was known have reactivated in 1992 (Pasuto et al., 1992). In December 1991, perhaps at the same time as a light seismic shock, significant movements occurred in the eastern sector of the landslide. Triggered by heavy rainfall (160 mm in 15 days) on 17th of April 1992, a large area suddenly collapsed as a multiple rotational landslide, which affected the local moraine and the Flysch substratum. The landslide material passed through the temporary accumulation zone and moved downslope as a mudflow, which reached the road connecting Funes to Pedol in just 5 days. Here, a channel was constructed across the road in order to allow the more fluid part of the flow to discharge. This mass, about 5 m wide and 1 m thick, moved at about 10 m per hour whereas the main slide was moving at the speed of about 15 m per day (Angeli et al., 1994). In May 1992, the same sector again reactivated and the flow reached an embankment built near the hamlet of Tarcogna near Lamosano. The maximum landslide advance, which was followed by a decrease in movement, was recorded on 15 June 1992. In July and August 1993, still more reactivations took place (Mantovani et al., 2000).

The features related to this 1992 event were mapped directly in 1998 using a 1:5000 scale contour map, and making using of videoimages and oblique photos from 1992. A very large reactivation was observed on the right lateral flank of the landslide (Fig. 5B). Here, the mass advanced towards the pre-1954 right lateral scarp and minor headscarp. No major change was observed on the left lateral scarp, although the small building still on top of the scarp, as interpreted from the 1991 airphotos, was now partly destroyed. This major reactivation almost doubled the size of the depletion zone. In the grass-covered areas above the reactivated landslide, a number of semicircular cracks in the morainic deposit can be observed. The 1992 events more or less coincided with landslide blocks that were previously observed in the 1954 photos, and they are interpreted as reactivations of the early Holocene Tessina landslide masses.

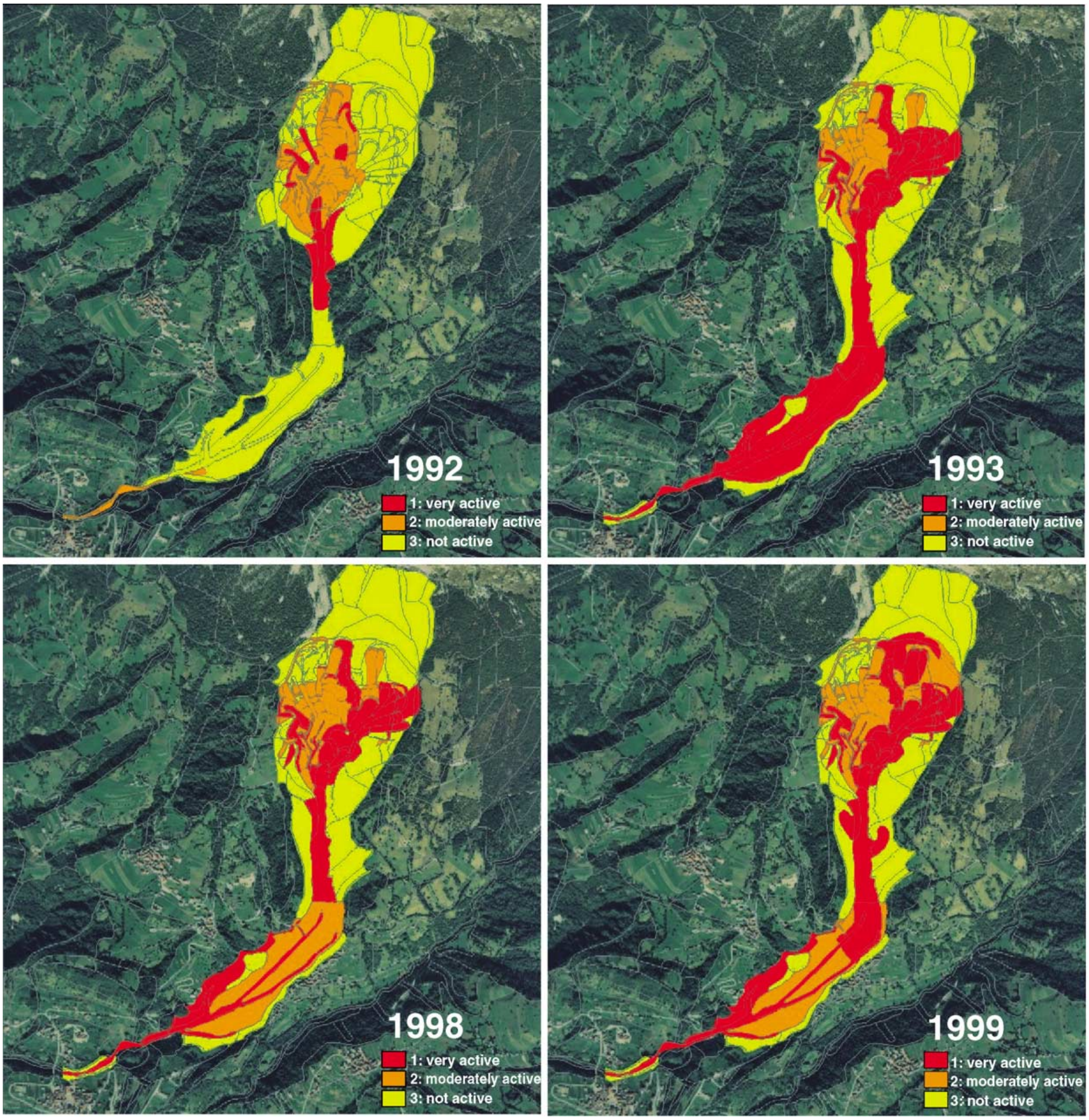

Fig. 5. Tessina landslide activity. (A) Upper left, in 1991/1992 as mapped from aerial photos. (B) Upper right, in 1993 as mapped from videoimages and oblique photos. (C) Lower left, in 1998 as mapped in the field. (D) Lower right, in 1999 as mapped in the field.

2.7. Mapping the landslide in 1998

The 1998 geomorphological map of the Tessina landslide shows how the landforms changed between 1993 and the 1998 fieldwork (Fig. 5C). In May 1995, there was a small reactivation, and the mudflow reached the village of Lamosano within 10 days.

Between 1993 and 1998, a large drainage gallery was constructed through the Monte Cavallo Limestone formation (Fig. 2) North of the landslide area.

This gallery, 1.2 km long and with a quite large average discharge, drains towards the East in a side valley. It was constructed to drain groundwater flow through the limestone, which was believed to have a major influence on the saturation of the Tessina landslide mass. However, until now, no significant decrease in the activity of the landslide has been observed. On the contrary, in 1998 and 1999, some important reactivations occurred. During the fieldwork in October 1998, the landslide moved yet again. After 4 days (from 5 to 8 October 1998) of less intense but long-duration rainfall, the right lateral scarp near the mouth of the valley and the temporary debris accumulation zone of the landslide were reactivated as flowslides. The scarp on the debris accumulation advanced inwards approximately 4–5 m, whereas on the valley sides the flow passed rapidly through a smooth slickensided channel. The existing mudflow, saturated by the rainfall, also reactivated. During this internal movement, the Funes–Pedol road started to fracture and on the next day, one side was displaced by the flow.

2.8. The landslide grows further in 1999

The latest phase, mapped by a team of the University of Ferrara represents the situation in the spring of 1999. In 1999, the landslide advanced further to the NE, reactivating the minor head scarp of pre-1954 and the right valley side near to the mouth of the Tessina valley (Fig. 5D). In 1999, the active part of the Tessina landslide was almost back to its early Holocene limits, especially in the lower part of the depletion zone. The reactivation also starts in the forested area above the landslide, covered by scree deposits. We expect the landslide will continue to grow in a northern direction toward the limestone cliffs until it will finally have reached its old boundaries (Fig. 3).

3. Quantitative analysis of the Tessina landslide

3.1. Method of analysis

The areas and volumes in the depletion and accumulation zones were analyzed quantitatively for each reactivation phase. The calculations were performed by the ILWIS GIS package (ILWIS, 2000) with the following input data:

- Multitemporal activity maps made by photointerpretation and fieldwork (1954, 1961, 1969, 1980, 1991, 1993, 1998 and 1999);
- Multitemporal digital elevation models derived from contour maps. For the Tessina area, digital topographic maps (in AutoCad DXF format) were obtained from Italian CNR for 1948, 1964, 1980, 1992 and 1993. The map from 1948 was at 1:25,000 scale with contour interval of 50 m, whereas all other maps were at 1:5000 scale with 5-m contour interval. After converting these maps from AutoCad to ILWIS, the contour lines were separated from the rest of the topographic data, coded, rasterized using a pixel size of 5 m and interpolated into a DEM.

3.2. Results

The entire pre-1954 Tessina landslide covered an area of about 121 ha. About 68 ha, including the depletion and accumulation zones, were reactivated at various times from 1954 to 1999. Therefore, about 56% of the pre-1954 landslide area is reactivated now. Volumetric analysis was also carried out for the DEMs generated from the available 1:5000 scale digital contour maps for 1948, 1964, 1980, 1991 and 1993. From DEMs derived from the contour maps, the total volume of material removed and accumulated was calculated for the entire Tessina landslide and for the active areas which were interpreted from aerial photographs. The results are shown in Table 1 and Fig. 6. Large volumes of material were removed between 1948 and 1964 during the main reactivations in 1960–1964 and from 1964 to 1980. The difference between the depletion and accumulation volumes

Table 1
Volumetric analysis for DEMs derived from contour maps

DEMs	Volume of material removed in 1000 m^3	Volume of material accumulated in 1000 m^3
1964–1948	942.2	162.5
1980–1964	162.2	100.7
1992–1980	93.2	155.9
1993–1992	8.9	19.8

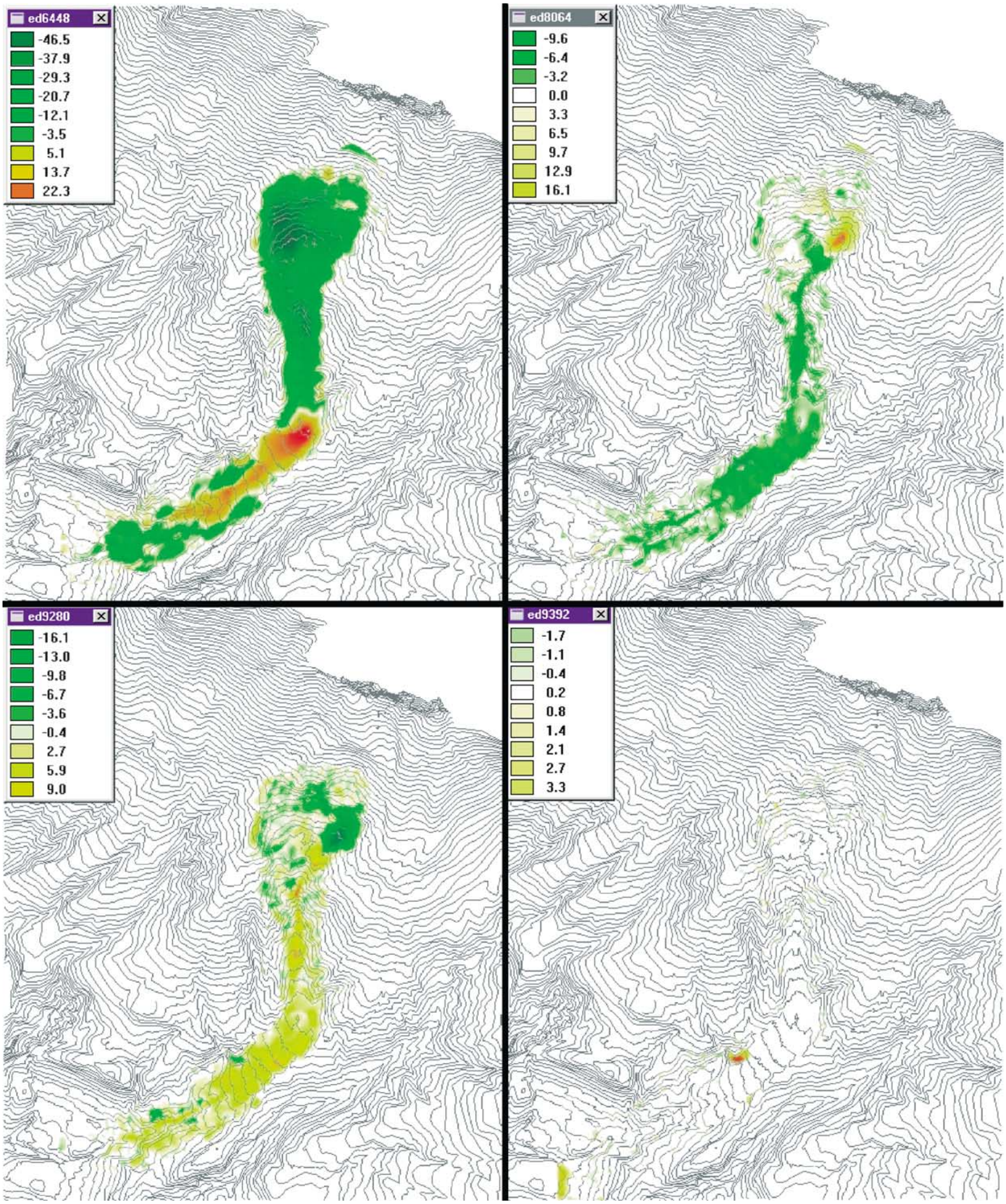

Fig. 6. Elevation difference between DEMs constructed from multitemporal contour maps. Upper left: 1964 – 1948. Upper right: 1980 – 1964. Lower left: 1992 – 1980. Lower right: 1993 – 1992.

reflect the large temporary storage zone in the lower part of the depletion area. Due to a reduction of this temporary storage area for the period 1980 to 1992, the volume of accumulated materials was greater than the total volume of materials removed.

We caution, however, that the reliability of the digital elevation models is not too high, especially for 1980. By comparing Fig. 6 with Fig. 5, it is clear that the upper right area of the Tessina landslide failed in 1992, whereas the 1980–1964 DEM comparison shows an area of extreme accumulation there. In addition, it appears that the DEMs from 1992 and 1993 are actually the same, with only minor differences. Since the original paper topomaps were not available, we were unable to check the quality of the DEMs.

4. Discussion and conclusions

The Tessina landslide development has followed its pre-1954 morphology, and all reactivations fall within the boundaries of an old landslide, which is estimated to be of early Holocene age. Reactivation originated in the centre of the depletion zone of the landslide between 1954 and 1961, whereupon its full-scale development can be observed on the 1969 and 1980 photographs. Although the 1991 aerial photo-interpretation suggests the landslide appears more stabile, field work showed the landslide area to be almost double that at the 1991 airphotos, especially on the right lateral scarp. The right lateral flank was still very active during and after the fieldwork, leading to an emergency and partial evacuation of the Funes village. In determining the causes of the Tessina landslide, detailed geomorphological work presented here as well as geological and hydrogeological surveying (Mantovani et al., 2000) led to the following conclusions.

4.1. Existence of an old landslide

The general geomorphological map (Fig. 3) and the multitemporal landslide evolution maps (Figs. 4 and 5) show that the post-1960 landslide retrogressively advanced towards the margins of the old landslide, indicating that the current Tessina landslide is actually a reactivation of an existing old landslide. Based on geomorphological evidence, this landslide was estimated to be of early Holocene age. However, C-14 dating will be required for precise age determination.

4.2. Materials and geological structure

The materials and their structural setting also contribute to movement of the Tessina landslide. The old Tessina landslide occurred due to loading of the Flysch and morainic materials by large volumes of scree. The landslide blocks in Flysch have weathered extensively, enabling the new Tessina reactivations to develop into a large flow, rather than behaving like the old landslide blocks. The faulted contact between Flysch and the Monte Cavallo limestone and the bedding of the Flysch formation might also aid movement, especially the lower older substratum where the clay and sandstone layers are dipping steeply.

4.3. Hydrogeological characteristics

The area's hydrogeology depend on the lithology and structure. Whereas the quaternary deposits are highly permeable, the underlying weathered Flysch is relatively impermeable and contains swelling clays (Michaelides, 1995). Another important factor is the high inflow of groundwater from the limestone massif upslope, which did not substantially decrease after the constructing of the large drainage gallery.

Finally, we point out that the left flank of the Tessina landslide has changed little since 1980 due to the fact that it has already reached the old landslide boundary. The right and head scarp of the Tessina landslide, however, still are advancing toward the boundary of the old Tessina landslide. Therefore, it is expected that the large upslope area, which also formed part of the old Tessina landslide, will soon start to become unstable. This warning is confirmed by other authors (Avolio et al., 2000) who have used a cellular automata model to simulate the future extension of the Tessina landslide.

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