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LONG-TERM SLOPE DEFORMATION MONITORING IN THE HIGH MOUNTAINS OF THE WESTERN CARPATHIANS

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ABSTRACT
In this paper, results from the long-term monitoring of two deep-seated slope deformations are presented. These deformations are considered typical of the types of landslide that occur in the high mountains of the Western Carpathians. The localities are situated in similar geological settings and this has enabled direct comparison of their development over the past 30 years. The monitoring has been undertaken using the extensometric gauges, TM71. At the Parohy Site, results from the scarp area show a significant vertical displacement trend of 0.07 mm per year. At the Štrochy Site, results from the crown area show a horizontal crack opening trend of 0.015 mm per year. Monitoring is ongoing at both sites.

KEYWORDS: deep-seated, topple, slope deformation, displacements, long-term monitoring, extensometer, high mountains, Western Carpathians.

1. INTRODUCTION

During the 1970s, the urgent need to study deep-seated slope deformations within high mountainous regions was recognised. This recognition followed the tragedy in Vajont, Italy, when, on October 9, 1963, an enormous landslide (~ 260 million m^3 of debris) slid into a mountain water reservoir. The landslide caused 50 million m^3 of water to overtop the dam in a 250-metre high wave. The consequences were catastrophic (Mantovania and Vita-Finzi, 2003; Kilburn and Petley, 2003).

In Slovakia, deep-seated slope deformations were selected in order to monitor their activity at two localities (Parohy in the Malá Fatra Mts and Štrochy in the Veľká Fatra Mts). Consequently, three extensometric TM71 gauges were installed to observe the massif and its behaviour. Despite it initially being a short-term monitoring project, measurements continue to be taken on two of the three gauges. This paper presents the results of this slope deformation study and interprets the data in terms of the long-term displacement trends.

2. GEOLOGICAL AND GEOMORPHOLOGICAL SITUATION

The mountainous part of the Western Carpathians includes the Malá Fatra and Veľká Fatra Mts. in Slovakia. The core of these mountains comprises metamorphic rocks of Precambrian age. These metamorphic rocks are overlain by sedimentary rocks of Triassic-Lower Cretaceous age (Polák et al., 2008): the oldest variegated sandstone-marlstone-limestone formation; the intermediate limestone-dolomitic formation; and the youngest terrigenous formation. The majority of slope deformations are developed in the variegated sandstone-marlstone-limestone formation. Their development has been influenced by the local tectonic situation, neotectonic uplift, and fluvial erosion. The primarily control on landslide development here is provided by the differential strength of the individual rock complexes: the soft argillaceous layers can be plastically modified whereas the overlying rigid thick-bedded complexes do not accommodate such deformations. The latter usually creep over schistose strata into valleys, accompanied by rockfalls.

2.1. PAROHY SITE (MALÁ FATRA MTS) **49°11'25.00'' N, 19°03'44.00'' E**

The slope deformation at the Parohy Site (also referred to as the Steny Site) forms part of a vast slope deformation area that has affected a large part of the Mala Fatra Mts ridge. The site is characterised by southeasterly deep-seated sagging (*sensu* Hutchinson,

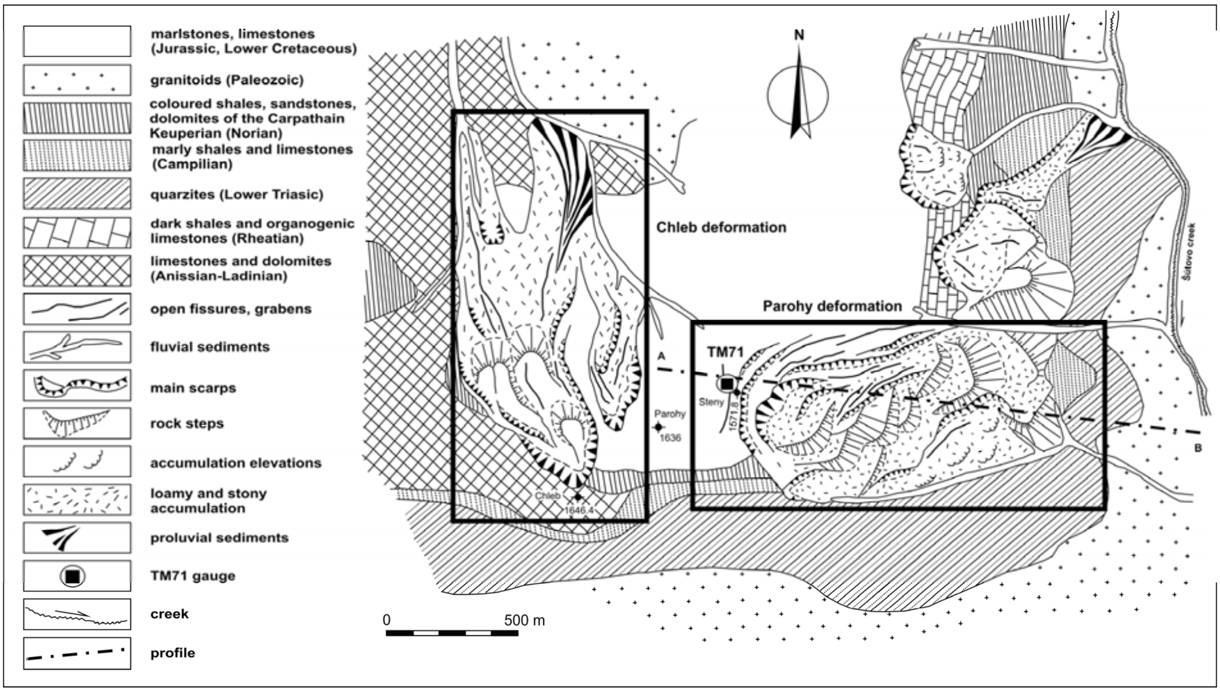

Fig. 1 Geological map showing the location of the TM71 and the area surrounding the Parohy Site (after Nemčok, 1973).

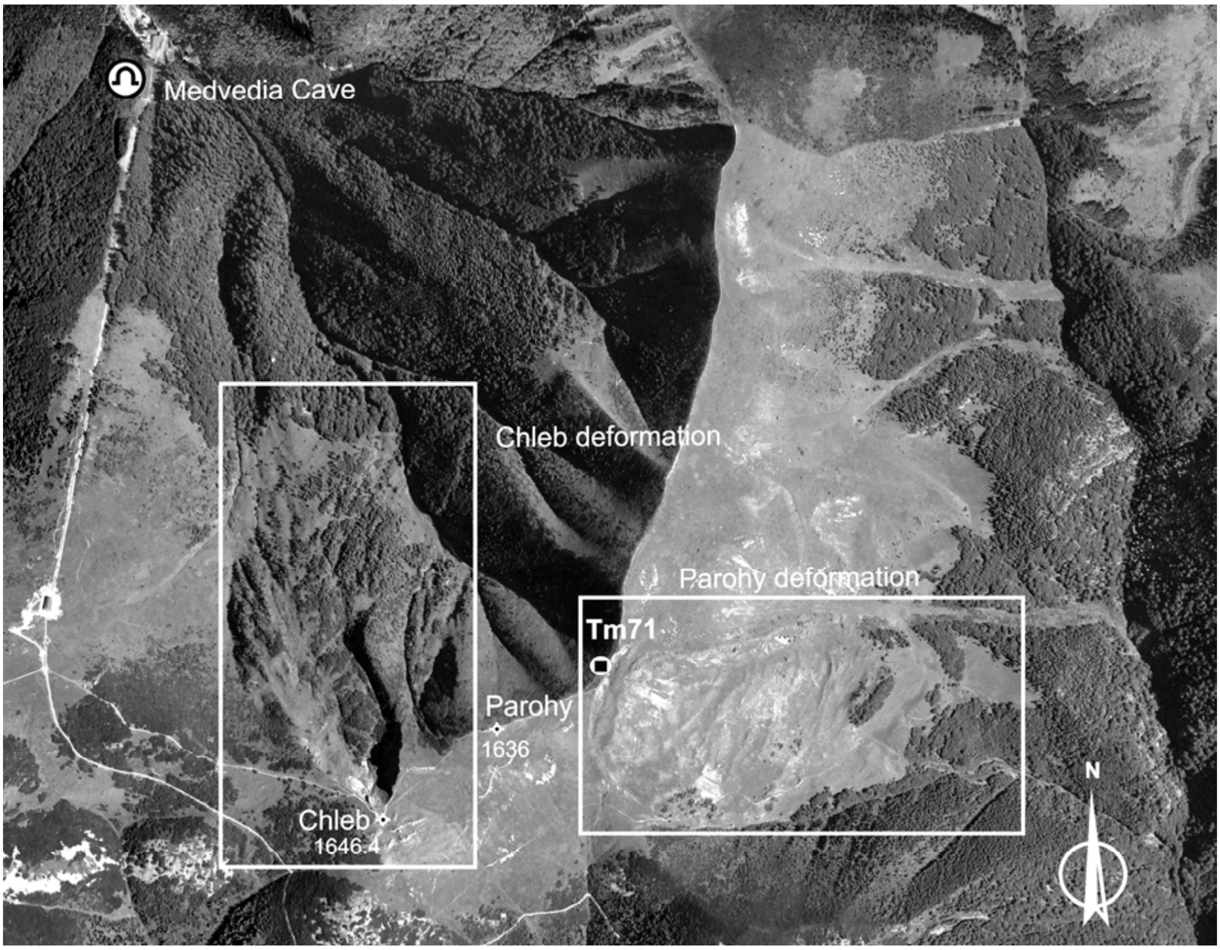

Fig. 2 Satellite image showing the slope deformation in the vicinity of the Parohy Site, Malá Fatra and the location of Medvedia Cave. The image is adopted from GoogleEarth.

1988), relicts of which can be seen on the ridge and southern slopes of Parohy. This deformation has a length of 1 200 m and a width of 600 m (Figs. 1, 2). The accumulation part (*sensu* Dikau et al., 1996) is constructed by two marginal slope deformations with a width of 1 000 m. The slope deformation developed in a carbonate nappe (Krížna) overlying a soft shale complex (Verfén). The northern side of the deformation was predisposed by a tectonic fault, with shear zones and scarps formed in this area. The upper part of the slope deformation is characterised by scarps behind hill crest and also grabens (Nemčok, 1982).

The nearby slope deformation at Chleb developed on the opposite side of the ridge to the slope deformation at Parohy (Figs. 1, 2). Although the geological setting is similar, this slope deformation was not deep-seated (*sensu* Hutchinson, 1995). Instead, it took the form of a rock slide (Nemčok, 1973). The massif deformations in wider vicinity of the rock slide (*sensu* Dikau et al., 1996) can be seen in Medvedia Cave (Fig. 3), which is located north-northwest of the Chleb deformation (Fig. 2). Neotectonic activity on the fault (54°→228°), crossing the cave, was discussed by Pavlarčík and Peško (1983). The slide could result from slope deformation across a wide area or from recent tectonic activity on the nearby fault zone, as reflected in Medvedia Cave.

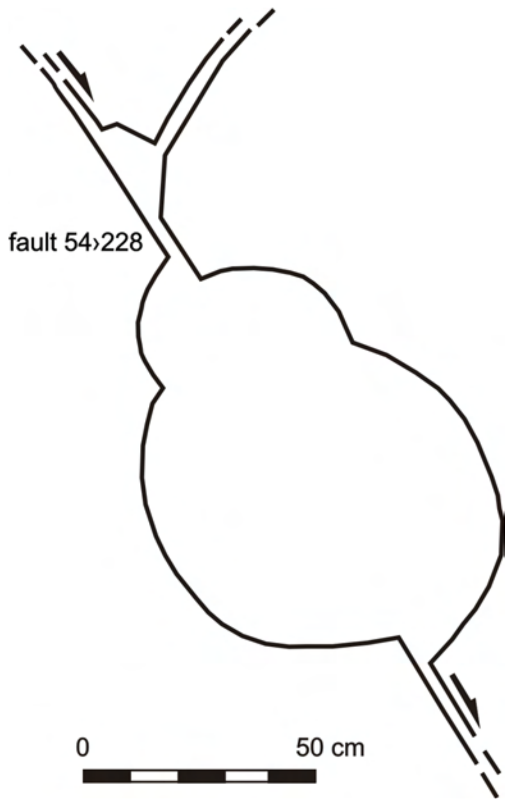

Fig. 3 Profile of the gallery in Medvedia Cave (modified after Pavlarčík and Peško, 1983).

2.2. ŠTROCHY SITE (VEĽKÁ FATRA MTS)
48°54'32.72'' N, 19°03'33.15'' E

This site is characterised by a deep-seated slope deformation of the topple type (*sensu* Dikau et al., 1996). The development of the slope deformation here occurred in a similar geological setting to that of the Parohy Site. As Gader stream incised into the massif, the flanking limestones of the Choč nappe slid over the softer, more plastic, marlstones and marly limestones of the Krížna nappe and into the incised valley (Fig. 4). This sliding was also accompanied by rockfalls (Fig. 5). A shallow slide has also been generated in the marlstones and marly limestones in the toe area of the slope deformation (Fig. 6).

3. METHODOLOGY

In order to investigate three dimensional microdisplacements in harsh field conditions, we have used the combined extensometric gauge, TM71 (e.g. Košťák, 1991; Briestenský and Stemberk, 2008; Briestenský et al., 2010). The gauge is a mechanical-optical instrument without any electrical components. It is known to be capable of surviving for tens of years in the field without any maintenance. The gauge indicates three fault displacement components (strike-slip, crack opening, and vertical displacements) and rotations in two transversal planes. The resulting accuracy is better than 0.01 mm per year.

Data are collected manually or by camera. Theoretically, the monitoring interval is monthly although the harsh climatic conditions of the high mountains sometimes make it impossible to achieve that. However, to fully understand slope deformations, the most fundamental requisite is a protracted monitoring period (Košťák and Rybář, 1978; Briestenský et al., 2010).

4. RESULTS

4.1. PAROHY SITE

At the Parohy Site, regular monitoring started in 1973 (Pašek and Košťák, 1977). A TM71 crack gauge was installed in a scarp furrow behind the hill crest close to Steny Peak (1571 m asl) (Figs. 1, 2 and 7). Data have been recorded at least twice per year with higher frequencies only attained at the beginning of the monitoring period.

The most remarkable movement component is vertical displacement. This shows subsidence of the southeastern block, i.e. active landslide movements with a trend of 0.07 mm/year. A secondary movement component shows clear dextral strike-slip with a trend of 0.032 mm/year for the period 1988-2010. The same movement component is also seen in the period 1978-1986. It appears that the long-term dextral linear trend is sometimes broken by a sinistral effect. This was the

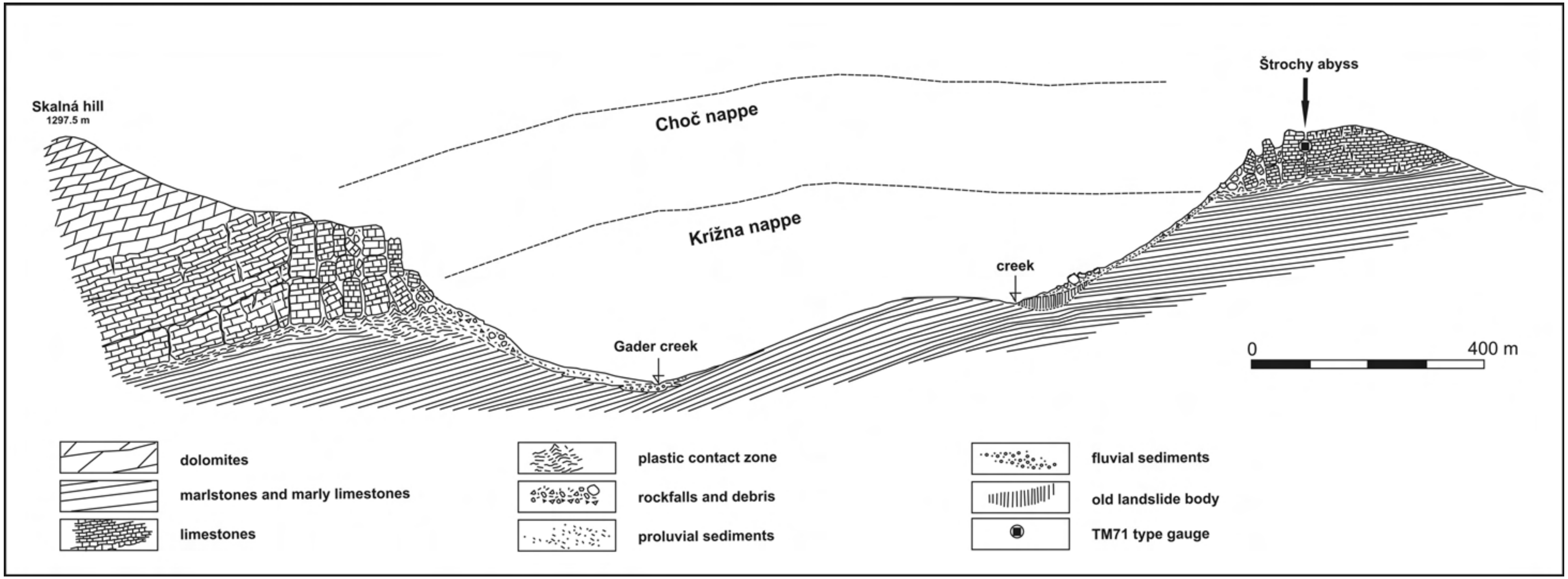

Fig. 4 Geological profile showing the area surrounding the Štrochy Site. The profile refers to the profile line in Figure 6 (after Fussgänger et al., 1983).

Fig. 5 A limestone block of a significant size found in the toe accumulation (photograph: M. Briestenský).

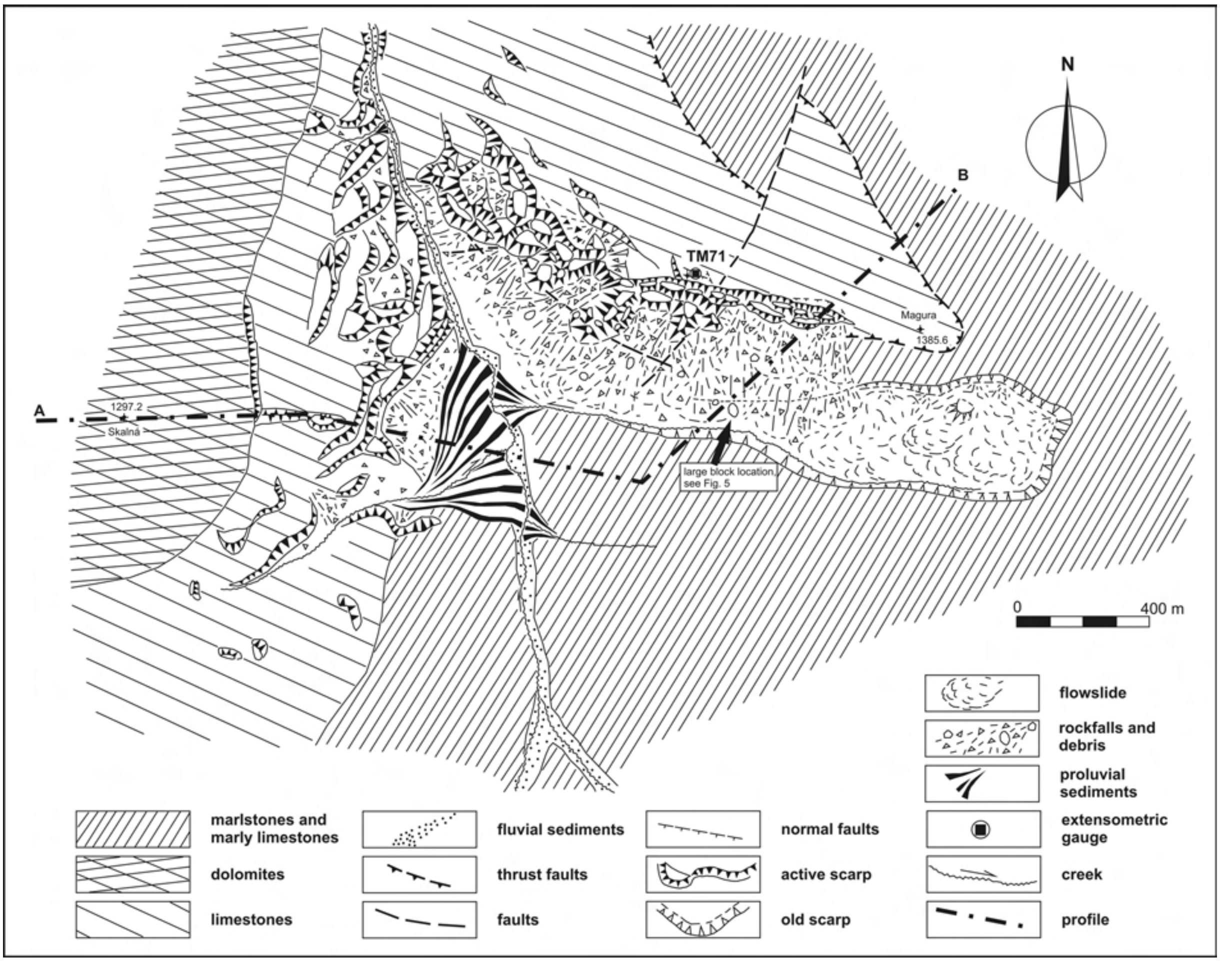

Fig. 6 Geological map showing the location of the TM71 and the area surrounding the Štrochy Site (modified after Nemčok, 1982).

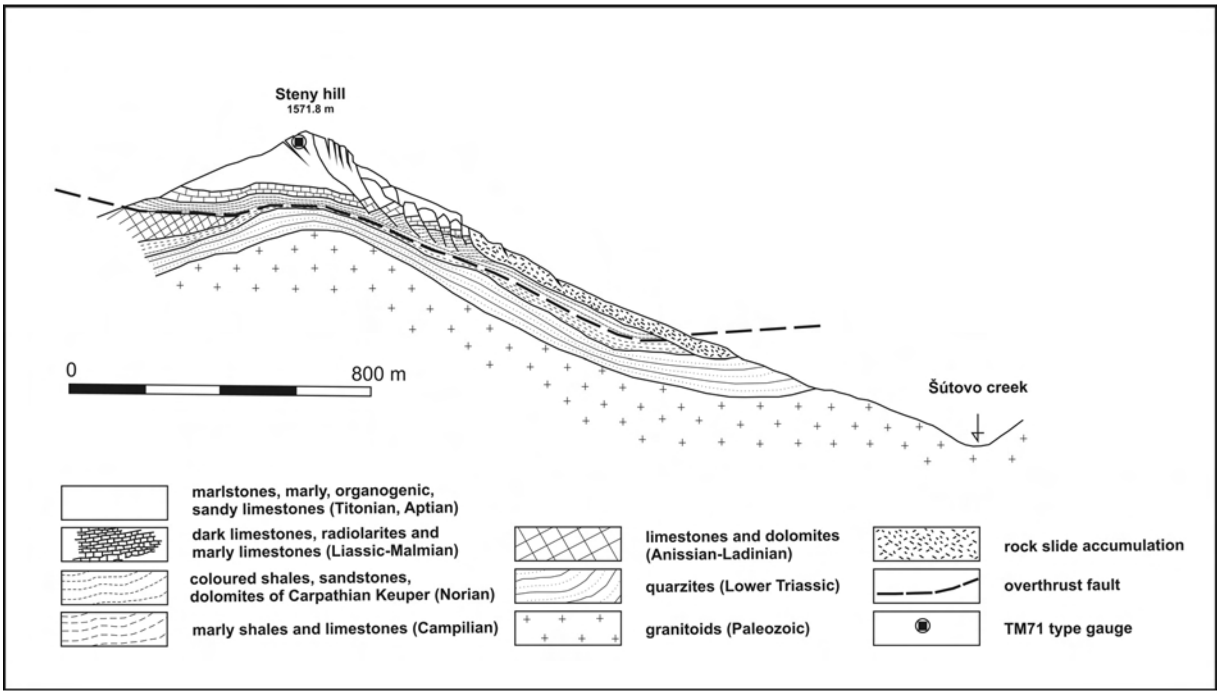

Fig. 7 A geological profile showing the position of the TM71 at the Parohy Site. The profile refers to the profile line in Figure 1 (after Nemčok, 1982).

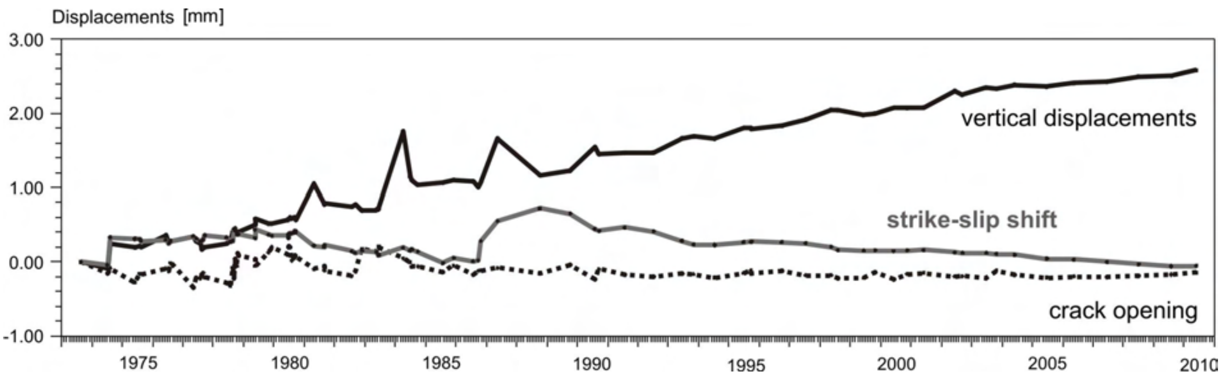

Fig. 8 Graph of the displacement data recorded at the Parohy Site.

case connected with the occurrence of spring subsidence peaks. The peaks developed regularly every three years between 1980 and 1990 during spring snow thaw periods (Fig. 8). The peaks died out just within a turn into sinistral strike-slip. It is only possible to speculate about the progressive crack failures that may develop locally within the main scarp zone. Certainly, the infiltration of water during the spring becomes a triggering factor. A more detailed discussion of such effects can be found in Košťák (1993).

It is interesting to note that it is not possible to observe any correlation between precipitation and the recorded monitoring data (Fig. 9). This suggests that the process of creep within the slope is principally gravitational and independent of precipitation levels.

4.2. ŠTROCHY SITE

At the Štrochy Site, two gauges were installed in 1982. The first gauge was located at the surface, in a tension crack above the cliff of the deformation. This gauge has subsequently been damaged due, most likely, to climatic factors. The second gauge was installed in Štrochy Cave (or Štrochy Abyss), 25 m below the surface in a tension crack (*sensu* Dikau et al., 1996). Unfortunately, monitoring was not undertaken at this site between 1993 and 2008. Nonetheless, the long-term displacement trends are

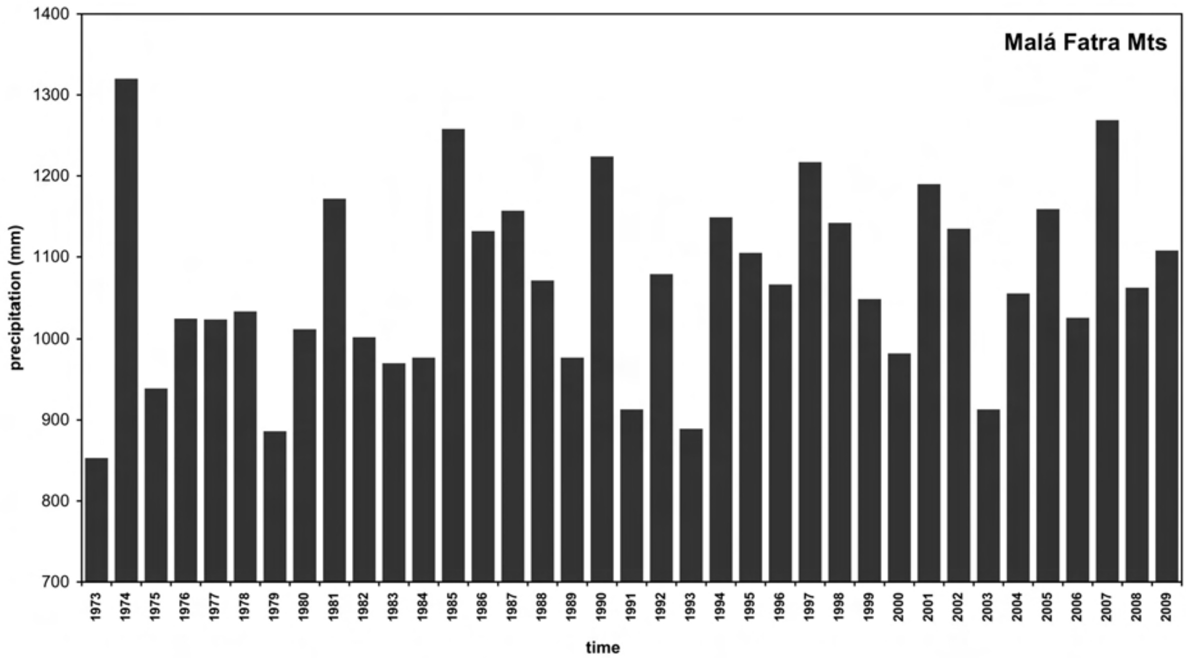

Fig. 9 Annual precipitation at the Parohy Site (data reproduced with the permission of SHI).

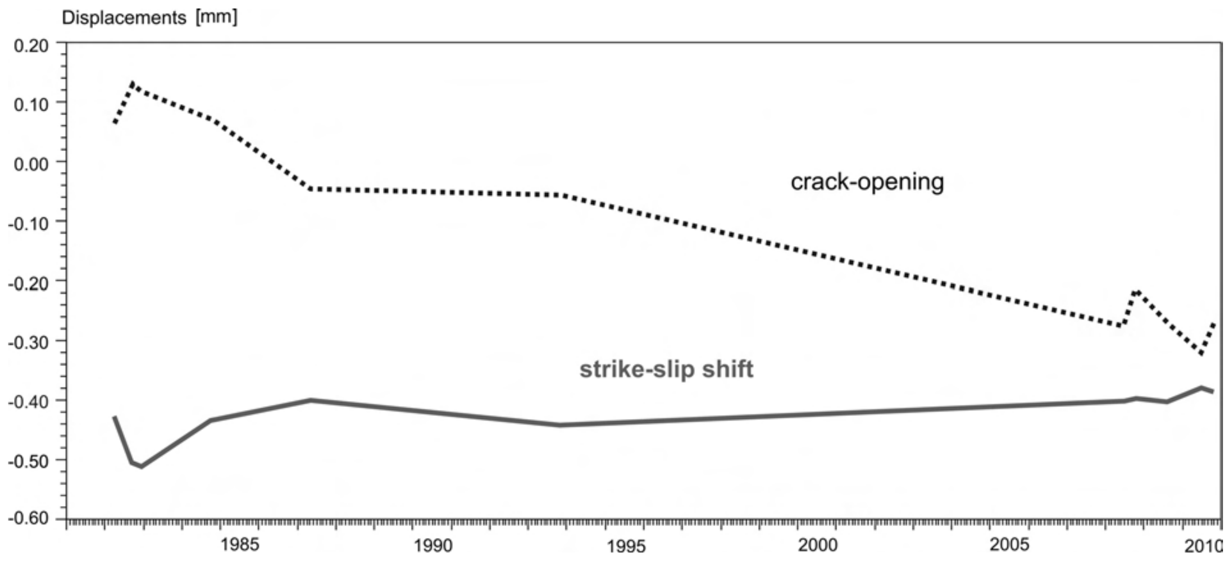

Fig. 10 Graph of the displacement data recorded at the Štrochy Site.

still easily recognisable. The horizontal component shows that the fissure has opened by 0.44 mm in 29 years (Fig. 10). Therefore, recent movements are now known to occur in the crown area of the landform.

In addition, fissure opening is displayed at the surface. The linear sinkholes above the cave show active subsidence of the cave ceiling (Fig. 11) as well as possible active flexural toppling (*sensu* Dikau et al., 1996). According to our survey, the cave developed along a vertical tectonic fault (strike: 290°) with a previous dextral strike-slip sense of movement. Within the cave, opposite walls are decorated by slickensides. Due to this, it appears that the crown area of the slope deformation was formed predominantly by the tectonic fault that crosses here. Moreover, a silent trend of 0.002 mm per year demonstrates a sinistral strike-slip mechanism (Fig. 10), which further supports recent active

Fig. 11 A sinkhole above the Štrochy Abyss. This reflects subsidence of the cave ceiling due to active fracture opening (photograph: M. Briestenský).

tectonics in the development of the slope deformation. Again, as at the Parohy Site, no precipitation effect can be observed at the Štrochy Site (Fig. 12). Therefore, gravitation movements cannot be precluded here but the measurements suggest tectonic predisposition.

5. DISCUSSION

During the long-term monitoring of the two selected sites in the high mountains, results show extremely slow displacements across and along the failures in the crown areas of the slope deformations. Due to the very slow nature of the movements, no

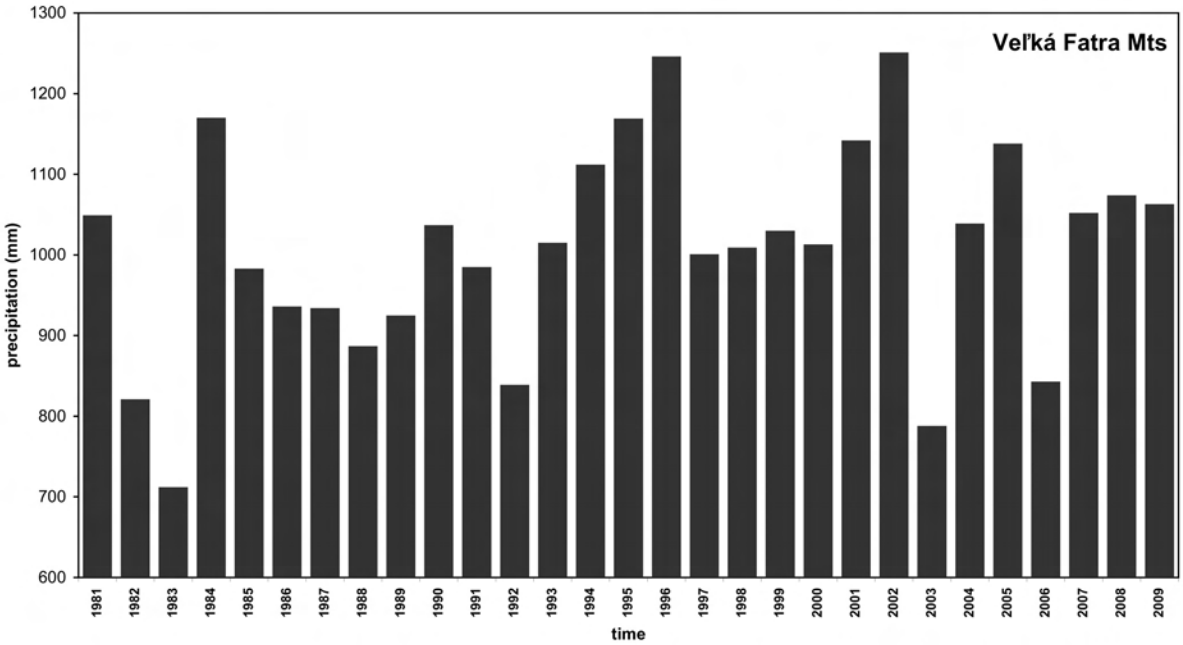

Fig. 12 Annual precipitation at the Štrochy Site (data reproduced with the permission of SHI).

additional monitoring methods have been suggested. Such displacements as those presented in this paper are not detectable with other methods such as geodetic measurements, GPS, or InSAR. The accuracy of these methods are at least an order of magnitude less than that of the TM71 (e.g. precise levelling = 0.2-1 mm/km, GPS = 5-10 mm + 1-2 ppm, PS InSAR^{TM} < 0.1 mm/year; see e.g. Gilli et al., 2000, Massironi et al., 2009). Moreover, the underground setting of the TM71 gauges at sites such as Štrochy allows us to exclude the influence of seasonal massive dilations in our results (Briestenský et al., 2010). These dilations cannot be eliminated by other methods that are used to record such small displacements at the surface. A further advantage of the gauge is that the results are presented in a three-dimensional framework. The devices also only require minimal maintenance (Petro et al., 2004). Therefore, the results of such monitoring are extremely valuable for not only recording slope deformation creep movements but they also stand as a benchmark with which the accuracy of other types of measurement should be assessed.

6. SUMMARY

Thirty years of monitoring data has proved the active and continuing development of two large deep-seated slope deformations in Malá Fatra and Veľká Fatra, Western Carpathians. At the Parohy Site in Malá Fatra, results from the scarp area show a significant vertical displacement trend of 0.07 mm per year. This value is in accord with a previous interpretation of its deep-seated genesis (Nemčok, 1973). At the Štrochy Site in the Veľká Fatra, results from the crown area show an active horizontal crack mening trend of 0.015 mm per year. Furthermore, a silent strike-slip mechanism is recognised along the monitored fault. This suggests that the slope deformation may have been initiated by tectonic movements on the fault. There is no correlation between precipitation and the monitoring data recorded at either of the deep-seated slope deformations.

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