Zusammenfassung / Rekapitulation / Gedanken zu: The 1963 Vajont landslide (Genevois & Ghirotti, 2005).

And partially: Engineering geomorphological characterisation of the Vajont Slide, Italy, and a new interpretation of the chronology and evolution of the landslide (Wolter et al. 2016)

The Vajont Landslide, with which approximately 270 million cubic metres rushed into the Vajont reservoir, caused a wave that exceeded the top of the 267 m high dam with 140 m and killed more than two thousand people. It is therefore maybe one of the most studied landslides as a lot of – not only geological - questions were left open (legal, economic, social etc.). The situation of Vajont Valley was therefore highly discussed, sometimes also controversially.

Introduction and studies before October 1963

Preceding to the beginning of the construction works only a few generic geological models exist of the Vajont Valley The dam was built between 1957 to 1960 as a double curvature thin arch dam. The top of the dam is located 267 m above the bottom of the valley and was the highest one in Europe. In the years 1959 to 1960 the geological situation in the reservoir area was first studied in detail by F. Giudici and E. Semenza (on behalf of L. Müller) and only because of a landslide which slid into the nearby reservoir of Pontesei during its first filling in March 1959. By this time, the construction works of the Vajont dam went on, but it was obvious, that the slope stability in the Vajont Valley should be analysed in detail. The results of the study of Giudici and Semenza showed:

- The sediments of the pre-existing old landslide which is situated on the left bank of the Vajont Valley filled the gorge and forced the river to shift. The main deposit of the landslide mass remained on the left side, while a portion stayed on the right – named as “Colle Isolato” it was the only distinguishable from the in situ rock mass.
- Outline of a zone with uncemented cataclasites at the base of Pian del Toc
- Chair like structure of the bedding planes of the slope
- Fault separating the in-situ rock mass from the old landslide on the eastern part of Pian del Toc
- Definition of the shape and the perimeter of the failure surface of the old landslide and the possibility of a reactivation during the filling of the reservoir

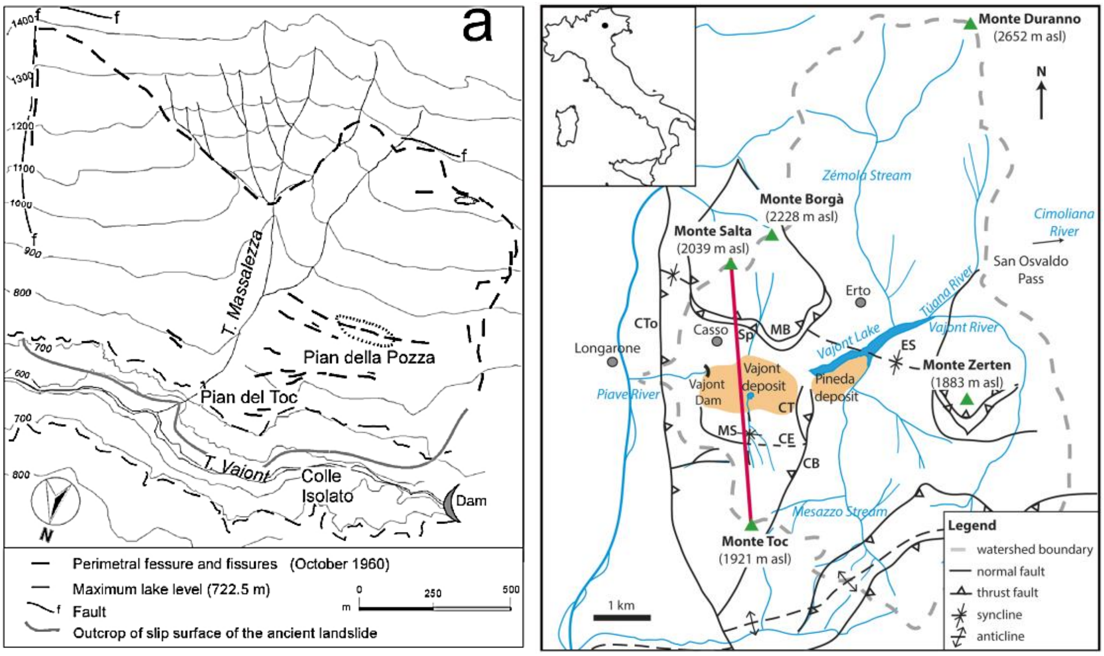

Fig. 1: left: Overview of the study area and its geologic features before 9th October 1963 (Genevois & Ghirotti, 2005), right: Overview of the region of the Vajont valley with the geologic structures, the Vajont deposit as well as the 1959 Pineda deposit are highlighted in orange (A. Wolter et al., 2016)

The presence of the old landslide was not accepted by the majority of the scientific community and neither by the experts accompanying the construction works. This was due to the shape and appearance of the landslide mass material – it showed almost no internal deformation with undisturbed data.

→ Nowadays it is known, that landslides can preserve the strata in the landslide body.

Furthermore, the designers of the dam thought that a big resp. deep-seated landslide would be very unlikely due to the asymmetric form of the syncline. It was concluded, that it would act as a natural break on slope movement.

Chronology of the landslide movements

Based on the study of Semenza, Müller suggested at leas some of precaution measures, which consisted in daily topographical surveys of the superficial movements and the adapted controlled changes of the water level in the reservoir according to the observed movements. The different movement steps are listed below.

- March 1960: Reservoir level at 590 m a. s. l. (equals the toe of the old failure surface) – surface movement began
- June 1960: Reservoir level more than 600 m a. s. l. – start of mass movement of the old landslide closest to the lake, three boreholes drilled to examine the failure surface (but the boreholes were not deep enough)
- End October 1960: Opening of a continuous crack – ca. one metre wide and two and a half kilometre long. The movement rate exceeded 3 cm / day. The transition zone from stable in-situ rock to a fractured rock mass – which corresponds to the upper boundary of the old landslide was figured out by a second study of Semenza at a height of 920 m a. s. l.
- 4th November 1960: Reservoir level around 650 m a. s. l. – a landslide of about seventy-thousand cubic metres from the old deposit slid into the reservoir. The wave reached a hight of ca. 30 metre. The reservoir level was then lowered to 600 m a. s. l.. Furthermore, a by-pass tunnel was constructed. The lowering of the water level in the reservoir needed a clear observation of the "Colle Isolato" (underlying gravels of the old Vajont River).
- July to October 1961: Installation of four piezometers
- October to December 1962: slow raise of the water level in the reservoir up to 700 m a. s. l. – movement rate more than 1.5 cm per day
- December 1962 to March 1963: lowering water level in the reservoir to 650 m a. s. l. – movement stopped
- April 1963: start of a water level raise – movement starting with water level at 700 m a. s. l.
- April to September 1963: further raise of the water level to 710 m a. s. l. despite the slow movements of about 0.5 cm per day (1.8 m per year)
- Early September 1963: Increase of the movement to 1.0 cm per day.
- Beginning of October 1963: Increase of the movement to 4 cm per day and an anew beginning to lower the water level in the reservoir with an increased movement of about 20 cm per day at that moment
- 9th October 1963, 22:39: failure of the southern rock slope of Monte Toc over a length of 2 km. The mass slid about 300 to 400 m horizontally with a 250 m thickness.

➔ Today with an advanced knowledge and a much more implemented risk management the "play" with the water levels in the reservoir and the different movement velocities without further studies appears really questionable.

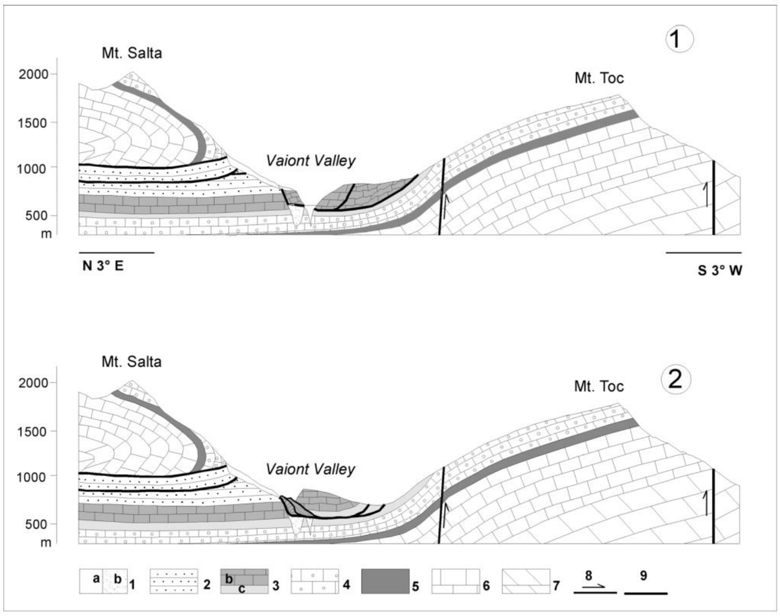

Fig. 2: Profiles through the study area before (1) 1963 and after (2), 1) a Quaternary; b stratified alluvial gravels; 2) Scaglia Rossa Fm. (Upper Cretaceous - Lower Paleocene); 3) Cretaceous-Jurassic Fms. (Socchér Formation sensu lato and coeval): b) Socchér Fm. sensu stricto, c) Ammonitico Rosso and Fonzaso Fms.; 4) Calcare del Vaiont Fm. (Dogger); 5) Igne Fm. (Upper Liassic); 6) Soverzene Fm. (Lower and Middle Liassic); 7) Dolomia Principale (Upper Triassic); 8) Faults and overthrusts; 9) Failure surfaces of landslide (from SEMENZA & GHIROTTI, 2000).

Interpretations of the landslide mechanisms

Since the 9th of October 1963 a lot of research work has been done and not all of them are single-minded about the importance and the influence of the controlling mechanisms of the landslide. Some of the conclusions of the studies are listed below (list by far non-exhaustive):

- Müller (1964): Change in behaviour of the landslide due to slight exceed of driving forces due to joint water thrust or decrease in resisting forces (buoyancy and softening of clayey substances)
- Kiersch (1964, 1965): considered the existence of a prehistoric landslide as well as of a weak zone of fractured rocks (de-stressing effects) and supposed the actual trigger to be a rise in subsurface water level from bank infiltration (increased hydrostatic uplift) and increasing swelling pressures (eg. clays).
- Selli et al (1964): comprehensive work on the Vajont landslide (geological characteristics). Stated a pseudo-plastic behaviour and an appearance of secondary shear surfaces at the base of the landslide. Cause of the landslide due to geological structure, the morphology of the slope and variations in water level of the reservoir. Movement velocity stated to have been about 17 m/s.
- Mencil (1966): significant strength loss was needed to explain the high velocity of the landslide. Which factors lead to the acceleration of the movement in such a short time?
- Broili (1967): analysis of the three borehole logs – no clay beds or intercalations "may have been responsible for some aspects of the phenomenon"

➔ Therefore, it would be interesting: how the locations of the drillings were defined, how and who decided about the depth of the boreholes, why wasn't the depth of the proceeding boreholes adjusted to reach the failure surface (the sound in-situ rock?)

- Müller (1968): re-analysing all available data, stated that there were no clay beds existing on the failure surface (→ which was not reached?), material characterization showed that static calculations should be considered as inappropriate to explain the phenomena, mentioned creeping as a reducing factor of frictional resistance.
- Voight (1988): shows consistency between slope movement before failure and failure behaviour of clay at high pressure (Petley, 1999), Burland, 1990 and Petley, 1995 showed that clay can behave as brittle material under high loads
- Voight & Faust (1982): heat generation during movement may rise high pore-water pressures (which was used to explain the low kinetic friction value for the limit equilibrium in terms of frictional heat and increase in pore water pressure). Semenza & Melidoro (1992) considered effects of frictional heat as necessary to produce the long trajectory of the Vajont slide, and can really contribute to the reduction of the shear strength, but this effect may only contribute with time (not the same effectiveness for short events)
- Hendron & Patton (1985): stated the landslide as a reactivation of the old landslide, stated the contribution of clay layers (ca. 10 cm thick), could act as impermeable as well as a weak layer whose residual friction angle was as low as 5°, two aquifers could be conjectured by the evidence of karstic and solution features, which is supported by the water level of the piezometers. The water level of the fractured zone / permeable landslide mass is influenced by the reservoir level. The lower aquifer is influenced by the reservoir and the precipitation.

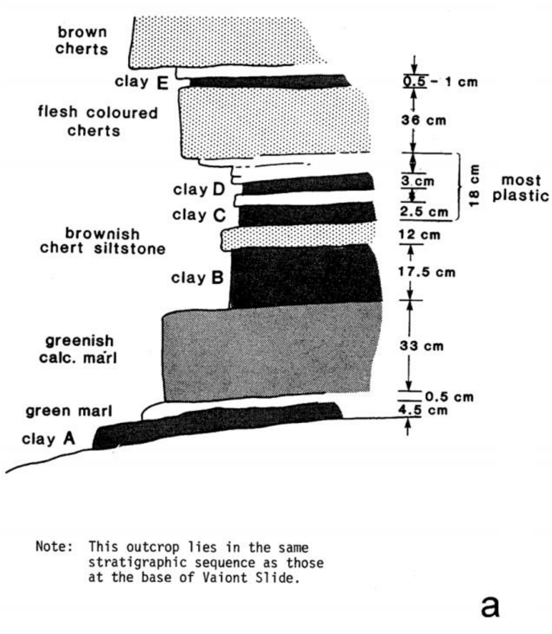

Fig. 3: stratigraphic profile from a section similar to the base of the landslide

- Further studies showed, that two-dimensional limit equilibrium analysis would not be sufficient and more effects should be accounted (in different models) like:
  - History of movements
  - Record of reservoir levels
  - Shape of the failure surface
  - Assumed distribution of water pressure and water levels
  - Appropriate shear strength values
- In the years after the Vajont catastrophe, the general interest in the prediction of such big landslides (also because of their large social impacts). In these days it seemed to be nearly impossible to predict large mass movements and their behaviour. Nevertheless, in the end, some authors concluded, that the data of the movement observation of the Vajont valley would have allowed predictions 20 days to failure.

Later Studies (eg. A. Wolter et al. 2016)

Even fifty years after the catastrophic event, the Vajont landslide is subject to different studies. After the above-mentioned paper(s) the impact of different effects of mechanisms of landslides were analysed. With further studies more details of the regional geology are revealed. In the following are some figures from a paper of A. Wolter et al from 2016 in which they discuss the mechanisms that contribute to trigger a landslide. In Fig. 4 and 5 are examples of maps which show more information than in the years of dam construction and the years after. The development of these maps could be enabled with the aid of advanced techniques and knowledge. Figure 6 shows a diagram of different endogenic and exogenic mechanics resp. processes that can influence landslides. This diagram shows how complex the mechanisms can interact between themselves. The paper of Wolter et al. is very interesting, nevertheless it would exaggerate the scope of this summary.

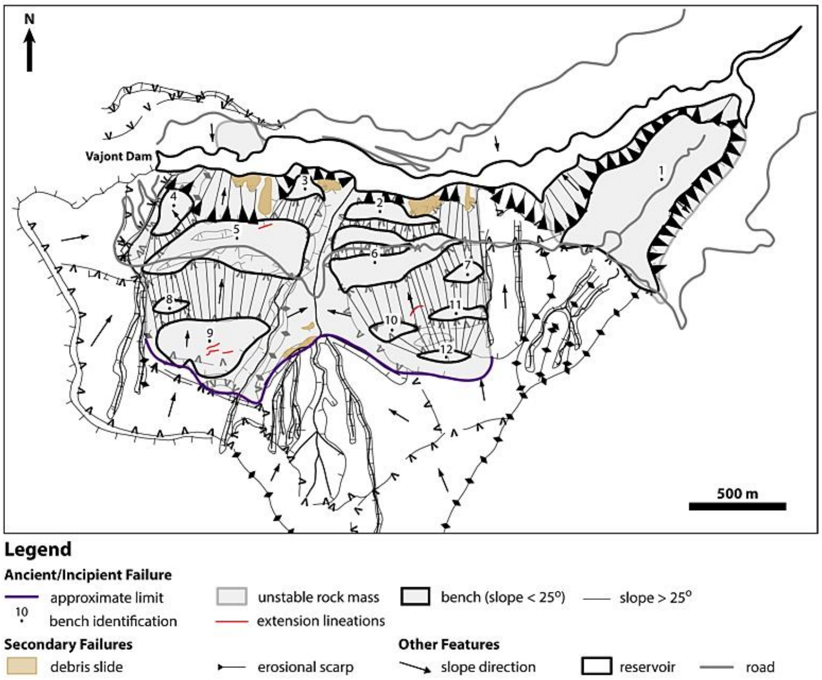

Fig. 4: map with morphological structures of 1960 based on aerial photographs (A. Wolter et al., 2016)

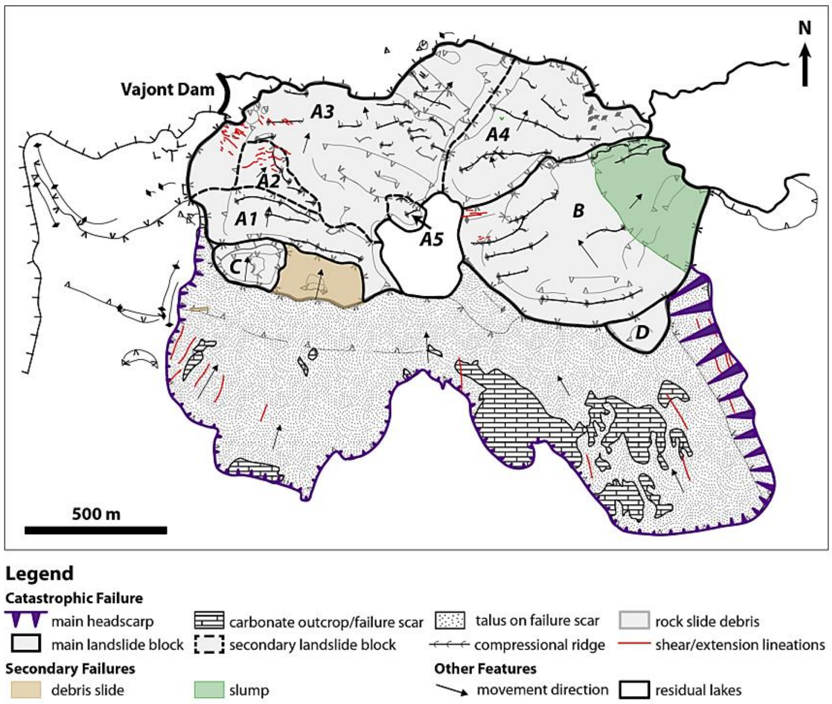

Fig. 5: map of the geological structures after the landslide in 1963 with the different landslide blocks (A. Wolter et al., 2016)

Fig. 6: diagram with interaction between different endogenic (red) and exogenic (green) mechanisms / processes contributing to a landslide (A. Wolter et al., 2016)

Personal Conclusions:

The advance made in the recent years to predict, manage and sometimes even prevent such catastrophic landslides is astonishing. The prediction of events can nowadays be supported by various measurement techniques like cameras observing the critical area, radar, inclinometers and so on. Further, the geological models have been evolved sufficiently to adapt for different landslide types. Also the study of different movement types and classification can contribute to the risk management in dangerous areas. Last but not least there is a different acknowledgement of dangers due to mass movements. The internet and therefore the fast data exchange and news may have enhanced the sensibility to “bad” or even catastrophic news which is generally to be avoided (→ results in better risk management, situation analysis and prevention).