Long-term investigation of a deep-seated creeping landslide in crystalline rock. Part I. Geological and hydromechanical factors controlling the Campo Vallemaggia landslide

L. Bonzanigo, E. Eberhardt, and S. Loew

Abstract: Slope movements of the deep-seated Campo Vallemaggia landslide in the southern Swiss Alps have been reported for over 200 years. Surface and borehole investigations of the unstable mass reveal an up to 300 m deep complex structure incorporating 800 million cubic metres of disturbed metamorphic rocks divided into blocks along primary fault zones. An average slide velocity of approximately 5 cm/year can be calculated from various monitoring data recorded between 1892 and 1995. Block movements primarily involve mechanisms relating to multiple shear surfaces, but in cases where slide blocks are constrained by other blocks, creep deformations are observed. Borehole investigations revealed the presence of artesian water pressures, which when integrated with inclinometer and surface geodetic data, helped to provide key insights into the underlying instability mechanisms. This paper reports the findings of an extensive mapping, geophysical, and monitoring investigation carried out over a 20 year period. Results from the analysis are presented with respect to the hydromechanical factors controlling the unstable mass, the significance of which were instrumental in resolving conflicts with regards to the slope mitigation measures required to stabilize the slope. In Part II (see companion paper, this issue), the stabilization works performed at Campo Vallemaggia and their effectiveness are presented.

Key words: deep-seated landslide, crystalline rock, artesian pressures, coupled hydromechanical processes, Campo Vallemaggia, Swiss Alps.

Résumé : Depuis plus de 200 ans, on a fait rapport de l'activité du glissement profond de Campo Vallemaggia situé dans les Alpes méridionales suisses. Des relevés de surface et des compagnes de forage du massif instable ont révélé la présence d'une structure complexe de 300 m de profondeur incorporant 800 millions de m^3 de roches métamorphiques remaniées divisées en blocs le long des zones de faille primaires. Une vitesse moyenne de glissement d'environ 5 cm par année a pu être calculée en partant de diverses données de mesures enregistrées entre 1892 et 1995. Les mouvements des blocs impliquent principalement des mécanismes découlant de multiples surfaces de rupture, mais dans des cas où des blocs de glissement sont confinés par d'autres blocs, on observe des déformations en fluage. Les relevés de forages ont révélé la présence de pressions d'eau artésiennes qui, lorsqu'intégrées avec les données inclinométriques et géodésiques ont aidé à fournir des éclaircissements clés sur les mécanismes sous-jacents à l'instabilité. Cet article présente les constatations d'une cartographie élaborée des études de géophysique et de mesures réalisées durant une période de 20 ans. On présente les résultats de l'analyse portant sur les facteurs hydrodynamiques qui contrôlent la masse instable, dont la signification était fondamentale pour résoudre les conflits concernant les mesures de confortement requises pour stabiliser la pente. Dans la Partie 2 (voir l'article qui accompagne celui-ci) on présente les travaux de stabilisation réalisés à Campo Vallemaggia et leur efficacité.

Mots-clés : glissement profond, roches cristallines, pressions artésiennes, processus hydromécaniques couplés, Campo Vallemaggia, Alpes suisses.

[Traduit par la Rédaction]

Introduction

The Campo Vallemaggia landslide is located in the crystalline Penninic nappes of the Canton Ticino, in the southern Swiss Alps near the Italian border (Fig. 1). This deep-seated, creeping landslide is extraordinary in many ways, chief amongst which is its immense size. The slide mass reaches depths of up to 300 m and incorporates

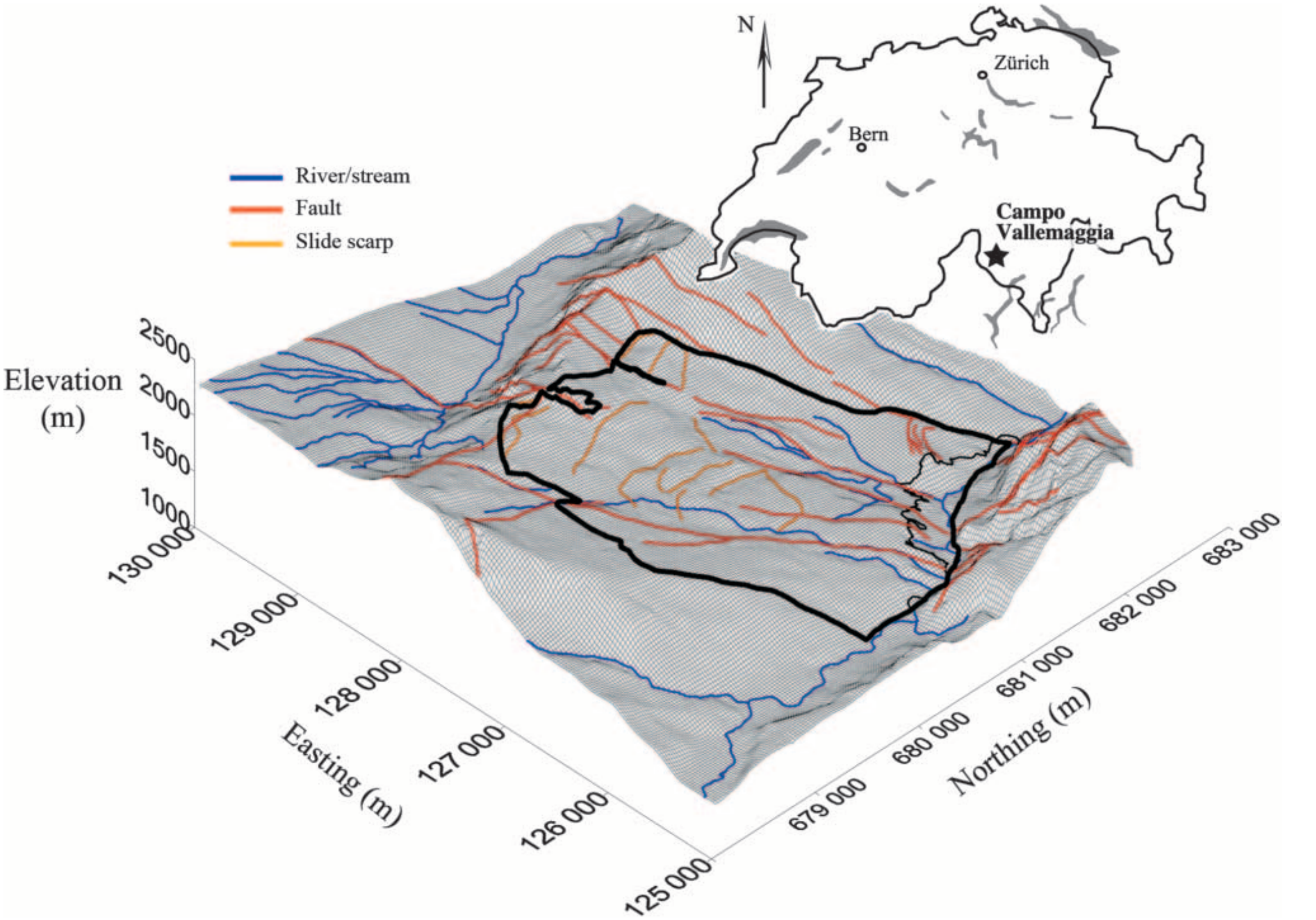
Received 31 March 2006. Accepted 14 April 2007. Published on the NRC Research Press Web site at cgj.nrc.ca on 27 November 2007.

L. Bonzanigo,[1] E. Eberhardt,[2,3] and S. Loew. Engineering Geology, Swiss Federal Institute of Technology (ETH Zurich), Hoenggerberg, CH-8093 Zurich, Switzerland.

[1]Present address: geolog.ch Ltd, Geologi Consulente, Box 1152, CH-6501 Bellinzona, Switzerland.
[2]Corresponding author (e-mail: erik@eos.ubc.ca).
[3]Present address: Geological Engineering, Department of Earth and Ocean Sciences, The University of British Columbia, Vancouver, BC V6T 1Z4, Canada.

 doi:10.1139/T07-043

Fig. 1. Location map and digital elevation model of the Campo Vallemaggia landslide in the southern Swiss Alps. Reference is made to the Swiss coordinate system. The latitude and longitude of the centre point of the landslide is approximately 46°17′N, 8°29′E.



approximately 800 million cubic metres of crystalline rock. The body of the slide mass is subdivided into several blocks by subvertical fault zones varying in thickness from several metres to tens of metres, with subhorizontal shear–slip surfaces developed along lithological boundaries or zones of varying alteration. As a result, its movements are complex and difficult to describe with simple geomechanical models.

Two small villages, Campo Vallemaggia and Cimalmotto, are situated on the slide mass where surface displacements have been geodetically measured for over 100 years. Recorded observations in the villages go back 200 years. Based on these surveys, it could be resolved that the horizontal translation of the slide mass had advanced approximately 30 m between 1892 and 1995. These displacements were of great concern in the two villages, as with each passing year of slope movement, the villages moved closer and closer to a steep erosional front at the toe of the slide mass (Fig. 2). Inspection of the displacement–time record showed a pulsing or stick-slip behaviour; accelerated movements were associated with periods of intense precipitation, often provoking fear amongst the local population and authorities. Such incidences date back to 1780 in the historical record, when the region was temporarily abandoned because of an accelerated period of slope movement (Mondada 1977). Intervention to stabilize the landslide has repeatedly been called for and emergency plans prepared in the event evacuation was deemed necessary. Yet the implementation of such plans were problematic for decision makers given the unpredictable nature of the slide mass; when velocities reached alarming levels and a costly evacuation of the population seemed warranted, the movements would return to normal.

In 1983, the heightened danger posed to the local population combined with uncertainty and disagreements over the underlying processes responsible for the unstable slope movements (and thus which mitigation solutions would be the most effective), led to the initiation of a detailed investigation of the Campo Vallemaggia landslide. This paper presents the history of the slide activity, the geological, geotechnical, and hydrogeological investigations carried out, and the conclusions arrived at with respect to the kinematics and landsliding mechanisms. In Part II (see companion paper, Eberhardt et al. 2007), the history of mitigation works to stabilize Campo Vallemaggia and the monitored and modelled response of the slide mass to those measures implemented following the detailed investigation described here are presented and discussed.

Historical overview of slope movements

The village of Campo Vallemaggia sits on the moving slide mass approximately 100 m above the Rovana River, which continuously acts to erode away the toe of the slide

Fig. 2. Aerial view of the foot of the Campo Vallemaggia landslide and the two villages located on it (Cimalmotto: 46°17′01"N, 8°29′23"E; Campo Vallemaggia: 46°17′22"N, 8°29′41"E).

(Figs. 1 and 2). The long-term effects of the slope movements can be easily recognized through the misalignment of homes and slanting of historical buildings in the village. Historical documents point to the temporary abandonment of the village in 1780 and the occurrence and reoccurrence of damages since then. Over time, the population learned ways to limit damage to property and when to evacuate homes before they collapsed. Albert Heim, one of the preeminent landslide experts in his time who carried out a detailed investigation of Campo Vallemaggia, cited the prior absence of fatalities when first defining the instability as a creeping landslide (Heim 1897). A historical overview of several key events relating to down-slope movements at Campo Vallemaggia is given in Table 1.

In reviewing the history of slope movements at Campo Vallemaggia and the subsequent reactions of the local population to them, an accounting of the conflicting professional opinions as to the primary causes responsible for the landslide movements becomes apparent. Amongst these, erosion at the toe of the slide body has long been held to be the primary factor driving the instability. Reasons for this likely date back to periods of increased logging activities where water flow along the Rovana River was increased (circa. 1857) resulting in accelerated toe erosion, slope undercutting, and increased landslide activity. Concerns were such that logging activities were abandoned (circa. 1859). Other reasons for the promotion of toe erosion as the primary cause of sliding activity may be partly phenomenological, relating to the overt nature of surficial erosion as opposed to those processes that may be working in the subsurface. As noted in Table 1, during the second half of the 19th century, the Rovana River cut downwards several tens of metres in a 40 year period, increasing the vertical height of the exposed toe to 150 m. This change in topography would have been evident to all given the position of the villages on the slide body overlooking the erosion of the toe (Fig. 2). Even after logging activity ceased, erosion due to heavy precipitation continued to undercut the toe of the slope causing small landslips and sometimes sudden surges of the entire slide mass. As such, erosion was clearly a powerful and perceptible force, and several attempts were made to construct protection works to limit the undercutting of the slope.

However, this was not the only opinion. During his investigations of Campo Vallemaggia, Heim (1897) had observed the presence of special hydrogeological conditions, most notably artesian overpressures in the form of anomalous springs found across the landslide body. In his conclusions, he noted that the sliding activity at Campo Vallemaggia was due to the combined effects of surface erosion by the floodwaters of the Rovana River attacking the toe of the slide and movement of the upper sections of the slope induced through saturation of the slide mass (Heim 1932; also see the English translation of this work by N.A. Skermer). He went on to note that both can appear together at the same time but can be dispersed in different years, with the latter constituting the more effective landslide promoting agent. Heim found it astonishing that prior to his investigation, all expert opinions considered the sliding of Campo Vallemaggia to be solely

Table 1. Historical events related to movements of the Campo Vallemaggia landslide (1780–1993).

Year	Event
1780	Historical reference to abandonment of settlements in the sliding area
1834–1839	Heavy floods result in small slips at toe of slope
1857	Increased forestry activity leads to construction of water reservoirs to transport logs along the Rovana river through the gorge at the slope's toe (i.e., transport by sluicing). Highly swollen waters rage with such force that the ground in Campo trembles, the slope toe is undercut and the gorge deepens by 12 m in 6 months. Slide activity increases and roads crossing lateral fissure at boundaries of the slide body show offsets of 1 m in 1 year
1859	After long-lasting disputes, the logging reservoirs are removed
1867–1868	Intense precipitation and flooding leads to increased erosion and sliding activity at toe of slope. Several houses in Campo become uninhabitable. A large rockfall from the other side of the valley pushes the river against the toe of the slide
1887–1892	The Rovana river at the toe of the slide body erodes to a depth of 150 m below the terrace of Campo, several tens of metres of which occurred over the previous 40 years. Protection works are started to limit undercutting of slope
1889	Several check dams are constructed to reduce erosion at the slope's toe but are washed away during heavy flooding. An important historic palace, the Palazzo Pedrazini, collapses
1892–1896	After a series of dry years, slide activity quiets and Campo is believed to be saved
1897	Excessive snowmelt in spring (snow depths reached 7 m in upper slope and 4 m in village at toe of slope) result in initiation of slide activity again. One house collapses and many others start to break apart. Albert Heim, ETH professor and pre-eminent landslide expert, called in to investigate
1907–1937	Several occurrences of intense precipitation and heightened fears of slide reactivation but without any incident (1907, 1924). Conversely, unexpected slide reactivation following long periods of inactivity (1921, 1937). The church tower, once tilting 30 cm from vertical, strangely returns to its upright position. Over this period (1900–1929), the terrace on which Campo sits moves 12.6 m towards the Rovana and drops by 2.8 m, suggesting a slide plane inclination of 12.8°
1940	Following a particularly rainy year, movements increase to exceed 5 cm per day for a short period of time (the highest velocity recorded over the history of slope displacement measurements). Movements return to normal rates by 1942
1950–1954	Short acceleration of slide mass following exceptional precipitation events (1950); in contrast, periods of heavy precipitation occur with no increased activity (1953–1954)
1959–1961	Acceleration of slide mass causing displacements of 80 cm in one year
1962–1986	No notable changes in activity, even following exceptional precipitation in 1978, which heavily erodes toe of slope
1987	Beginning of acceleration of slide mass to velocity of 1 m/year, even though erosional activity at the slide toe is reduced compared to that seen in 1978 following a flood event
1993	Sudden one-time surge of 40 cm

the result of erosion of the toe of the slope by the Rovana River. Even after his investigations, Heim met with local and political resistance leaving him frustrated:

> "Understanding and courage are lacking to tackle the problem at the right places, and politics impede consensus. Lovely magnificent Campo Vallemaggia, soon you will be merely a bygone dream"! [A. Heim (1932); translated from German by N.A. Skermer, 1989]

These opinions continued into the present day and largely influenced the different measures taken to stabilize the slope, up until the detailed 1983–1991 landslide investigation of Bonzanigo (1999). The success and failure of the different mitigation strategies employed at Campo Vallemaggia are described in further detail in the Part II companion paper (Eberhardt et al. 2007).

Detailed investigations (1983–1991)

A series of detailed investigations were carried out between 1983 and 1991, building on several earlier mapping studies performed during the previous 50 years. The subsequent detailed investigations included geological, structural and geomorphological mapping, seismic refraction and reflection surveys, borehole drilling, inclinometer and pore pressure measurements, hydrogeological and hydrogeochemical analyses, and surface geodetic monitoring.

Landslide geology, structure, and geomorphology

The local geology involves a metamorphic series of amphibolites and micaceous schists, several types of gneiss, ultramafic metaperidotites, and metacarbonates. The gneisses frequently alternate with more schistose lithologies, in particular, biotite schists. The slide mass reflects the local lithology, but is more disturbed and weathered. Outcrop observations, especially those along scarps dissecting the slide mass, suggest that the mineralogical composition of the rock partly controls the behaviour of the slide mass, at least with respect to creep deformations and the development of internal shear zones. Petrographic descriptions of the key rock types are presented in Table 2.

The cartographic distinction between the various formations is not always clear, mainly due to multiphased folding on various scales. Distinction between the various types of gneisses is further hindered by gradual transitions, weathering, and (or) tectonic disturbances. Figures 3 and 4 present a simplified geological map and cross-section of the zone of sliding, condensed from detailed maps made during the investigation. These detailed maps also included lithology, structure, geomorphology, hydrogeology (springs and surficial drainage patterns), and geomorphological features relating to sliding (see Bonzanigo 1999).

The structural geology is characterized by isoclinal folding, with the fold axial plane dipping approximately at 30°SSE. Based on regional investigations by Grütter (1929)

Table 2. Petrographic descriptions of major rock units at Campo Vallemaggia.

Name	Description
Orthogneiss	Medium-grained, linear fabric, with lenticular feldspar crystals (3–7 mm on average, but sometimes larger). Generally banded, with thicknesses varying between 10 cm and 2 m, interwoven with biotite schist intervals of 2–5 m
Leucocratic gneiss	Massive, fine-grained. Often appears in bands 30–40 cm thick, inserted in complexes accompanied by mica schists, aluminosilicate schists, amphibolites, and chlorites
Biotite gneiss	Medium-grained, essentially composed of biotite and quartz. Biotite sometimes appears in near pure, centimetre-thick layers
Schistose gneiss (Aluminosilicate)	Diverse with many important mineralogical variations. Includes chlorite schists with staurolite, aplites with decimetre thicknesses, and quartz-rich mica schists. Also includes amphibolite intervals of irregular thickness. Presence of massive carbonate bands suggest a metasedimentary origin (see Metacarbonates below)
Amphibolites	Massive, complex zones of hornblende, with some fine-grained chlorite and quartz, crossed with epidote, chlorite, pyrite, and other metalliferous minerals (locally abundant). No clear distinction between massive amphibolites and amphibole gneiss. Amphibole schists are also found. Can be considered as metamorphosed basalts
Metaperidotite	Metre-sized lenses of massive peridotite, composed of olivine, pyroxenes, and spinels. Structure is irregular and without schistosity. Locally, lenses of pure hornblende, biotite schist, amphibolites, and other schists composed of talc, epidote, chlorite, and sericite can be found
Metacarbonates	Diffused, varying between carbonatic metamorphic schists (silicate schists with calcite) and silicate marbles of centimetre to decimetre thickness. Confirm predominantly sedimentary origin of the isoclinal lithological complex. Presence of sugar dolomite at depth, with 20–30 cm band of dolomite exposed in toe of slide

and Hall (1972), the amphibolitic formations shown in Figs. 3 and 4 correspond to the core of a large regional isoclinal fold. This folded succession of crystalline rocks was later subjected to subvertical brittle faulting, displacing the succession along NNW–SSE striking faults. The longitudinal blocks shaped by these faults can be described as displaced rock that are primarily intact higher up near the head of the slope and pass gradually to a highly weathered material towards the toe. These features are clearly visible in the morphology of the slide mass as well as in seismic reflection profiles. Of key significance is a major fault scarp that divides the slide mass into two main bodies (the Campo block and Cimalmotto block; see Figs. 3 and 5).

A second key set of structures is aligned parallel to the foliation of the schistose zones, which dip locally between 20°SE and 30°SE. As this dip direction coincides with the direction of sliding, it can be assumed that the basal rupture surface and any internal shear surfaces have developed along these weaker zones. Other systems of fractures are minor and diffused, particularly those dipping 70°–80° towards the north and east.

Geomorphologically, the slide area can be divided into four zones. These include:

(1) *Head scarp*. Large intact blocks and large open tension cracks spanning metres can be found where the slide mass separates from the in-place stable bedrock. The surface morphology is typical of a slow, creeping landslide (i.e., "sagging").
(2) *Upper and central slide mass*. The large intact blocks found here are highly disturbed due to downslope displacements and are partially covered by a thin veneer of glacial till and dry colluvium. Open fractures between moving blocks are filled with weathered material. The surface morphology is irregular due to transverse fractures and rotated and subsided blocks. Precipitation easily infiltrates into the subsurface through large fractures and voids formed by differential block movements. In contrast, those fractures filled and sealed by fine-grained materials form small irregular ponds.
(3) *Lower terrace*. The lower part of the slide body is highly fractured and weathered. This material represents the area of greatest disturbance and deformation. The surface is covered by a few metres of glacial deposits, showing little consolidation.
(4) *Slide toe (erosion front)*. The frontal toe of the slide is one of its most striking features. It is 4 km long, reaches heights of 150 m, and is composed of strongly fragmented and weathered soil-like material with poorly sorted grain sizes and rafts of intact rock. It is in constant change due to the high rates of erosion imposed by the Rovana River.

Hydrogeology

The regional hydrogeology is typical of that seen in most crystalline metamorphic environments. Jointing and faulting primarily control the hydraulic conductivity, with schistosity playing a less significant role. As a result, the hydrogeology of the Campo Vallemaggia landslide is strongly influenced by the compositional layering and moderately dipping basal shear zones of the slide mass and the subvertical NNW–SSE striking faults. Numerous springs were found along the traces of the NE bounding fault and the subvertical faults associated with the Campo block, 65 of which were mapped and monitored during the investigation (Fig. 6). Various hydrogeochemical analyses were performed on water samples taken from these sources, including deuterium (^{2}H) and oxygen-18 (^{18}O) stable isotopes, used to determine the origin of the waters (i.e., recharge source). Spring waters sampled along the key subvertical fault zones dividing the slide mass generally showed mineralization characteristic of a deep crystalline bedrock source (Bonzanigo 1999). The presence of hydrogen gas bubbles and increased water temperatures (Fig. 6*b*) also supported a deeper origin. At the same time, localized hydrogeochemical (Mg/Ca) anomalies between neighbouring blocks suggest an impeded subhori-

Fig. 3. Simplified geological and structural map of the Campo Vallemaggia landslide.

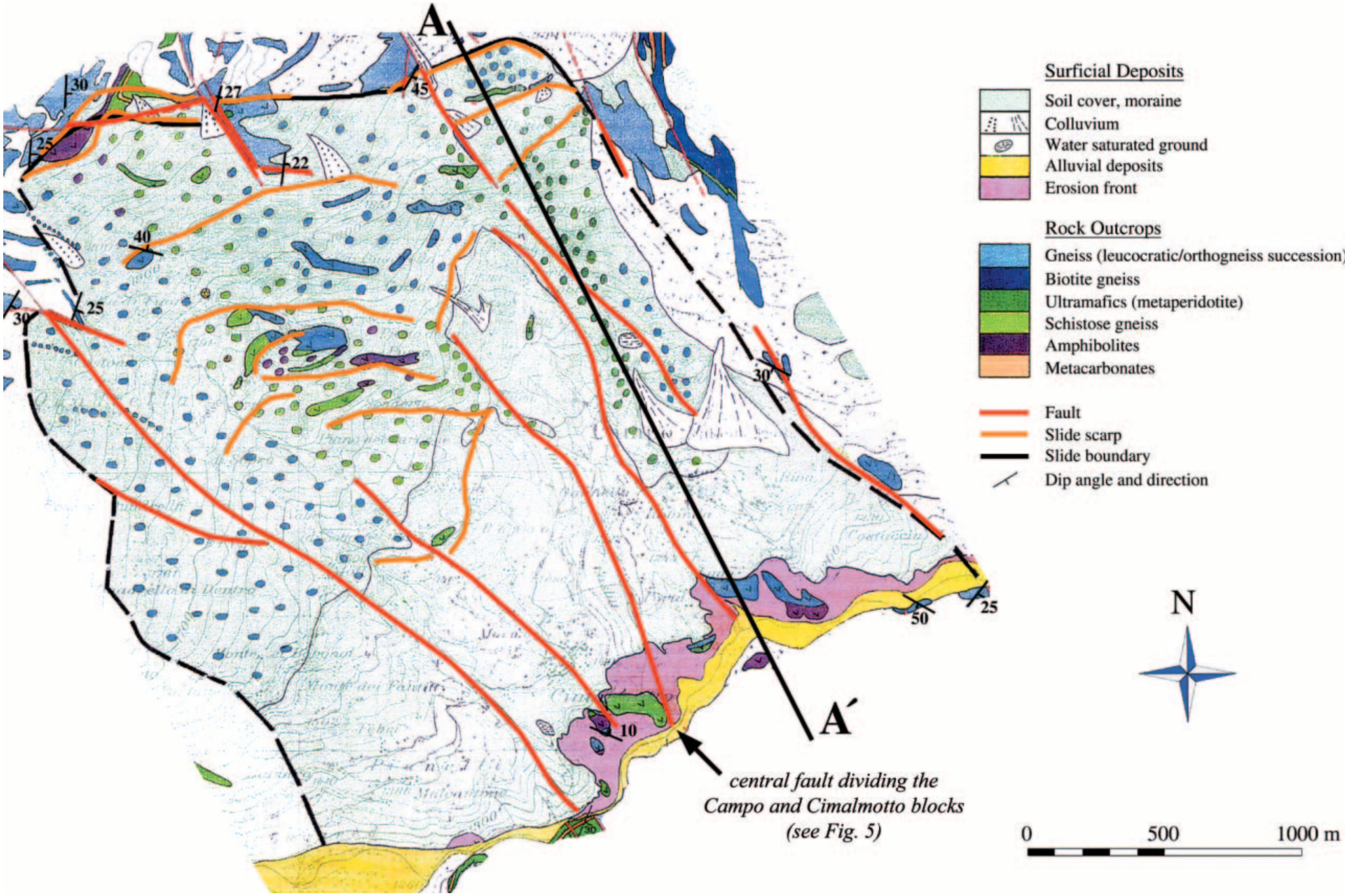


Fig. 4. Geological cross-section A-A' taken longitudinally through slide body (see Fig. 3).

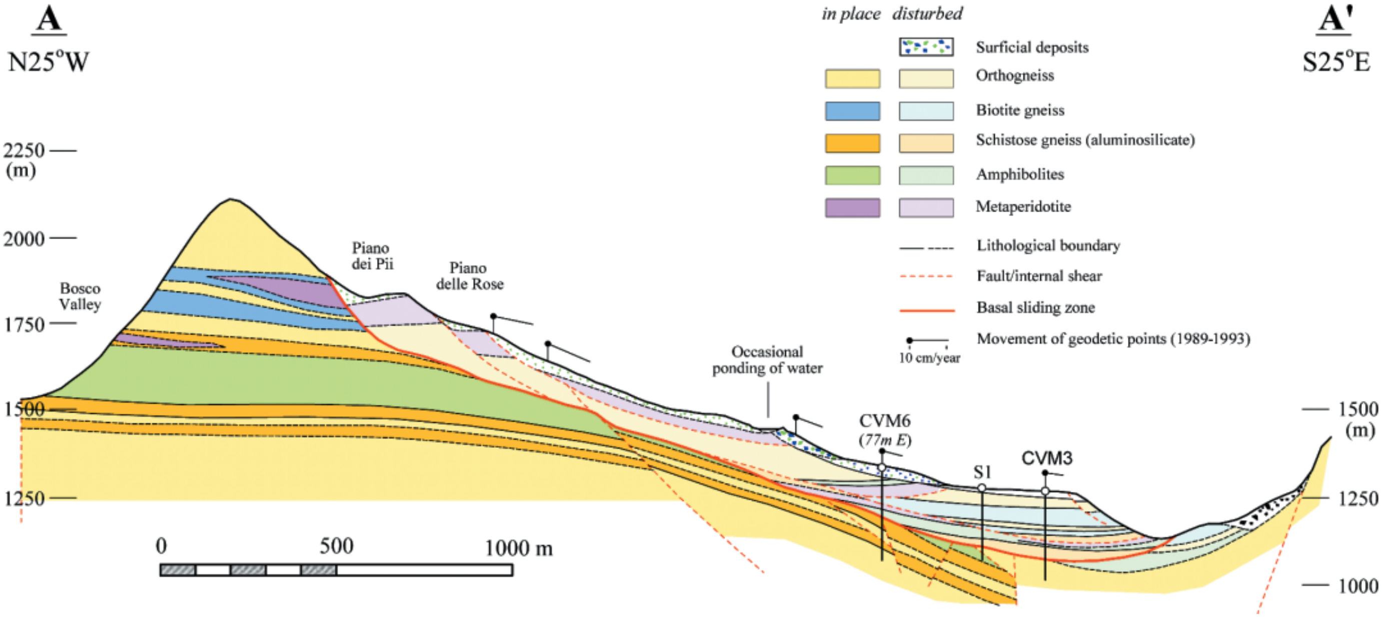
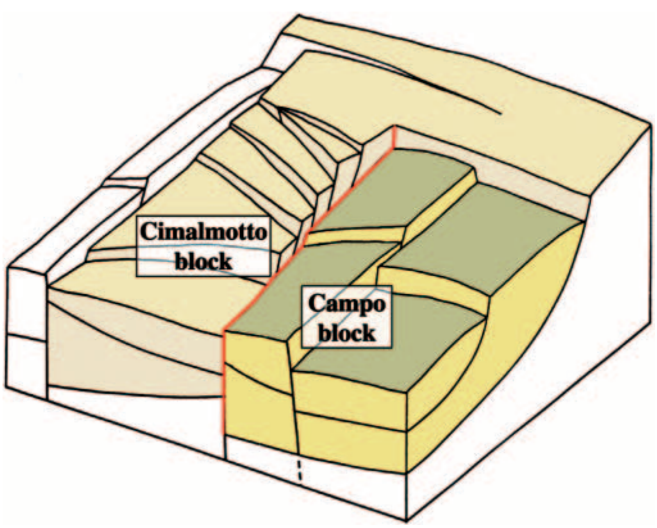


Fig. 5. Three-dimensional block model showing subdivision of the Campo Vallemaggia landslide along major fault zones and internal shears. Highlighted is a major fault zone (red line; in the Web version of the paper) that subdivides the mass into the Campo and Cimalmotto blocks.



zontal flow caused by the central gouge of the subvertical fault zones (Bonzanigo 1999).

Further analysis and interpretation of the hydrogeology is presented later where supporting data from several boreholes is used to better understand the hydrogeological conditions at depth.

Geophysical surveys

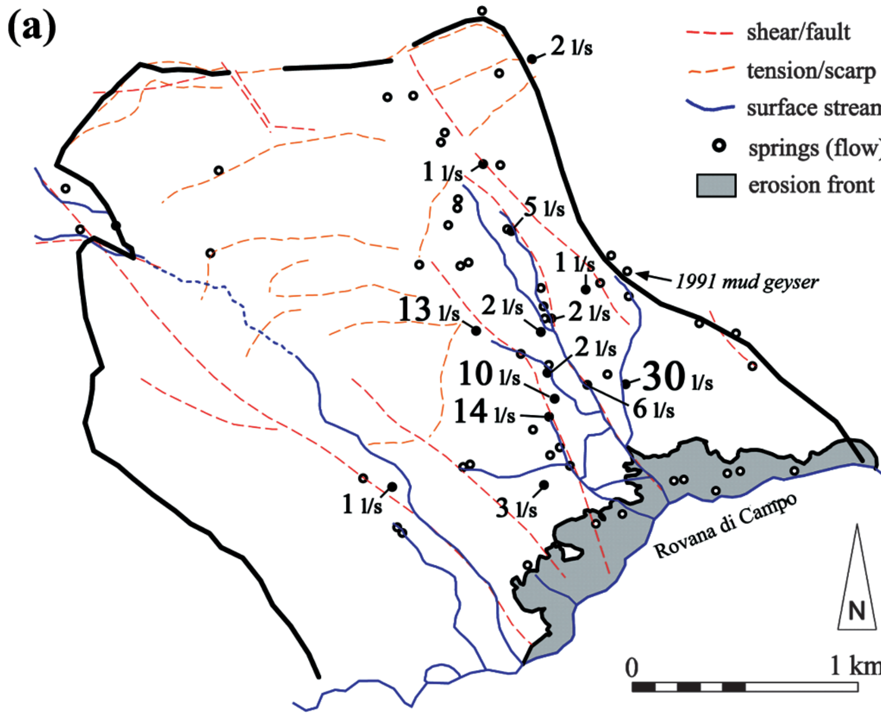
During the course of the investigation, several geophysical exploration programs were conducted to obtain more information regarding the subsurface structure of the slide mass. Initially, in 1984, several electrical resistivity profiles were generated across the lower terrace of the slide mass. These measurements were inexpensive and relatively simple to perform, but provided little information other than the approximate depth of the glacial till cover. Similarly, electromagnetic very low frequency (VLF) surveys provided little in terms of additional information. The VLF surveys were able to delineate subvertical faults within the slide mass, but such features were already clearly visible in the morphology. Limitations with respect to depth of penetration (around 50 m for the VLF under the best conditions) meant that no information could be gained with respect to the nature of the basal slide surface or any internal shear zones.

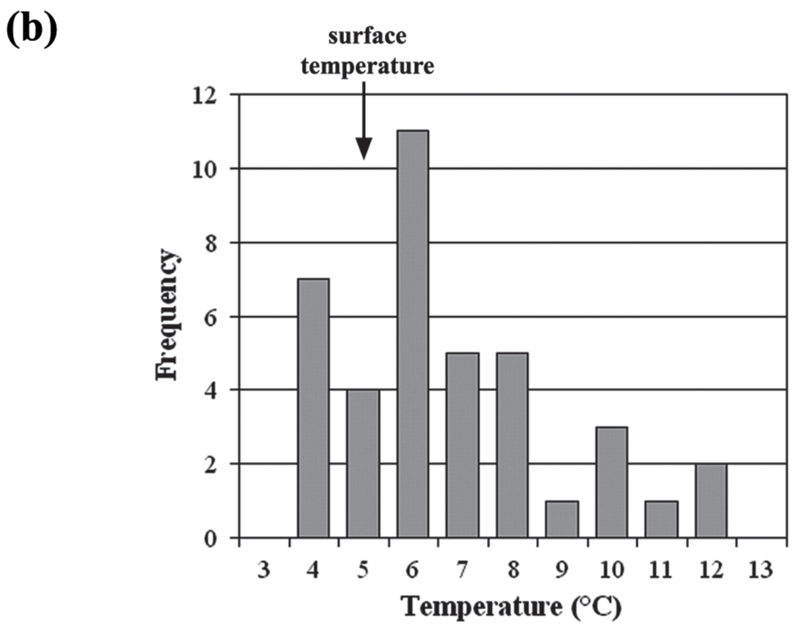
In contrast, numerous seismic surveys performed between 1988 and 1991 proved to be very effective. Several refraction and one reflection survey were performed. A borehole velocity survey was also performed in one of the deep investigative boreholes (CVM4) to help calibrate and constrain the processing of the seismic reflection survey. Figure 7 shows the location of these surveys with respect to the slide mass. Based on velocity contrasts, three general zones could be differentiated (Table 3). However, in some sections the contrast between the slide mass and the in-place rock mass was not clear. This helped to support the working hypothesis that due to the great depth of the moving mass, the base of the slide is represented more by a transition zone dominated by creep and shear deformation than a distinct, well defined slide surface, especially for the Cimalmotto block. Based on the borehole-derived velocities (averaging 2660 m/s), the thickness of the slide mass near its centre was determined to be approximately 250 m, reaching up to 300 m near the foot of the slope (Fig. 8).

Borehole drilling and installation of instrumentation

Several deep boreholes were drilled for the purpose of determining the depth of the unstable slide mass and to collect core samples (Fig. 7). These boreholes were also used to monitor the behaviour of the landslide at depth through installed instrumentation (inclinometers and multipoint piezometers). Table 4 provides the approximate depth of the deep-seated movements as determined from core logging

Fig. 6. (*a*) Location of artesian springs and respective flow rates (where significant flows were recorded). (*b*) Measured water temperatures from springs relative to average annual surface temperature.





and inclinometer measurements. In most cases, confined aquifers and artesian pressures were encountered (Fig. 9*a*), the exception being borehole CVM2, which did not show any inflows down to 200 m depth. Besides the direct measure of artesian pressures during drilling, which in some cases reached up to 12 bar (1 bar = 100 kPa) at ground surface, Lugeon hydraulic tests were performed to measure rock mass permeability.

Completion of these holes included the installation of six deep inclinometers. The first three of these (CVM1–CVM3), installed in 1987, were sheared off following accelerated movements of the slide mass between 1987 and 1989. The next set of three (CVM4–CVM6) were installed subsequent to these movements and proved effective in providing long-term data. For two of these (CVM4 and CVM6), a special multipoint piezometer – inclinometer system was developed to allow for the concurrent measurement of pore pressures and displacements. The multipoint piezometers included five to six predesignated measurement intervals, which were fitted with a cluster of small filter cells attached along the outer surface of the inclinometer casing over a 2 m interval (Fig. 9*b*). These intervals were then sealed off using geo-

Fig. 7. Location of boreholes and geophysical investigations.

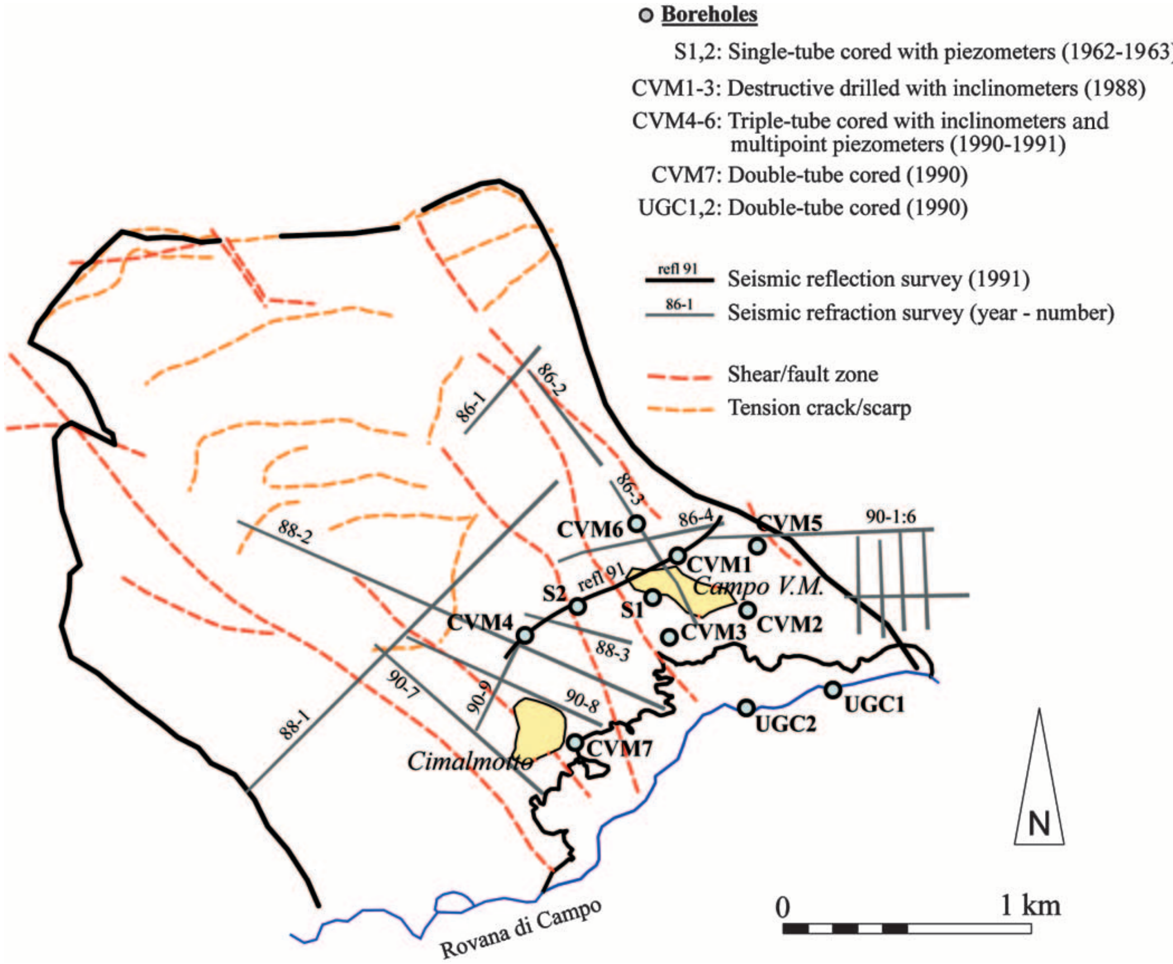


Table 3. Observed seismic velocities and grouping of different rock mass zones based on seismic investigations.

Zone	Velocities (m/s)
Superficial layer (up to 10 m deep)	500–1000
Slide mass	1200–3000
In-place rock (i.e., undisturbed)	3700–5500

textile socks injected with cement to form packers 20–40 m in length above and below.

The extended thickness of the landslide body, and thus the depths to which the inclinometers were installed, created several challenges. In reviewing inclinometer measurements in deep-seated landslides, Noverraz (1996) remarked that the 253 m deep inclinometer at Campo Vallemaggia (i.e., CVM4) was one of the deepest ever installed for a landslide. In addition to applying the standard torsion corrections to the data, consideration had to be given to the possibility that the bottom of the inclinometers may not have reached stable rock. To contend with this, the borehole heads were periodically surveyed as part of a larger geodetic monitoring program. Corrections were then applied for the downslope migration of the borehole head, enabling the calculation of absolute subsurface deformation along the borehole axis in X–Y Cartesian space. The measurements were then integrated from top to bottom, with the standard inclinometer instrument errors accumulating downwards. Figure 10 provides a 3-D plot of the corrected cumulative biaxial inclinometer displacements for borehole CVM4 and the respective error circles at the top and bottom of the borehole. The results for the different inclinometer measurements and subsequent interpretations are presented in later sections.

Geodetic measurements

The first geodetic measurements performed at Campo Vallemaggia involved triangulating three fixed points on the moving mass (two of which were the respective church steeples in Campo and Cimalmotto). These surveys were performed between 1892 and 1927, and provided a precision of approximately 10 cm (Fig. 11*a*). In 1927, this network was expanded and surveyed by means of triangulation until 1943 (Fig. 11*b*–*d*). It was with this system that in July 1940, the largest recorded movements were observed (averaging more than 5 cm/day). Between 1943 and 1986 the system of triangulation was replaced by polygonal levelling using standard theodolites (Fig. 11*e*–*f*).

In 1986, following accelerations recorded in 1984, the principal network was upgraded and recalibrated using an infrared laser-based distance measurement device with a precision on the scale of millimetres (Fig. 11*g*–*i*). The network also required some redefinition due to older survey

Fig. 8. Processed seismic reflection profile based on velocities determined through downhole seismics (CVM4) and constrained by borehole cores and cuttings (CVM4, S2, and CVM1). See Fig. 7 for location (marked as "refl 91").

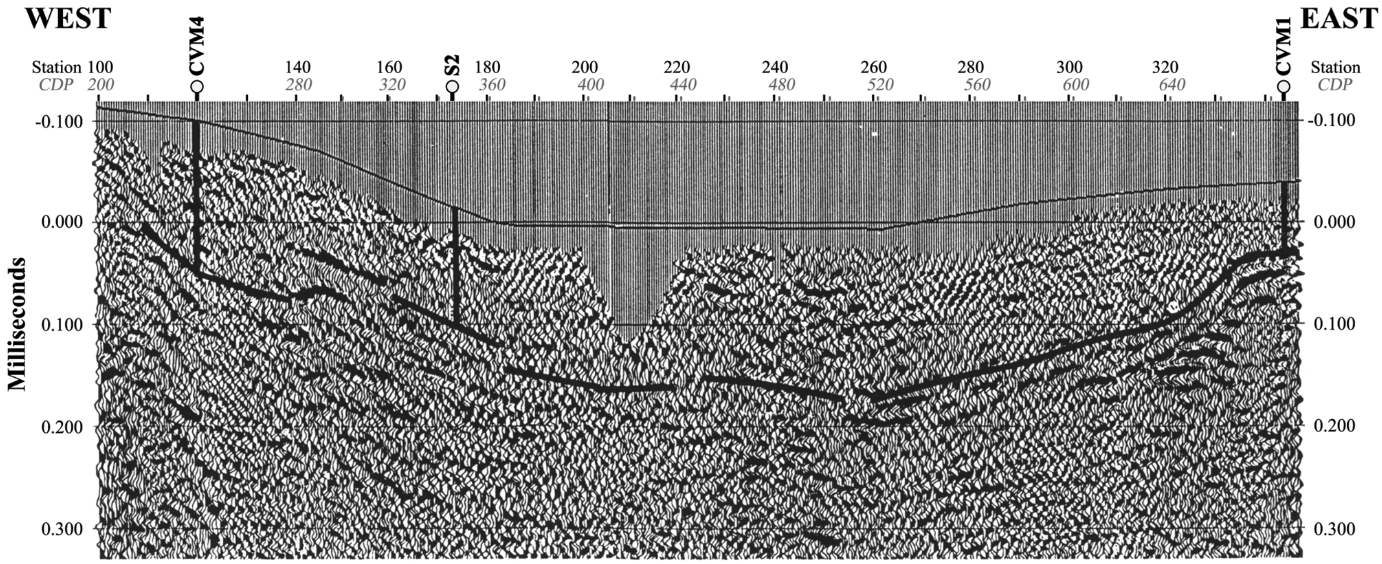


Table 4. Boreholes drilled during investigation of slide mass and estimated depth to base of unstable zone based on recovered core observations and inclinometer readings, where applicable.

Borehole	Technology	Year	Elevation (m)	Drill depth (m)	Depth to base of unstable zone (m)	Instrumentation notes
S1	Single tube	1962	1274	202	167.5	Piezometer only
S2	Single tube	1963	1307	198	165.4	Piezometer only (multipoint from 80 to 198 m depth)
CVM1	Destructive	1987	1309.5	144	110 (?)	Inclinometer only – aluminum casing installed to full depth
CVM2	Destructive	1987	1309.5	201	Not reached (?)	Inclinometer only – aluminum casing installed to full depth
CVM3	Destructive	1987	1265	250	190	Inclinometer only – aluminum casing installed to full depth
UGC1	Single tube	1990	1055	30	Not reached	
UGC2	Single tube	1990	1112	30	Not reached	
CVM4	Wireline triple tube	1990	1398	328.5	>253.0	Multipoint piezometer and inclinometer casing (PVC) installed to 253 m depth
CVM5	Wireline triple tube	1990	1332.9	201.0	84.4	Inclinometer only – PVC casing installed to 95 m depth
CVM6	Wireline triple tube	1991	1333.3	262.2	107 (130)	Multipoint piezometer and inclinometer casing (PVC) installed to 150 m depth
CVM7	Double tube	1990	1390	51	Not reached (?)	

Note: Question marks in table refer to the absence of a clear indicator that the basal shear zone was or was not reached.

points that had disappeared or needed realignment because of changing vegetation or excessive movements of the slide. Points coinciding with the top of the inclinometer boreholes were also added. To compliment these periodic surveys, a total station was installed in 1986 on the body of the slide mass to automatically target three fixed points on the opposite valley wall facing the slide (i.e., serving as fixed reference points). The total station movement was then continuously monitored.

Geotechnical characteristics and properties

The highly disturbed nature of the slide material, especially in the frontal region (Fig. 2), can be attributed to a long history of deep-seated slope movement. The material is very weak and easily breaks apart, particularly where chlorite and clays (e.g., montmorillonite) are produced due to weathering and alteration of the rock. When water pressures in the material are elevated, localized liquefaction can occur. Following the cessation of heavy precipitation events, the material consolidates into a very cohesive material. The influence of water is thus seen to play an important rheological role in terms of creep movements in the lower portions of the landslide.

During the detailed investigation, numerous samples were collected and laboratory tests performed to determine approximate geotechnical properties. These are presented in Table 5. In many cases, the samples tested were taken from highly disturbed zones and were soil-like in nature. For ex-

Fig. 9. (*a*) Deep artesian water pressures encountered during borehole drilling. (*b*) Design used for borehole instrumentation, combining deep inclinometer casing with multipoint piezometers.

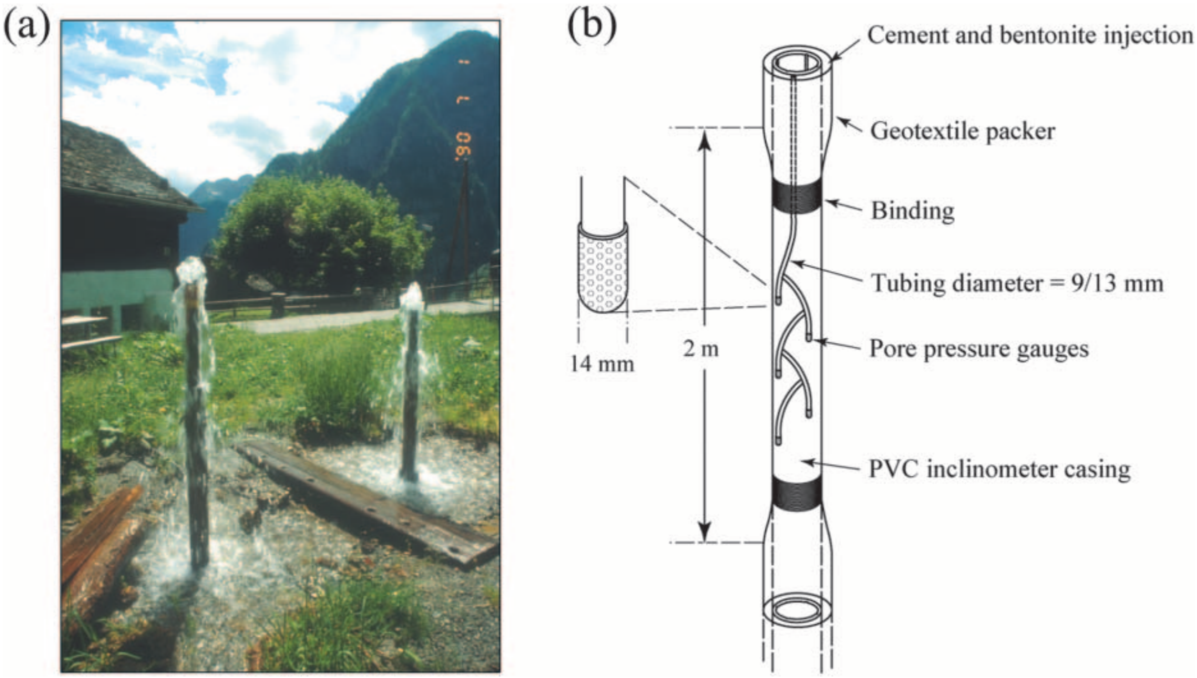
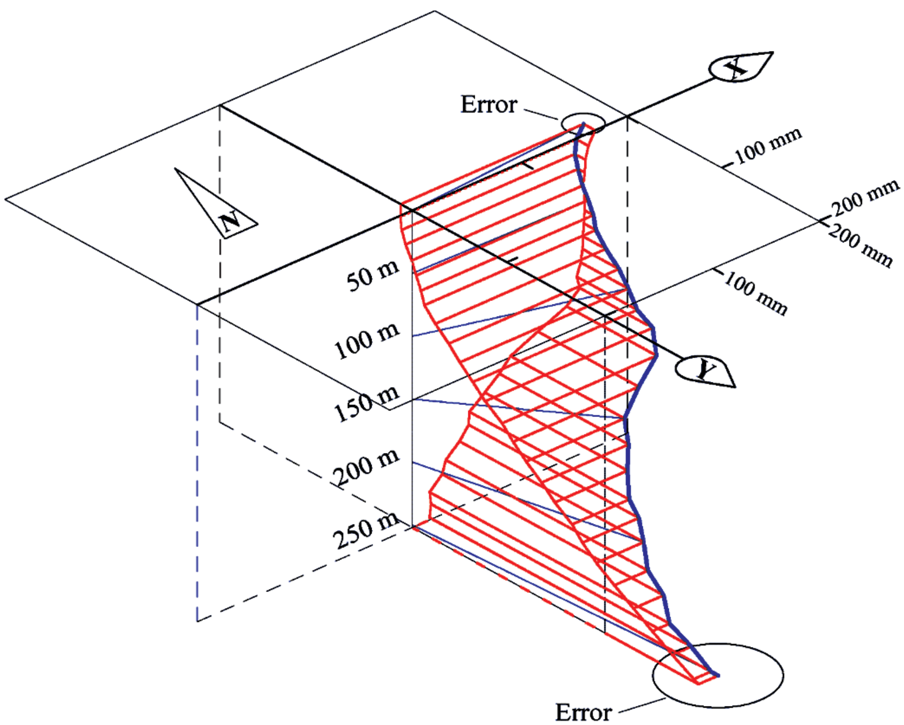


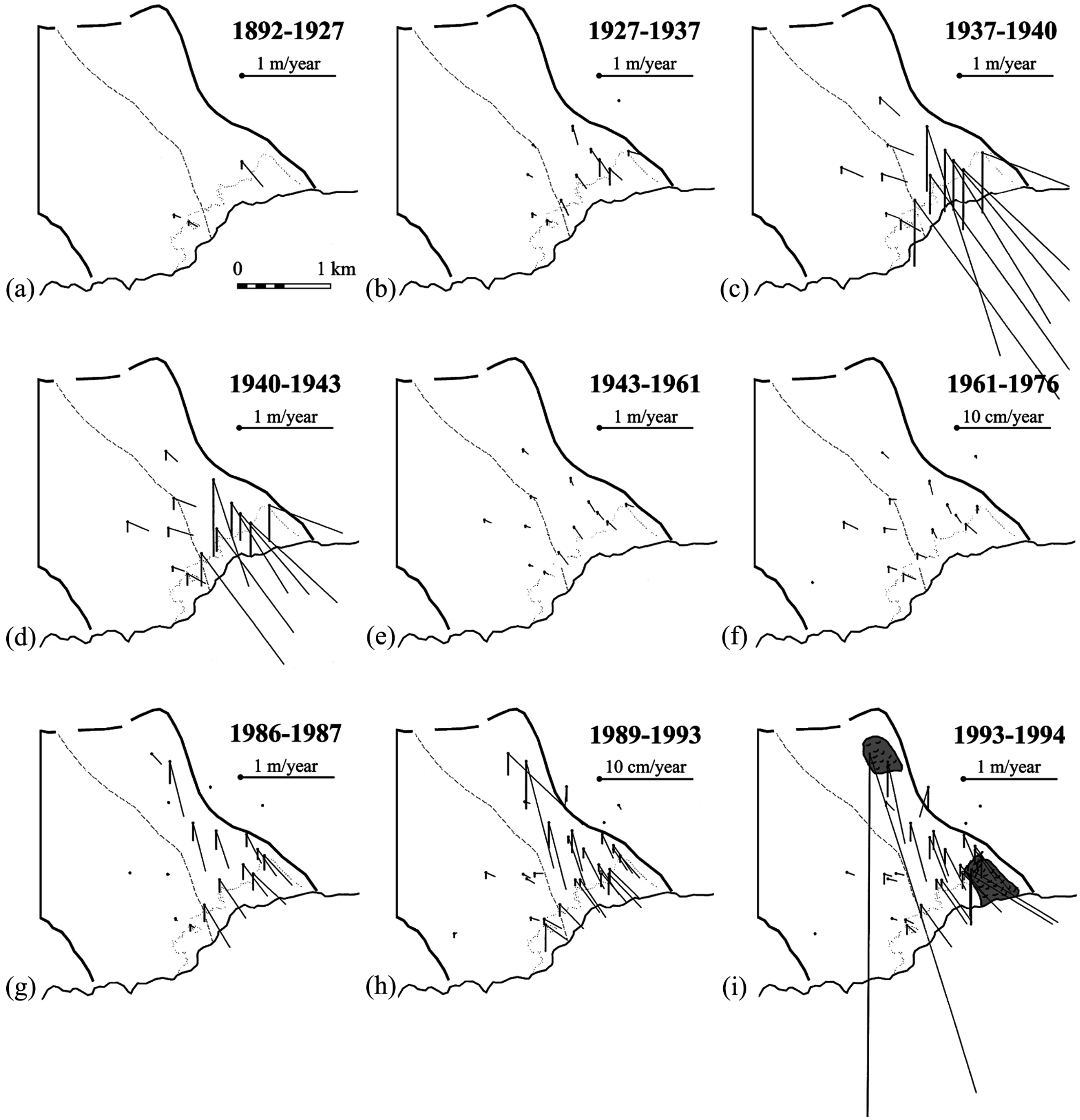
Fig. 10. Biaxial inclinometer plot for borehole CVM4 (Cimalmotto block), as measured between 3 October 1990 and 10 June 1997. Error estimates are given by the circle diameters.



ample, the samples listed as originating from boreholes S1 and S2 (Table 5) were highly disturbed and broken into granular fragments. The materials sampled from borehole CVM7 were found to be highly sensitive to water, where only a small increase in water content would be enough to liquefy the material. In the case of boreholes CVM4–CVM6, deeper coherent rock samples were obtained allowing for the testing of uniaxial compressive strength.

To supplement these laboratory values, geomechanical properties were also back-calculated using limit equilibrium techniques (Bonzanigo 1999). In effect, the high degree of heterogeneity encountered throughout the slide mass was

Fig. 11. Surface geodetic measurements over time (*a*)–(*i*), showing horizontal and vertical displacements. Note change in displacement scale in (*f*) and (*h*).



simplified to that of an equivalent continuum (i.e., disturbed–disintegrated rock). The properties from these back-analyses are presented in Table 6.

Other observed phenomena important for the understanding of the sliding mechanisms

On 10 August 1991, a spring on the NE bounding fault of the slide body (see Fig. 6*a*) began to erupt producing sporadic discharges of watery mud at rates of several litres per second above the normal flow. The material from this "mud geyser" consisted of a grey-green mud, the composition of which was determined to be 10% biotite and amphibole fines, 60% fine sand, 15%–20% lime mud, and 1%–5% clay. Chlorite was also present, as was montmorillonite in the clay component. This corresponds closely with the disturbed material found near the foot of the slide body. Hydrogeochemical analyses of the waters produced by the mud geyser indicated that they had slightly elevated sulphate contents (73 mg/L) relative to those of other superficial sources, but comparable to deep waters sampled from CVM6. As such, it was believed that the source of the water mixing with the mud material had deep origins, likely related to

Table 5. Measured geotechnical properties derived for slide materials at Campo Vallemaggia.

Parameter	Value	Sample remarks
Unit weight, γ (kN/m^3)	22.3–22.7	Borehole S1
	21.6–25.7	Borehole S2
Water content, w (%)	9.0	Average value for borehole CVM7
Liquid limit, w_L (%)	16.0–24.4	Borehole S2 (slide disturbed zone)
Plasticity index, I_P (%)	7.8–12.3	Borehole S1 (slide disturbed zone)
	4.0–9.3	Borehole S2 (slide disturbed zone)
Permeability, K (m/s)	2×10^{-7}	Borehole S1 (Lugeon test in rock)
	2×10^{-5} to 1×10^{-4}	Borehole CVM4 (hydraulic tests in artesian zones; highly disturbed by sliding activity; 75–133 m)
Uniaxial compressive strength, UCS (MPa)	110	Orthogneiss (boreholes CVM4–CVM6)
	90	Schistose gneiss (boreholes CVM4–CVM6)
	100–220	Amphibolite (boreholes CVM4–CVM6)
	200–260	Metaperidotite (boreholes CVM4–CVM6)

deep artesian aquifers. Thus the mechanism under which the mud geyser formed, and the resulting large volume of material ejected, was ascribed to localized movements of the landslide mass compressing and forcing the water–mud mixture up to the surface along a fault.

A second conspicuous event occurred in October 1993, during a period of intense precipitation that resulted in much of the southern Alps being placed in a state of emergency. The principal rivers and most large lakes flooded, and many landslides occurred along these riverbanks. In Campo Vallemaggia, this meteorological event provoked an acceleration of the slide mass and triggered the occurrence of two large landslides, one at the foot of the slope and one higher up near the head scarp of the Campo block. The landslide at the foot of the Campo slide body (along the erosion front) involved approximately 2 million cubic metres. The position and the extension of these secondary slides are shown in Fig. 11*i*.

Analysis and interpretation of the landslide instability mechanism

3-D geological model of the landslide body

Based on mapping, geophysics and borehole data collected during the detailed investigation, geologic models of the Campo Vallemaggia slide body were prepared. One key aspect of the investigation was the confirmation that the moving mass encompassed more than just heavily fragmented rock and colluvium (as may be inferred if inspections were restricted to the disturbed material at the foot of slide). The cross-section constructed longitudinally through the slide body (Fig. 4), shows the unstable mass as being a deep-seated slide composed of several large blocks detached from one another through internal shearing. Moving downslope from the head of the slide, the size of these blocks breaks down further into slabs with thicknesses on the scale of tens of metres, separated from one another by bands of intense alteration. Along zones where the deformation has been very intense, the amount of clay material increases (derived from the weathering of feldspars). At the foot of the slide, the material is almost completely broken down into a clayey sand and gravel, although rock structures and lithologic boundaries are sometimes preserved in the matrix. In some cases the structure is so well preserved that the mineralogical banding of the gneissic rock, alternating between lighter minerals and darker biotite, is clearly visible in the form of undulating dark stripes. Periodically, large slabs of competent rock floating in the clayey sand matrix daylight in the erosion face at the toe of the slide body (e.g., Fig. 12).

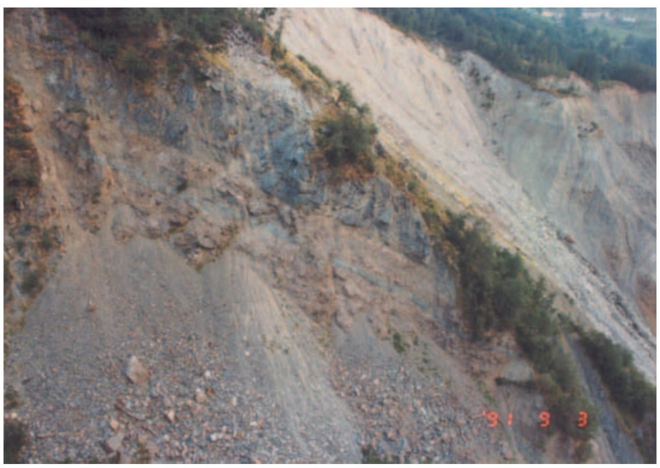
The geodetic measurements point unequivocally to the dispersed movement of the individual blocks (the movement of several blocks can be traced over a 200 year period following the different realignments of an old road). These data sets also corroborate geomorphologic observations that suggest that the slide mass is comprised of two main bodies – the Campo and Cimalmotto blocks. Figure 13 shows the relative movement directions ascribed to the different key blocks of the slide body as determined through geodetic measurements. When projected into 3-D, the slide body assumes a stepped appearance involving one key longitudinal division and several transverse divisions (Fig. 5). This 3-D geometry is consistent with that outlined for compound slides by Cronin (1992), in which a series of internal rotational shear surfaces develop due to drag along an irregular basal slip surface. Internal shearing can be envisioned as being largely controlled by preferential planes of weakness along foliation dipping subparallel to surface, and subvertical faulting across the foliation enables scarps and transverse shear zones to form. Back-tilting of blocks near the rear head scarp indicates a rotational component of movement, previously described by Heim (1897), although the movement of the entire slide body is primarily translational and involves downdropping of blocks as well (i.e., compound sliding).

Following the development of the 3-D block model (Fig. 5), a linear kriging analysis was performed for a 25 m × 25 m grid to estimate the total volume of the unstable mass. Input for this analysis was constrained using slide mass thicknesses derived from seismic and borehole surveys. The results are shown in Fig. 14, for which a total volume of 800 million cubic metres was estimated for the entire landslide body. Contour irregularities in the upper half of the landslide reflect the limited seismic and borehole data available, and thus the increased weighting given to the mapped slide boundaries as a constraint on slide thickness.

Table 6. Back-calculated geotechnical properties of various slide mass materials (after Bonzanigo 1999).

Parameter	Value	Material remarks
Unit weight, γ (kN/m^3	18–21	
Friction angle, ϕ (°)	32–35	CVM7 (disturbed material)
	45	Undisturbed gneiss
	25–30	Undisturbed gneiss (along foliation plane)
	30	Schist
	20–25	Schist (along foliation plane)
	30–40	Completely weathered rock
Cohesion, c (kPa)	10–50	CVM7 (disturbed material)
	1000	Undisturbed gneiss
	200	Schist
	30	Completely weathered rock
Elastic modulus, E (MPa)	30 000	Undisturbed gneiss
	1000	Schist
	100	Completely weathered rock
Modulus of consolidation, M (MPa)	4000–8000	CVM7 (disturbed material)

Fig. 12. Photo of an intact gneissic block encapsulated in weathered and altered material at the toe of the slide.



3-D kinematics of the landslide body based on displacement and deformation measurements

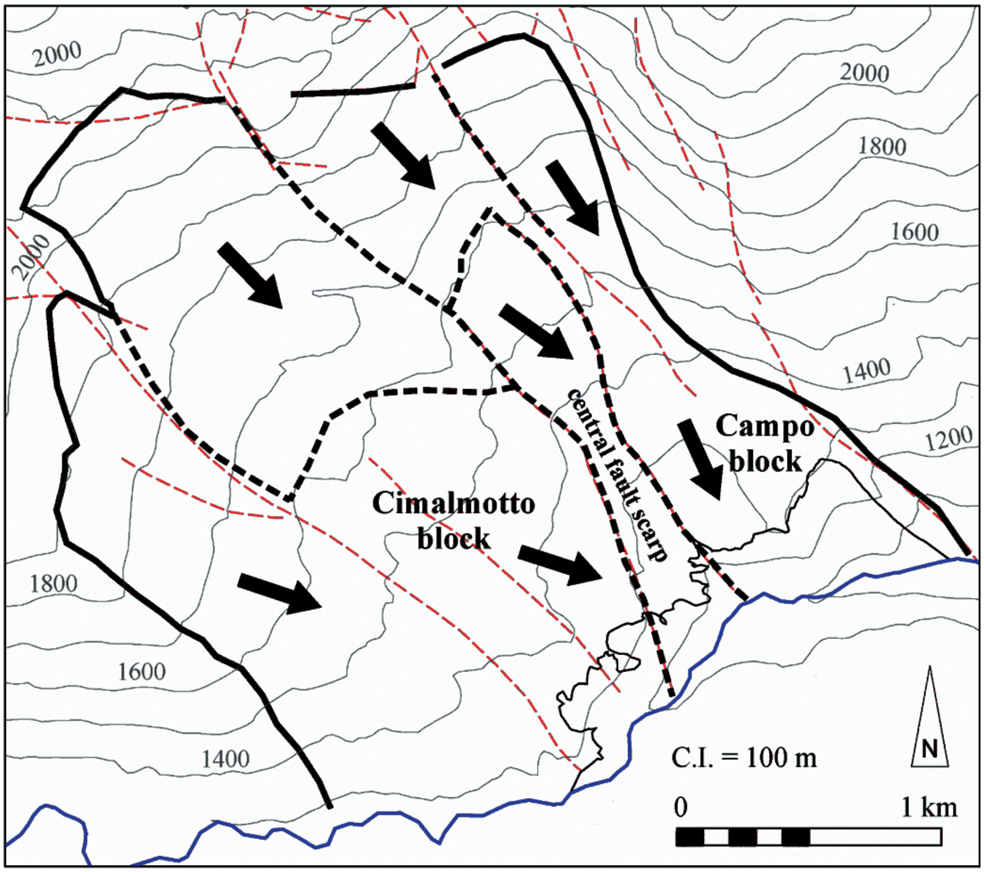
Geodetic and inclinometer measurements were analysed to develop a 3-D kinematic model for the landslide body. Figure 15 compares the cumulative inclinometer responses for boreholes CVM4 and CVM6 (for the period 1991 to 1994). The eight repeat surveys carried out during this period were consistent with one another, although for the latter surveys, deformation of the inclinometer casing eventually prevented the bottom segments of the boreholes from being measured (indicated in Fig. 15 with a dashed line).

The comparison of CVM4 and CVM6 is of key interest in that the two inclinometers are located separately in each of the two main blocks forming the slide body – CVM4 is located in the main Cimalmotto block and CVM6 in the main Campo block (borehole locations are given in Fig. 7). The interpretation of these measurements, aided by correlations with the subsurface geology observed in the borehole cores, shows a markedly different behaviour between the two blocks. In CVM4 (Fig. 15*a*), numerous shear zones are observed separating intervals of altered orthogneiss and schists across which displacements appear to accumulate incrementally. In CVM6 (Fig. 15*b*), the displacements appear to concentrate more along discrete shear zones. The relatively rigid behaviour of the rock mass between 50 and 80 m corresponds to a moderately altered fine-grained metaperidotite, and between 80 and 120 m with metaperidotites and leucocratic gneisses (Table 2). The large perturbation at 80 m corresponds to a shear zone involving a mixture of sandy clay diffused with fragments of metaperidotite.

These differences in borehole lithology and the measured inclinometer-rock mass response, play an important role in understanding the kinematics of the Campo Vallemaggia landslide. Within the Campo block (i.e., CVM6), it is clear that the subsurface deformations are concentrated along internal shears and that absolute displacements decrease with depth. This inclinometer signature corresponds with Amstad et al.'s (1988) idealized description of rigid-body translational sliding. This mechanism is further corroborated by the more brittle nature of the rock types observed in the core samples (i.e., more likely to develop localized discrete brittle shear surfaces) and geodetic measurements showing that the movement of the Campo block is kinematically unrestricted in its downslope direction of movement (i.e., the block freely toes out into the open valley; Fig. 13).

In contrast, geodetic measurements for the Cimalmotto block suggest that its toe buttresses up against the Campo block and is therefore more kinematically constrained (Fig. 13). Likewise, the inclinometer signature for CVM4 shows smaller deformations increasing with depth that are more evenly distributed across both individual shear zones and the rock mass in general. Several authors point to deep-seated slope creep as a possible mechanism to explain such inclinometer readings (e.g., Amstad et al. 1988; Lollino and Wasowski 1994). Thus it can be reasoned that the combination of reduced mobility caused by the buttressing effect of the neighbouring Campo block combined with the more heavily altered and ductile nature of the rock mass material, as observed in the core samples, results in an instability

Fig. 13. Subdivision of the Campo Vallemaggia slide mass into distinct blocks based on geological, geomorphological, and geodetic data. The subdivision involves two key bodies differentiated based on their kinematic state and mechanical behaviour – the Cimalmotto and Campo blocks.



mechanism for the Cimalmotto block that is dominated by diffused, creep-like deformations. This is illustrated in the 3-D kinematic model shown in Fig. 16, where the biaxial inclinometer signal for CVM4 shows the diffused downslope bending of the Cimalmotto block controlled by the translational movement of the Campo block (i.e., resulting in a dragging or smearing effect).

Temporal factors controlling the downslope movements

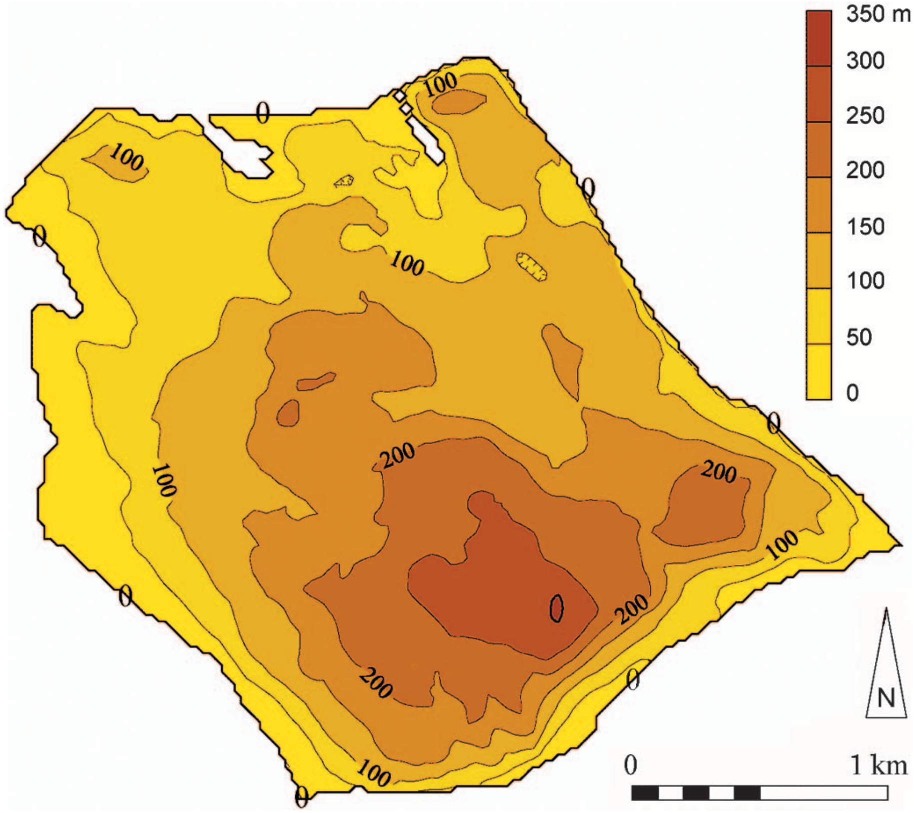
In examining the geodetic records between 1892 and the present (Fig. 11), it is clear that the differential movements between the main Campo and Cimalmotto blocks have varied over time. In examining the different dynamic factors that may be controlling these intermittent slope accelerations, three key processes have been singled out and are described below. These include heavy erosion and undermining at the toe of the landslide, high artesian pressures at depth and reduced effective stresses, and viscous diffused rock mass creep.

Erosion of the slope's toe

As noted earlier, the massive degree of erosion that occurs at the toe of the slide body is one of the most visible and striking features of Campo Vallemaggia. Heim (1932) and others estimated the average rate of erosion to be approximately 50 000 m^3/year. Extensive damage and the significant loss of pasture land over time has aroused such emotions so as to confuse the issue as to whether toe erosion is the primary factor destabilizing the slope or whether it is the consequence of slope movements driven by other processes, where downslope movements only serve to feed the erosion engine created by the Rovana River. Over the history of Campo Vallemaggia most have attributed the instability to the erosion itself.

To establish the quantity of eroded material, and to assess its effect on the stability of the slope, calculations were performed based on a topographic map of the Campo block from 1888 (scale 1:4000) and one developed in 1994 by means of photogrammatic techniques (scale 1:2000). The analysis was restricted to the toe of the Campo block, as insufficient historical data existed to perform a similar analysis for the neighbouring Cimalmotto block. Corrections were made to the digital terrain model (DTM) volume estimate to account for the horizontal displacements of the landslide based on the total displacement vector for the period 1888 to 1994 (Δx = 30.2 m, Δy = –33.7 m, Δz = –7 m). From this, 11.4 million cubic metres of eroded material was estimated (6.4 million cubic metres without the noted correction), with results showing that the erosion is not uniform across the toe of the Campo block but is concentrated along one or two key zones (Fig. 17). These results provide a somewhat higher erosion rate (56 000 to 100 000 m^3/year) than those estimated by Heim (1932), although it should be noted that they are averaged over a

Fig. 14. Approximate thickness of the landslide body based on kriging analysis (as constrained by seismic and borehole data). Landslide thickness represented as isopach contours.



longer period (106 years) and do not contain any information regarding fluctuations in erosion rates over time. Regardless, the volume of eroded material over the period 1888–1984 represents less than 1%–2% of the estimated total volume of the landslide.

Artesian groundwater pressures and coupled hydromechanical behaviour

Data from the geological and hydrogeological investigations carried out at Campo Vallemaggia suggest that the hydraulic conductivity distribution in the slide body is strongly anisotropic. Flow paths are largely controlled by discontinuities, especially those associated with fault zones. In crystalline rock masses, these fault zones are generally observed as having:

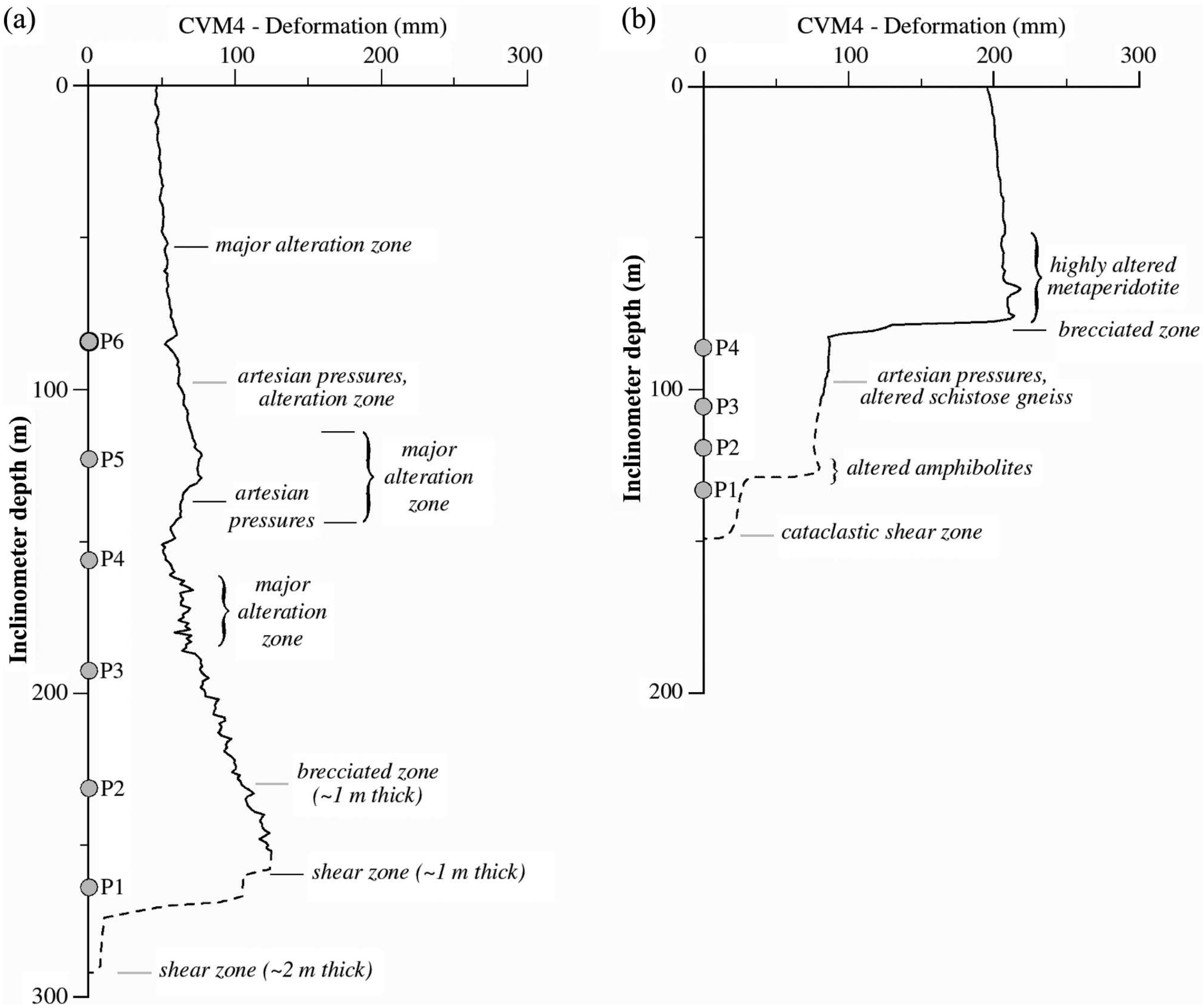
- an enhanced permeability along fracture–damage zones straddling a central fault gouge (i.e., parallel to the structure);
- a central fault gouge zone forming a relatively impervious aquiclude that impedes flow normal to the fault plane.

In the undisturbed crystalline rock outside and below the Campo Vallemaggia slide mass, brittle fault zones are primarily subvertical producing a preferential vertical groundwater flow along the NNW–SSE oriented fault planes. When combined with regional topographical effects, infiltration and downward flow can be predicted for the higher elevations at the head of the slide, reversing to upward flow towards the foot of the slide and valley bottom. Internally within the slide body, multiple subhorizontal zones of large shear deformation and mineralogical degradation (leading to the formation of mica and clay-rich layers) result in a strong hydraulic anisotropy and the observed artesian conditions (i.e., "overpressures"). Hydrogeochemical and isotopic analyses of water samples taken from several surface springs helped to support these observations (Bonzanigo 1999).

This data was used to construct a semiquantitative 2-D hydrogeological model for Campo Vallemaggia in which several semi-isolated aquifers exist within fault-bounded blocks where vertical flow is favoured along subvertical fault structures and horizontal flow is favoured within individual layers. Pore pressure data collected from piezometers were used to further constrain the flow model (Fig. 18). Given the anisotropic nature of the rock mass and permeability network, the flow net was constructed following the rules for a heterogeneous system as outlined by Freeze and Cherry (1979).

Using this conceptual hydrodynamic model, the coupled hydromechanical behaviour of the slide mass was analysed (on different temporal scales) to correlate precipitation, measured pore pressures, and slide movements. Examination of annual precipitation and displacement records between 1892 and 1995 (Fig. 19) show a significant increase in activity between 1938 and 1944, followed by several periods of acceleration and deceleration, attesting to the slide's characteristic pulsing nature (i.e., intermittent activity). These periods of increased activity roughly coincide with increases in

Fig. 15. Cumulative deformation plots for inclinometers: (*a*) CVM4 (i.e., Cimalmotto block) and (*b*) CVM6 (i.e., Campo block), as measured over several repeat surveys between 1991 and 1994. See Fig. 7 for location of boreholes. The dashed segments in these curves represent intervals for which later repeat surveys were not possible due to deformation of the inclinometer casing. The shaded circles indicate multipoint piezometer locations (e.g., P1–P4).

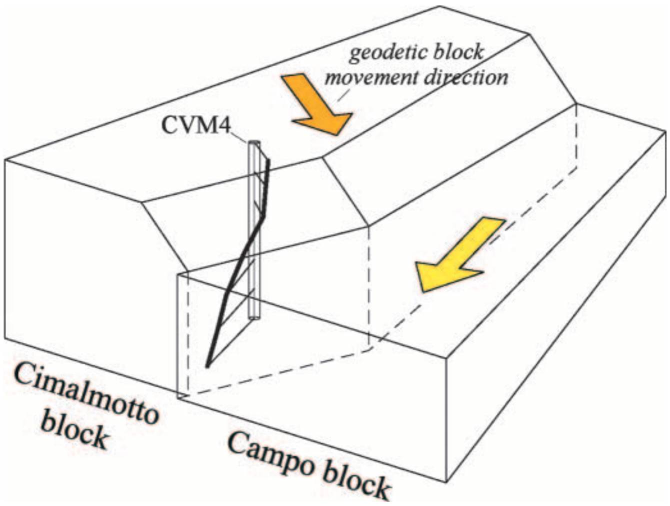


annual precipitation, at least relative to the preceding years. Prior to 1938, the plot seems to show a period of low activity and a near-uniform rate of movement, although it should be noted that the geodetic data during this time was more sparse and discontinuous.

Figure 19 also shows that slope accelerations are not necessarily proportional to the amount of precipitation. Following the drilling of borehole S2 in 1963, and the measurement of artesian overpressures in it, temporal correlations could be made between precipitation and pore pressures at depth, allowing some understanding of infiltration to be gained. Figure 20 shows the correlation between precipitation and pore pressures at 100 m depth for this borehole (located near the boundary of the Campo and Cimalmotto blocks; see Fig. 7). From this plot, there appears to be a time lag of approximately 1 to 3 months between precipitation and pore pressure response at depth. Part of the lagging effect may be attributed to snow melt, as snow melt is the key groundwater recharge source in the Alps. However, in several instances, the lagging effect is observed at times in the year where the infiltrating precipitation would only be in the form of rain.

A similar 3 month shift was observed in the higher resolution piezometers installed in boreholes CVM4 and CVM6. The completion of these boreholes in 1990–1991 coincided with the installation of the automatic geodetic station thereby allowing for the collection of both displacement and subsurface pore pressure data of a significantly higher time resolution. In the case of CVM6, where the multipoint piezometer measurements extend into the solid rock below the basal shear surface, the absolute magnitude of the pressure response below the sliding surface was not as substantial as those measured within the slide body. Although a general 3 month time lag could be recognized, closer scrutiny also showed that during intense precipitation events, an almost immediate pore pressure response occurs. Still, proportionality relationships indicate that the magnitudes of the pore pressure response depend more on the duration of the precipitation event (or the cumulative volume of water during the event) than on the intensity.

Fig. 16. Kinematic model of the Cimalmotto and Campo slide blocks based on geodetic and inclinometer data. The 3-D inclinometer response of CVM4 is superimposed on the Cimalmotto block to illustrate the dragging effect of the Campo block on the Cimalmotto block (see Fig. 10).



These proportionality relationships were also reflected in the coupled hydromechanical behaviour of the slide mass; intense precipitations could provoke an immediate reaction, but of minor significance, whereas prolonged precipitation (e.g., approximately 10 days) would result in more sizeable and longer reactions. Given the heterogeneous nature of the subsurface fracture permeability structures, this is obviously a simplified generalization. However, both aspects appear to work together where the first (intensity) serves to initiate movements and the second (duration) works to maintain the regularity of the traction. This behaviour was consistently observed throughout the high-resolution monitoring period (1991–1995). Figure 21 shows the response of the Campo main block to pore pressure responses at approximately 178 m depth (in borehole CVM6). By superimposing the two data sets, a very close fitting relationship can be derived showing that periods of accelerated slope movement occur whenever piezometer levels (hydraulic heads) exceed 1385 m elevation (i.e., 230 m pressure head, or 23 bar, at the pressure device, installed at 1156 m elevation).

Examining the data in closer detail with respect to the second half of 1993, during which a period of peak slope accelerations were recorded, the effects of intense and prolonged precipitation on the slide movements can be more easily seen. Figure 22 shows that towards the end of September, a 3 day period of intense rainfall averaging 150 mm/day occurred and was shortly followed 4 days later by slope movements that surpass any measured in the previous 5 years (43 mm in 1 day). In the days following this intense precipitation event, rainfalls subsided and the sudden surge forward by the slope abruptly stopped, thus appearing as a singular slip event. Several days later (beginning of October), the rainfall began again but at a more moderate level (<50 mm/day on average) and lasted for a 2 week period. At first no change was seen in the measured pore pressure response in borehole CVM6, nor in the slope velocities. Two weeks after its commencement though, the longer duration rainfall became perceptible in the pore pressure signal and slope movements were detected again. These displacements continued over the next 3 months maintaining a somewhat constant velocity of approximately 10–20 cm/week, in accordance with the relatively constant pulse of increased pore pressures. Finally, after approximately 3 months, the pore pressure "pulse" subsided to near normal levels and the slope movements ceased.

Rock mass creep deformation

The geodetic measurements on surface clearly show that slope movements for the Campo Vallemaggia landslide are not continuous but intermittent. Subsurface deformation records from the inclinometer measurements concur, especially with respect to the Campo block for which a translational sliding mechanism is clear. However, elements of viscous creep deformation also appear in the inclinometer records, especially for the Cimalmotto block, presumably because its movement is constrained by the Campo block. Figure 15*a* suggests that below 180 m the displacement mechanism in borehole CVM4 is largely controlled by diffused rock mass deformation. Above this zone, the heterogeneous nature of the slide mass behaves partly in a brittle elastic manner, especially in the unweathered gneisses, but as confinement and stresses increase with depth, a transition to ductile yielding appears to occur coinciding with a lithology change to deeper schists. This enables zones of yield or rupture to develop, along which localized shear deformation–displacements may concentrate, the deepest of which can be viewed as forming a basal yield zone separating the moving slide mass from the stable, undisturbed bedrock.

Thus, although stick-slip behaviour may be the dominant mechanism causing downslope movement of the Campo Vallemaggia landslide, the displacements were never zero. Viscous displacements in one form or another are always present, if not along definable shear surfaces, then through material creep within yielding blocks. Vulliet and Hutter (1988) developed a series of viscous-type constitutive laws to describe such movements, the most applicable for Campo Vallemaggia being a power sliding law where velocity monotonically increases as a function of shear stress (i.e., nonzero sliding velocity as long as the shear stresses are above zero). This sliding law can be written as

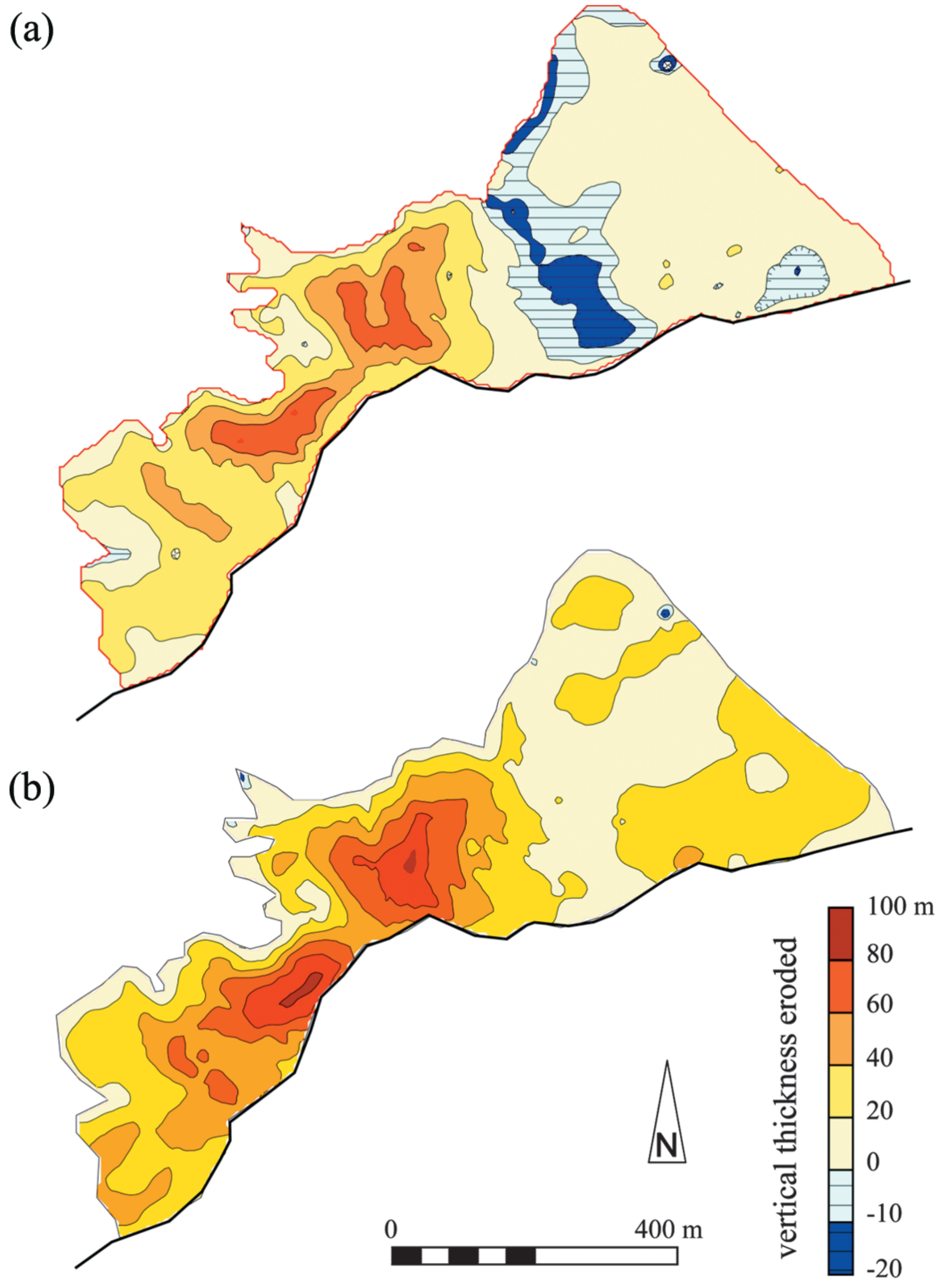
$$[1] \qquad f(\cdot) = \mathrm{B} \frac{\tau_{\mathrm{B}}^{\mathrm{n}-1}}{(c + \sigma'_{\mathrm{B}} \tan \phi)^{\mathrm{n}}} \qquad \mathrm{n} \geq 1$$

where $f(\cdot)$ is defined as a sliding coefficient (the inverse of viscosity), τ is the basal shear stress, B and n are phenomenological material constants, c is the cohesion, ϕ is the angle of friction, and σ'_{B} is the effective normal stress acting at the base. The term $f(\cdot)$ is then related to the sliding velocity along the base, v_{B}, by assuming that the counteraction exerted along the basal surface is effectively a viscous fluid resistance

$$[2] \qquad v_{\mathrm{B}} = f(\cdot)\, \tau_{\mathrm{B}}$$

Note that if n = 1, then the velocity is proportional to the viscosity, and as n increases, the mechanism becomes more and more controlled by friction and the influence of viscosity diminishes.

Fig. 17. Degree of erosion at the toe of the Campo block between 1888 and 1994. (*a*) Results based on DTM analysis of data set uncorrected for horizontal displacements of landslide over the given time period. (*b*) Results from corrected analysis. Contours represent the vertical thickness of eroded material (i.e., erosion isopachs). Horizontal hatched contours signify a net gain (i.e., slope movements are greater than the rate of erosion).



These relationships were used to calculate the coefficients B and n for the Campo and Cimalmotto main blocks using inclinometer data from boreholes located on each slide block (Fig. 23). Normal stresses were estimated using the 3-D geological model constructed to derive slide body thicknesses, pore pressures were calculated from piezometer data, and the Mohr–Coulomb shear strength parameters were obtained from limit equilibrium back-analysis (c = 100 kPa; ϕ = 31°). The results given in Fig. 23 show two different trends for the Campo and Cimalmotto blocks, with creep velocities being greater for the Cimalmotto block (stick-slip being a much greater contributor to displacements in the Campo block than creep). It should be noted that these values are based on displacements recorded over the autumn of 1993, during which time periods of increased movement were being measured by the automated geodetic system.

Discussion

Active landslides with dimensions similar to Campo Vallemaggia are rare (Petley 1996). In the last few decades there have been numerous studies examining deep-seated slope processes and phenomena beyond that of simple limit equilibrium back analyses, for example incorporating ele-

Fig. 18. Semiquantitative 2-D hydrodynamic flow model of the lower Campo block showing piezometric observations, equipotential contours and groundwater flow vectors.

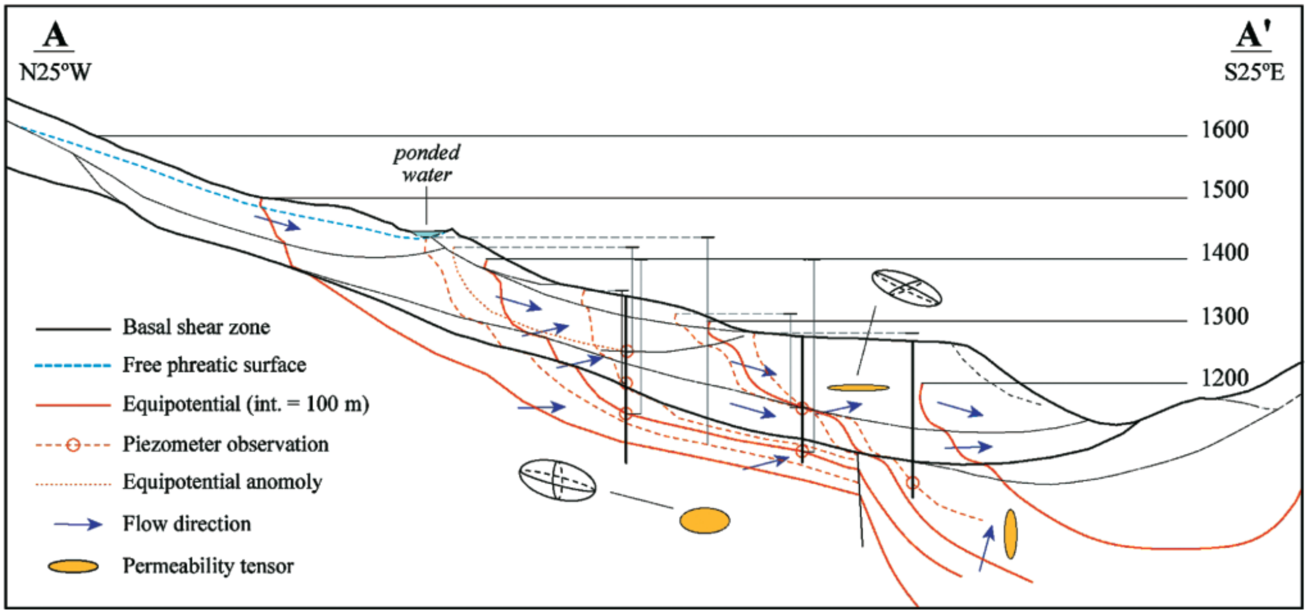


Fig. 19. Correlation between precipitation and landslide velocity for the period 1892 to 1995. Annual cumulative precipitations normalized to yearly average of 1825 mm/year recorded for that period. Slope velocities are based on geodetic measurements of the Campo block.

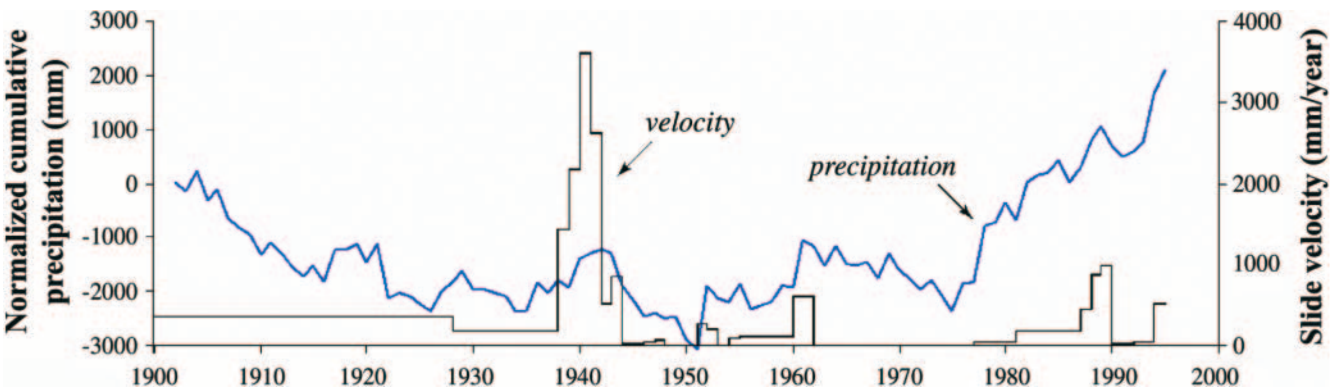


Fig. 20. Correlation between precipitation and the time lag in measured piezometer response in borehole S2 (1964 to 1969). Precipitation is normalized to the daily cumulative average of 4 mm/day measured for that period, and the piezometer response is expressed as the hydraulic head (i.e., elevation of the water column in the open-hole piezometer).

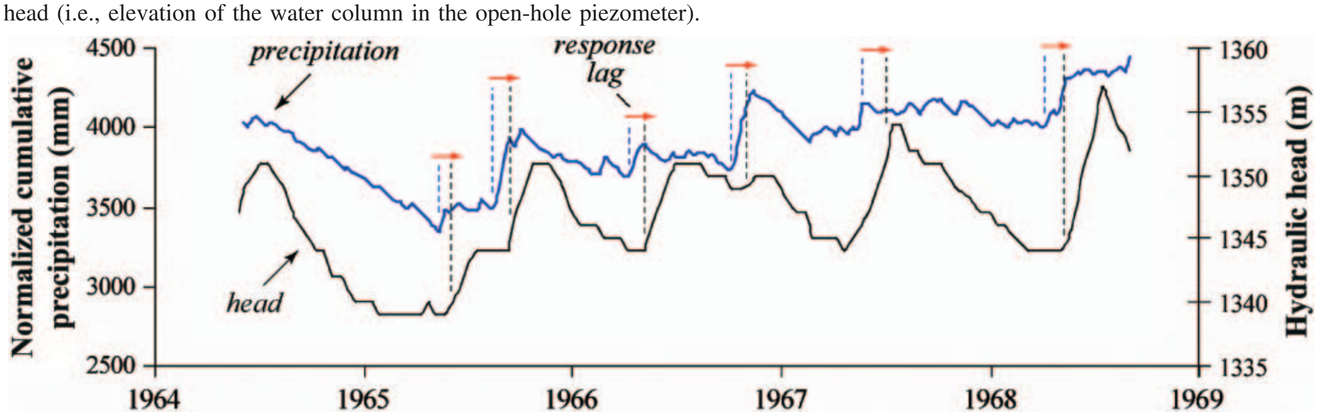


Fig. 21. Correlation between downslope velocities of the Campo block and pore pressures measured in borehole CVM6 between 1991 and 1995. Slide velocities were measured using an automated geodetic station; pore pressures are expressed as the hydraulic head (i.e., elevation of the water column in the piezometer).

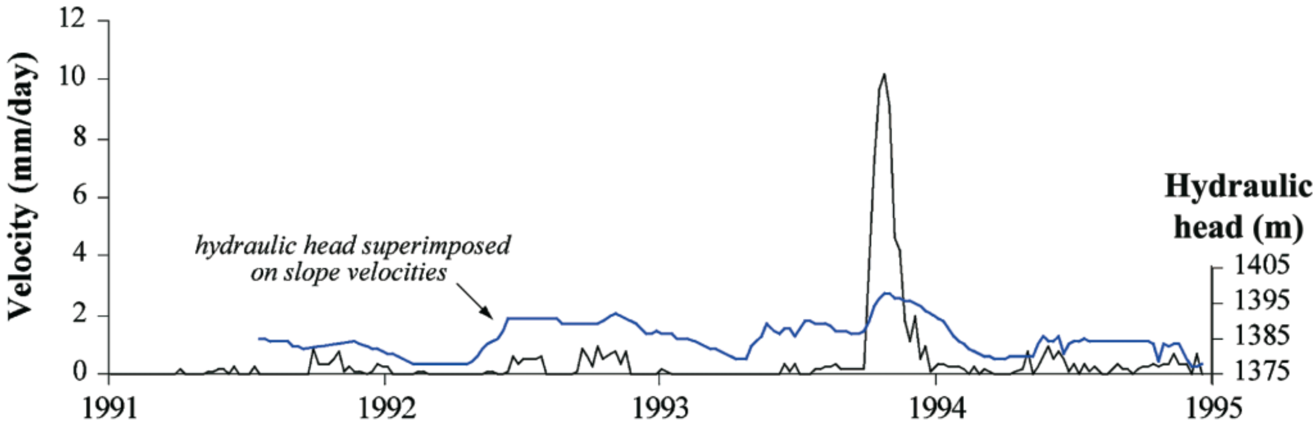
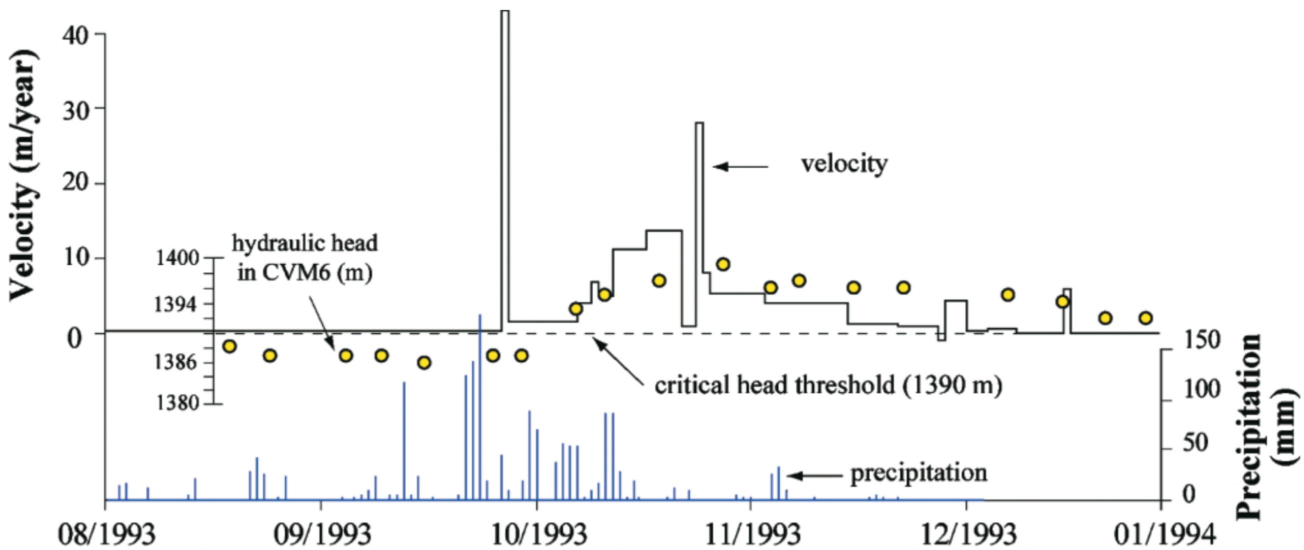


Fig. 22. Relationship between precipitation, pore pressure response at depth (CVM6), and slide block velocity as measured by the automatic geodetic station. Note that the pore pressures in CVM6 are plotted in terms of hydraulic head and superimposed on the velocity curve such that zero velocity corresponds to the critical threshold hydraulic head value of 1390 m elevation.



ments of viscous creep. Several analogies involving deep-seated creeping landslide behaviour can be made, although most involve instabilities in argillaceous rocks. These slides often only extend to depths of several tens of metres, and in some cases, involve more fully developed shear surfaces that exhibit characteristics better defined by residual strength than creep behaviour. Examples include the La Frasse (Vulliet and Hutter 1988) and Chlöwena (Vulliet and Bonnard 1996) landslides.

Deep-seated instabilities in crystalline rock tend to be deeper and involve processes dominated by brittle behaviour and internal shearing, and to a lesser degree viscoplastic creep. Examples of instabilities more analogous to that of Campo Vallemaggia include

- La Clapière landslide, France – also in gneissic schists with a volume of 50 million cubic metres (Julian and Anthony 1996);
- Ingapata, Ecuador – of smaller size than Campo Vallemaggia, but similar in terms of varying alteration of schists with depth (Riemer et al. 1988);
- Nine Mile Creek landslide, New Zealand – numerous faults and internal shearing in schists, with deep alteration and a maximum thickness of 150 m (Beetham et al. 1991);
- Dutchman's Ridge, Canada – weathered gneisses and mica schists, numerous faults separating pore pressure compartments, thickness of nearly 200 m and a volume of 115 million cubic metres (Moore and Imrie 1995).

Such comparisons help to reveal common characteristics of deep-seated landslide phenomena. For example, large slope instabilities in crystalline rock are often subdivided into several discrete blocks by internal shearing and faulting, and therefore act as a complex discontinuous assemblage of moving blocks as opposed to that of a more coherent continuum. In the case of Campo Vallemaggia, the division of the

Fig. 23. Relationship between stability state and slope creep. Derived values for B and n parameters based on viscosity power laws (after Vulliet and Hutter 1988) fitted to inclinometer data from the Cimalmotto and Campo slide blocks.

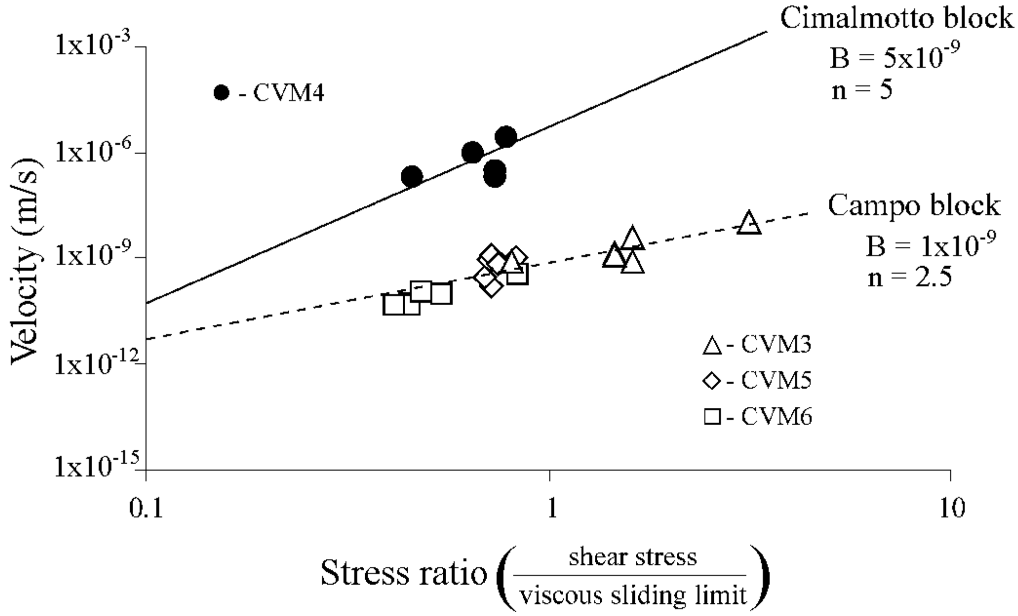
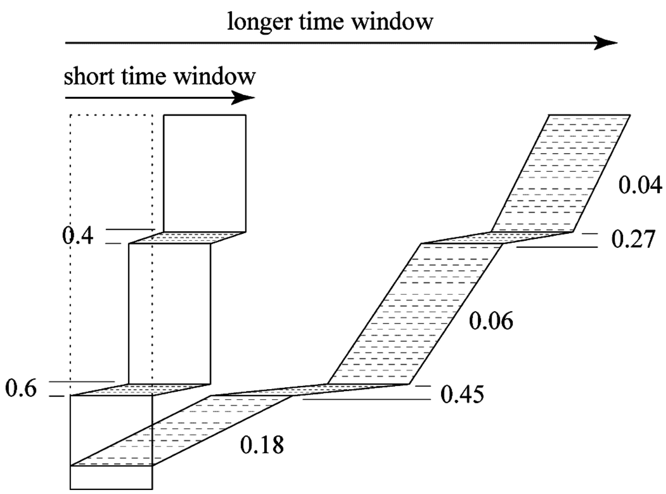


Fig. 24. Schematic representation of slide mass deformation with depth, showing ratio of displacements concentrated along internal shear zones for an arbitrary short time window and those also dispersed across intact rock blocks through interblock creep over a longer time window. Relative values referenced to those measured by inclinometers in the Campo block.



slide mass along fault structures and lateral shear zones plays a significant role in terms of the overall kinematics, movement, and rheological behaviour of the slide. Further complexity and heterogeneity is added through internal shearing and mineralogical degradation effects within the slide mass. A schematic representation of this complexity based on geodetic and inclinometer readings for the Campo block is given in Fig. 24. When examining the displacement record over a short arbitrary time window, most of the downslope movements appear to be accommodated along (two) internal shear zones and not a single basal rupture surface. When a longer time window is considered, movements still largely concentrate along the two internal shear zones but are supplemented by interblock creep in the intervals between the shears. Both the internal shearing and the interblock creep are seen to increase as a function of depth.

Pore pressures also play an important role in each of the cases listed above, although not always in the form of artesian pressures as is the case for Campo Vallemaggia. At Campo Vallemaggia, large open tension fractures at the head of the slide body act as pathways allowing precipitation to more easily infiltrate into the subsurface. Internal shearing and localized mineral alterations work to create anisotropic permeability conditions where subhorizontal flow is promoted within individual layers of the landslide mass. Steeply inclined and NNW trending brittle fault zones further subdivide the landslide into blocks and act to promote vertical flow upwards below the foot of the landslide. The resulting complex, heterogeneous hydrogeological situation introduces different forms of reaction delays between surface precipitation and its influence at depth along internal sliding surfaces. Intense precipitation events quickly infiltrate into upper portions of the slide mass resulting in sudden movements, some of which are localized, whereas prolonged precipitation events have a more significant effect on deeper flowing groundwater and artesian pressures, which in turn drive more continuous movements over a longer period of time.

Conclusions

The Campo Vallemaggia landslide is a massive deep-seated creeping slide mass of approximately 800 million cubic metres of metamorphic crystalline rock, subdivided into a complex assemblage of blocks by tectonic faults and internal shearing. The unstable mass reaches depths of up to 300 m, within which viscous rock deformations and artesian water pressures have been observed and measured. Several key factors and coupled hydromechanical processes have been examined in an attempt to better understand the acting mechanisms responsible for the slope movements. These include:

- compositional layering, mineralogical degradation, and deep artesian overpressures;
- preferential groundwater flow along steeply inclined brittle fault zones;
- slope movements that are not directly correlated to precipitation;
- the forward pulsing behaviour of the slide mass;
- the massive but unbalanced erosion at the slope's toe; and
- the presence of multiple subhorizontal sliding planes and interblock creep behaviour.

Inclinometer measurements reveal that displacements are distributed unevenly along the slide profile and concentrate along internal shear zones of several metres thickness. Displacements in these zones indicate stick-slip type deformations. Further analysis shows that this behaviour is highly sensitive to accumulated pore pressures resulting from longer-term precipitation events. Results show that pore pressure values exceeding an apparent threshold value coincide with sudden accelerations of the slide mass. Velocities then return to background levels as pore pressures dissipate and drop below the threshold.

Historically, expert opinions have focussed on surficial processes, primarily erosion of the slope's toe, to explain the slope movements at Campo Vallemaggia. Based on these opinions, numerous attempts were made to stabilize the slope through erosion control and surface drainage measures, but with limited success. Only after the detailed investigation reported in this paper was carried out, combining geological mapping, geophysical and hydrogeological testing, and surface and subsurface geotechnical monitoring, were the kinematics of the landslide and the important role deep artesian water pressures play in driving the instability better understood. Based on these results, alternative solutions calling for mitigation through deep drainage were considered. This action, its implementation, the monitored response of the slide mass, and numerical modelling results used to illustrate the effectiveness of deep drainage in deep-seated landslides are reported in Part II (Eberhardt et al. 2007).

Acknowledgments

The authors wish to acknowledge the input and assistance of the many people involved in the early days of the detailed investigation initiated in 1983. From the Canton of Ticino, Fulvio Caccia and Aldo Conca, and from the ETH Zurich, Prof. Conrad Schindler and Dr. Werner Balderer. Dr. Jean-Luc Michelot, University of Paris South, assisted with the isotope analyses, Dr. Erwin Scheller, Geotest Switzerland, with the seismic surveys, Drs. Walter Frei and Peter Lehner, National Plan 20, with the reflection surveys, Manfred Scherbl and Ivan Wucic, Swissboring company, with the borehole drilling, and Dr. Daniel Naterop, Solexperts Switzerland, with the borehole instrumentation.

References

Amstad, Ch., Koeppel, J., and Kovari, K. 1988. TRIVEC-measurements in geotechnical engineering. *In* Proceedings of the International Symposium on Field Measurements in Geomechanics, Kobe. *Edited by* S. Sakurai. A.A. Balkema, Rotterdam. Vol. 1, pp. 17–32.

Beetham, R.D., Smith, G., Jennings, D.N., and Newton, C.J. 1991. The geology of Nine Mile Creek schist landslide complex. *In* Proceedings of the 6th International Symposium on Landslides, Christchurch. *Edited by* D.H. Bell. A.A. Balkema, Rotterdam. Vol. 1, pp. 25–31.

Bonzanigo, L. 1999. Lo slittamento di Campo Vallemaggia. D.Sc. thesis, Engineering Geology, Swiss Federal Institute of Technology (ETH Zurich), Zurich, Switzerland.

Cronin, V.S. 1992. Compound landslides: Nature and hazard potential of secondary landslides within host landslides. Geological Society of America Reviews in Engineering Geology, **9**: 1–9.

Eberhardt, E., Bonzanigo, L., and Loew, S. 2007. Long-term investigation of a deep-seated creeping landslide in crystalline rock. Part II. Mitigation measures and numerical modelling of deep drainage at Campo Vallemaggia. Canadian Geotechnical Journal, **44**: 1181–1199.

Freeze, R., and Cherry, J.A. 1979. Groundwater. Prentice-Hall, Englewood Cliffs, New Jersey. p. 604.

Grütter, O. 1929. Petrographische und geologische Untersuchung in der Region von Bosco (Valle Maggia), Tessin. Verhandlungen der Namrforschenden Gesellschaft in Basel, **40**: 79–152.

Hall, W.D.M. 1972. The structural geology and metamorphic history of the lower penninic nappes, Valle di Bosco, Ticino, Switzerland. Ph.D. thesis, University of London, UK.

Heim, A. 1897. I movimenti di terreno di Campo V.M. *Report by* Albert Heim for the local regional authorities (translated from German into Italian by Alberto Totanzi, Cimalmotto).

Heim, A. 1932. Bergsturz und Menschenleben. Fretz and Wasmuth Verlag, Zurich. 218 pp. (English translation by Skermer, N.A. 1989. Landslides and Human Lives. BiTech Publishers, Vancouver. p. 195)

Julian, M., and Anthony, E. 1996. Aspects of landslide activity in the Mercantour Massif and the French Riviera, southeastern France. Geomorphology, **15**: 275–289. doi:10.1016/0169-555X(95)00075-G.

Lollino, G., and Wasowski, J. 1994. Deep inclinometer monitoring of a partially remobilised old landslide complex: Case of Caramanico Terme, south-central Italy. *In* Proceedings of the 7th Congress of the International Association of Engineering Geology and the Environment, Lisbon. *Edited by* R. Oliveira et al. A.A. Balkema, Rotterdam. Vol. 3, pp. 1451–1458.

Mondada, G. 1977. Commerci e commercianti di Campo Valmaggia nel settecento. Edizioni del Cantonetto, Lugano. p. 242.

Moore, D.P., and Imrie, A.S. 1995. Stabilization of Dutchman's Ridge. *In* Proceedings of the 6th International Symposium on Landslides, Christchurch. *Edited by* D.H. Bell. A.A. Balkema, Rotterdam. Vol. 3, pp. 1783–1788.

Noverraz, F. 1996. Sagging or deep-seated creep: Fiction or reality? *In* Proceedings of the 7th International Symposium on Landslides, Trondheim. *Edited by* K. Senneset. A.A. Balkema, Rotterdam. Vol. 2, pp. 821–828.

Petley, D. 1996. The mechanics and landforms of deep-seated landslides. *In* Advances in hillslope processes. *Edited by* M.G. Anderson and S.M. Brooks. John Wiley & Sons Ltd., New York. pp. 823–835.

Riemer, W., Locher, T., and Nunez, I. 1988. Mechanics of deep seated mass movements in metamorphic rocks of the Ecuadorian Andes. *In* Proceedings of the 5th International Symposium on

Landslides, Lausanne. *Edited by* Ch. Bonnard. A.A. Balkema, Rotterdam. Vol. 1, pp. 307–310.

Vulliet, L., and Bonnard, Ch. 1996. The Clöwena Landslide: Prediction with a viscous model. *In* Proceedings of the 7th International Symposium on Landslides, Trondheim. *Edited by* K. Senneset. A.A. Balkema, Rotterdam. Vol. 1, pp. 397–402.

Vulliet, L., and Hutter, K. 1988. Viscous-type sliding laws for landslides. Canadian Geotechnical Journal, **25**: 467–477.