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Advances in Geosciences

A complex geo-scientific strategy for landslide hazard mitigation – from airborne mapping to ground monitoring

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Abstract. After a large landslide event in Sibratsgfäll/Austria several exploration methods were evaluated on their applicability to investigate and monitor landslide areas. The resulting optimised strategy consists of the combined application of airborne electromagnetics, ground geoelectrical measurements and geoelectrical monitoring combined with hydrological and geological mapping and geotechnical modelling. Interdisciplinary communication and discussion was the primary key to assess this complicated hazard situation.

1 Introduction

Landslides are one of the major threats to human settlements and infrastructure, causing over time, enormous human suffering and property losses. Especially in alpine regions, population pressure has prompted settlement to more extreme areas, which are, due to their geological settings, vulnerable to landslides. Therefore effort has to be centred on risk detection, risk reduction and development of timely warning systems to prevent future loss of life and property.

In spring 1999, after a short period of heavy precipitation and the rapid melting of snow, a catastrophic landslide was triggered on the South-flank of the Rubach Valley near Sibratsgfäll in the province of Vorarlberg (Austria). Shortly after the first slide activity was observed, the State Department of Avalanche and Torrent Control authorized preliminary geological investigations.

2 The strategy (Fig. 1)

As a follow up of this first phase of investigation, a complex research program was initiated. The final goal of this study was to develop an operative strategy to optimise measures in case of future events. The applied methods incorporated geomorphological, hydro-geological and geophysical surveys of the area. It was determined that airborne geophysical measurements are a valuable tool to obtain a quick overview of the geological situation. Furthermore they can help to detect areas susceptible to a high sliding risk, to assist the follow up geological and hydrological mapping program and to optimise further ground-geophysical surveys. In a second step, ground geoelectrical surveys were used to achieve advanced understanding of the internal structure of the landslide. The location of survey lines was planned according to the resistivity pattern derived from the airborne electromagnetic survey. Based on these findings and on the results of the geo-hydrological mapping program, boreholes were drilled to calibrate the geoelectrical results. Labaratory tests were performed on soil and rock samples to determine the geotechnical parameters the main subsurface units. Additionally, geophysical and hydrophysical logging were carried out. Based on these results a geotechnical subsurface model was created and parameters and conditions of safety and failure were calculated. Finally a multi parameter monitoring network was installed and has been operated since 2002. In this paper we focus on the geophysical aspects of the strategy.

2.1 The geological framework

The research area is entirely located within the "Feuerstätter Unit", which is characterized by extensive rock disruption. The landslide area itself is mainly composed of rocks of the Junghansen and Schelpen series. These sub-units consist of marl and schist with highly variable stability as a result of tectonic fracturing. Due to their low resistance against weathering, rocks degrade under the influence of water into deeply weathered granular soils. Within these areas, all primary scarps are located. The Junghansen and Schelpen series

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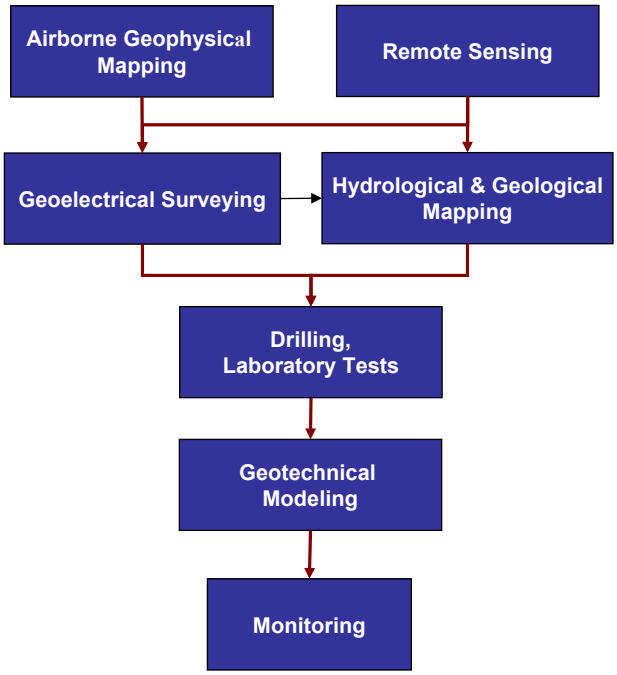

Fig. 1. Flow chart of the evaluated strategy.

are embedded into the more stabile Feuerstätter sandstones and limestones of the Aptychen series.

Figure 2 shows the results of the geological mapping of the landslide area (Jaritz et al., 2004) and surroundings.

2.2 The airborne geophysical survey

Soon after the landslide event, a high resolution, multi-parameter airborne survey was performed. The main part of the airborne system (Motschka, 2001) consisted of a GEOTECH-"Bird" of 5.6 m length and 140 kg weight. It was dragged on a tow cable 30 m below the helicopter. The frequency domain method works in such a way that a primary field induces currents in conductive underground structures. In turn the corresponding magnetic field induces a current in the receiver coils (secondary field). Variable frequencies and different geometric arrangements of the coils are being used to allow depth specific-sounding of the subsurface. The lowest frequency determines the maximum penetration depth of the method. Based on the amplitudes and the phases of the secondary fields, conclusions can be drawn on the electrical resistivity of the ground by applying delicate data inversion algorithms (Ahl, 2007[1]; Avdeev, 2005; Seiberl et al., 1998; Sengpiel et al., 1998; Winkler et al., 2003). For the "Sibratsgfäll" survey, electromagnetic alternating fields with frequencies of 3200 Hz (coaxial coil) and 7190 Hz (coplanar coil) were used, thus allowing investigation depths up to 70 m below ground surface. The electromagnetic bird was supplemented by a laser altimeter, two differential GPS sensors, one of them located in the "bird" and the other one in the helicopter, a Cs-magnetometer, a gamma spectrometer and a passive microwave soil moisture sensor.

[1]Ahl, A., Winkler, E., Bieber, G., and Römer, A.: Probabilistic inversion of aeroelectromagnetic data with a homogeneous halfspace model, J. Appl. Geophys., under review, 2007.

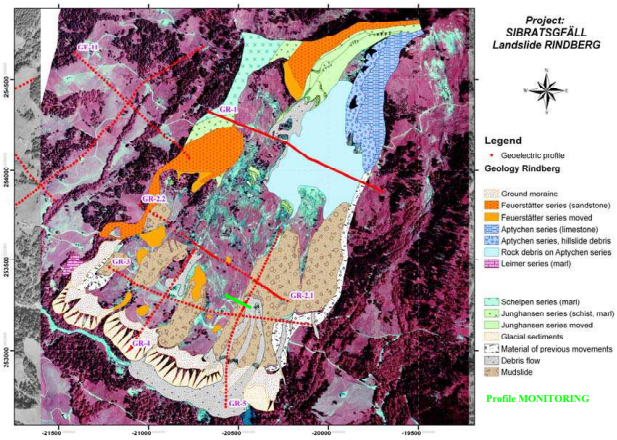

Fig. 2. Geological overview map of the landslide Rindberg.

Out of the set of different airborne techniques, the electromagnetic method was expected to deliver the most useful results for the investigation of landslide areas. This is due to the fact that with this method depth-specific sounding can be performed. Moreover the derived parameter, namely the electrical bulk resistivity of the subsurface, directly depends on fluid content, soil porosity and clay content. These parameters describe indirectly the internal lithological composition of the landslide. Using the results of a two-layer inversion cross-correlated with remote sensing data (satellite images, ortho-photographs and digital terrain data from airborne laser scanning) and results from geological mapping, a conceptual model of the subsurface structure was derived.

Figure 3 shows the results of the inversion of the electromagnetic data using a homogenous halfspace model (Ahl, 2007[1]). This approach is very useful in providing a first overview over geological structures in a research area. The territory affected by movement of clay and marl material is clearly detectable in the central zone of the landslide, exhibiting medium to low resistivities (35–100 Ohmm). Sandstones (resistivity > 175 Ohmm) of the Feuerstätter series, building up the unmoved frame of the landslide on the western side, can be delineated laterally with high resolution due to their contrast in resistivity to the surrounding materials. However, ground moraines, defining the south-western border of the landslide, and limestone material from the Aptychen series, dominating the north-eastern part of the landslide, show the same resistivity signature. Therefore they cannot be distinguished from the sandstone using only electromagnetic results.

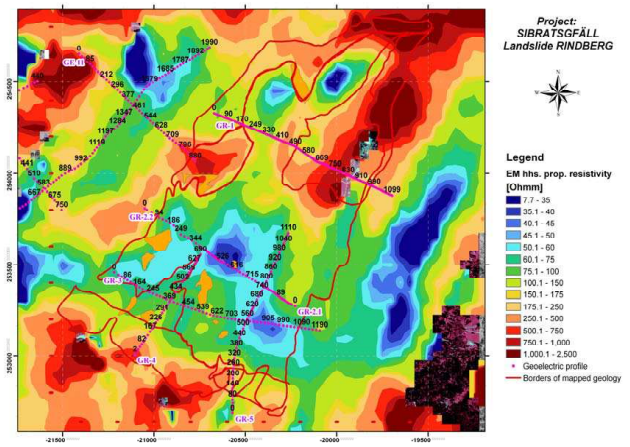

Fig. 3. Results of the inversion of airborne electromagnetic mapping: homogenous halfspace inversion – Parameter: Resistivity [Ohmm].

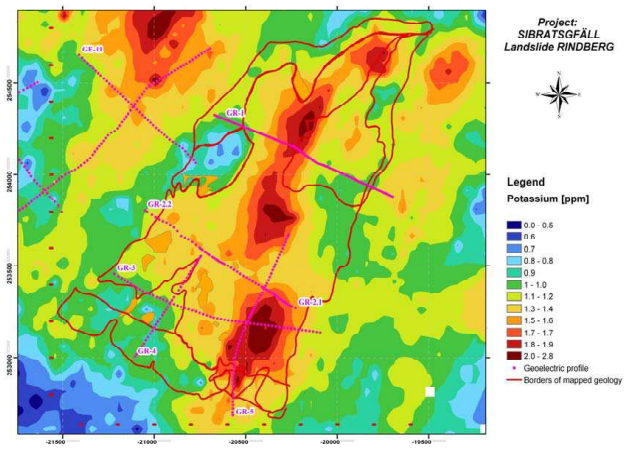

Fig. 4. Results of the inversion of airborne mapping: – Parameter: Gamma ray spectroscopy – Potassium [ppm].

Incorporating additionally results from the gamma ray mapping, particularly the potassium distribution (Fig. 4), a more accurate differentiation between Aptychen series (low potassium content) and sandstones (medium potassium values) was possible.

It is remarkable that the distribution of maximum potassium content follows the main flow track of the landslide (Fig. 4). The reason for that is not obvious. This might be due to the fact that the top layers in the landslide material are mainly mixtures of marl and schist originating from Junghansen and Schelpen series, which show also high potassium contents at in-situ position. Destruction of the vegetation cover and dehiscing of the sward by high movement rates could be other causes.

Within a second processing step, the geoelectric results as well as information from core drillings were used to con-

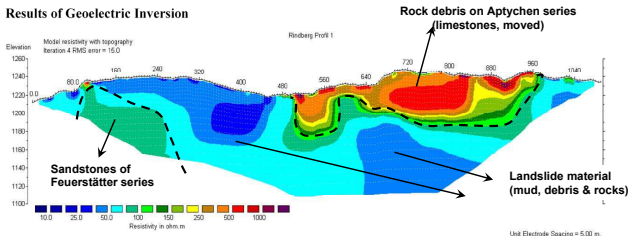

Fig. 5. Results of the inversion of geoelectric multielectrode data: subsurface resistivity model for Profile GR-1.

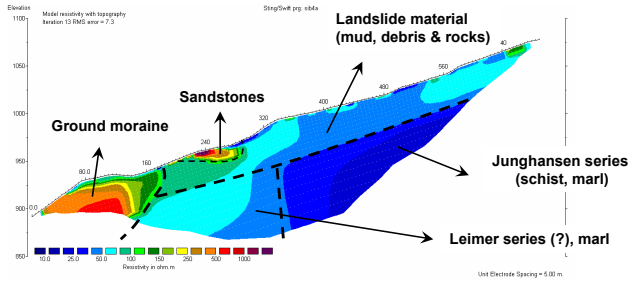

Fig. 6. Results of the inversion of geoelectric multielectrode data: subsurface resistivity model for Profile GR-4.

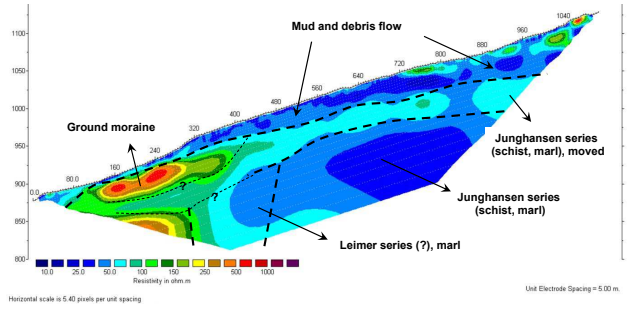

Fig. 7. Results of the inversion of geoelectric multielectrode data: subsurface resistivity model for Profile GR-5.

strain the inversion of the airborne electromagnetic data. This improved resistivity model was consequently used to refine the subsurface structural model, based on the complex interpretation of all available data.

Furthermore it has to be pointed out that all airborne geophysical results had been very valuable for mapping geologists as they helped to optimize the follow-up mapping procedures. Additionally it helped to minimize actual field work, which is often very difficult and time consuming in the rugged terrain of unstable slopes.

2.3 The ground geoelectrical surveys

Based on the preliminary subsurface resistivity model, a high resolution ground geoelectrical survey was planned. Several kilometers of multielectrode measurements on 29 profiles

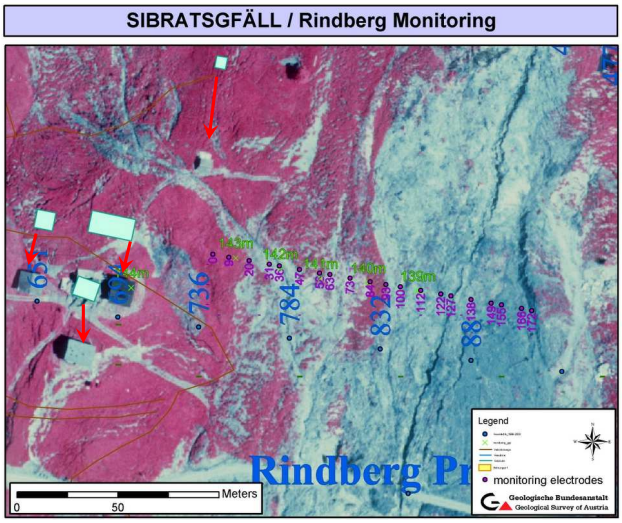

Fig. 8. Location of Profile MONITORING, background: orthophotography after landslide event light green rectangles: location of buildings before event.

were performed in the area of Rindberg and Sibratsgfäll to determine the detailed subsurface structure of the sliding area. For calibration purpose, several boreholes were drilled along the geoelectric profiles and logged with induction and gamma probes. Some of them were equipped with inclinometers in order to define the depth of slip surface. At the position of the geoelectrical monitoring profile (location see Fig. 2) hydrophysical logging (Pedler et al., 1992) was additionally performed to derive information on the variation of hydraulic conductivity with depth. Figures 5–7 show results from the geoelectric inversion of multielectrode data on some selected profiles (GR-1, GR-4 and GR-5). The location of the profiles in relation to geological units and airborne geophysical results can be identified in Figs. 2, 3 and 4.

Profile GR-1 is located near the top scarp of the landslide. The geoelectrical results (Fig. 5) give detailed information of the depth extent of the high resistive rock debris of Aptychen limestone composition. This material forms a compact plate of thicknesses up to 50 m, which is detached from in-situ position. Due to its heavy weight, this block puts pressure on the subjacent soft clay and marl. In case of heavy rainfall the additional force of this load can increase pore water pressure within underlain clays and marls. Consequently the triggering of movements can be supported. Therefore determination of size and depth extent of the detached limestone "block" was important to define the boundary conditions to quantify this effect using geotechnical modeling.

Figures 6 and 7 show the results on two parallel downhill profiles, encountering very similar geological settings. Schist and marls of the Junghansen series (resistivities below 50 Ohmm) are overlain by moved material of the same geological formation. This disturbed layer shows slightly higher resistivity values (50–100 Ohmm) and obtains a maximum thickness of 30 to 40 m. Only on profile GR-5, the Junghansen series is covered by a mud and debris flow of variable thickness up to 40 m (resistivity of mudflow: 10–35 Ohmm; of debris flow 50–500 Ohmm, depending on the composition).

The resistivity structure changes downslope completely. On profile GR-5 the mudslide has already eroded the base of the undercliffs, which is built up of ground moraines of sand-gravel composition. This situation is expressed in a low resistive top layer, followed by high resistive sequences. The depth of the moraines could not be determined due to insufficient penetration depth in the border area of the profile. Upslope of the moraines at depth, a different structure, showing resistivities between 35 and 50 Ohmm, could be hypothesized from the geoelectrical results. This unit could be interpreted as marls of the Leimer series, which can be found under in-situ position at the same altitude further to the west.

The findings of the geoelectric survey significantly contributed to the setup of the subsurface structure used within the geotechnical model. Geotechnical parameters for each lithological formation were derived from laboratory tests on soil samples and cuttings from the core drillings.

2.4 The geotechnical model

Morphological mapping found out that, at time of the survey, slip surfaces existed as well in the top mudflow as in the underlain mudslide material and moved Junghansen series. It is remarkable, that, even though deep reaching movements had occurred upslope, the mudslide has so far eroded the base of the undercliff only at one location (at the base of profile GR-5). Therefore a stable counter bearing must exist. Consequently, geotechnical modeling, based on the geoelectrical sections and geotechnical parameters, determined by laboratory test on rock samples, were carried out. These calculations showed that the quality of acting as abutment can neither be contributed to the ground moraines nor to unmoved marls of the Junghansen series. However, geotechnical probing of samples from a distant outcrop of Leimer marl suggested, that this series could overtake this role. Direct determination of the geotechnical parameters of the Leimer formation from in-situ position inside the landslide area would allow a more realistic modeling of future scenarios and to define pre-alarm conditions.

Continuative geotechnical calculations showed that soil water dynamics are the driving processes for triggering of movements on this landslide. Depending on different values for pore water pressure and assumptions on the mostly unknown geotechnical parameters of the Leimer marls, different scenarios of rock failure were obtained. The results ranged from very local, rotational sliding to the worse-case scenario of failure of the counter bearing, causing consequent damming of the river Ruhbach.

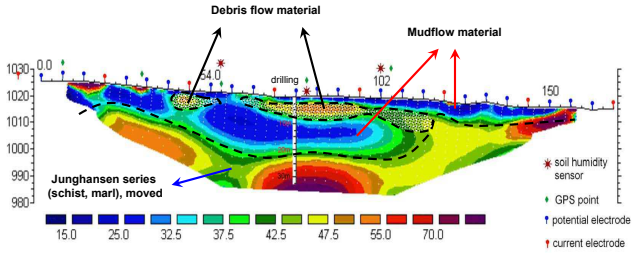

Fig. 9. Results of the inversion of geoelectric multielectrode data: subsurface resistivity model for Profile MONITORING.

The outcome underlined the importance of monitoring the subsurface water regime for risk estimation. Consequently, a multi-parameter monitoring system was designed, centered on the development of an innovative geoelectrical monitoring system.

2.5 The monitoring system

Due to the fact that triggering of movements on this landslide is directly correlated with hydrological processes, geoelectrics seemed to be a promising method for monitoring of similar landslides. In 2001 no commercially available geoelectrical instrument met the requirements of high resolution monitoring (high resolution data, direct noise control, short acquisition time, permanent remote access and automatic data broadcasting). Therefore the Geological Survey of Austria (Supper et al., 2002, 2003 and 2004) designed a new, high speed geoelectrical data acquisition system, called GEOMON^{4D}. A first prototype 2d system was installed at the landslide of Sibratsgfäll in spring 2002 (see location map Fig. 8). This system has been in operation since November 2002, measuring six complete sets of resistivity data, each compromising 3000 single measurements, and 24 self-potential data sets in gradient configuration each day. Since then, daily standard processing of actual data has been performed.

Figure 9 shows the result of one geoelectrical subsurface model obtained on the monitoring profile. The upper part is dominated by low resistive clays of the mudflow with embedded higher resistive debris flow components. Inclinometric measurements at the central drilling determined a well pronounced slip surface at a depth of 6 m (Fig. 10a), right below the embedded high resistivity body.

In 2003, the system was completely redesigned according to the experiences derived with the prototype. The instrument now offers a completely open architecture, allowing installation of any number of current or potential electrodes by adding parallel or serial cards. Moreover GPRS (General Packet Radio Service) data transfer was implemented. Therefore maintenance can be performed remote-controlled. Data (measurement results, test sequences and log files, containing information about system and GPRS connection sta-

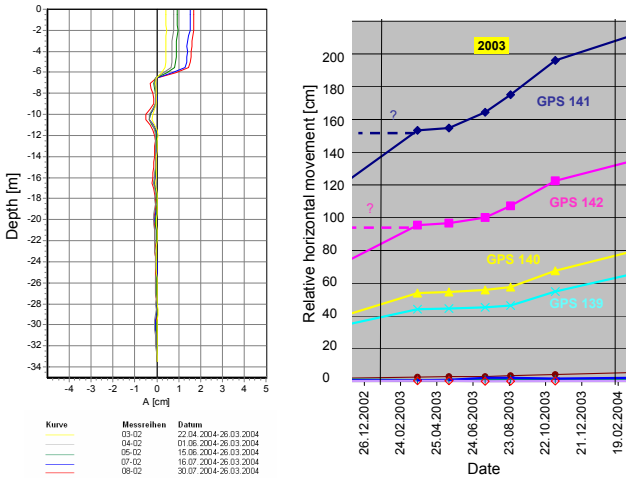

Fig. 10. Rates of movements on Profile MONITORING; **(a)** Inclinometric data at the central drilling; **(b)** Relative horizontal movement rates determined for 2003 using high accuracy GPS positioning.

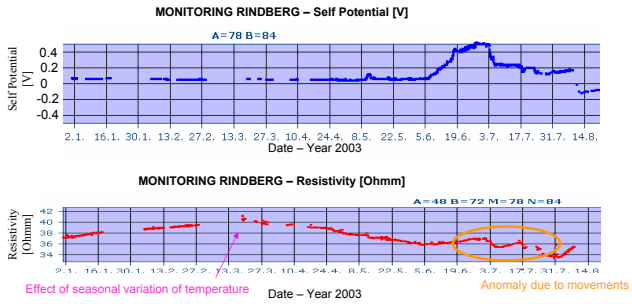

Fig. 11. Selection of monitoring results: **(a)** Self potential anomaly [V] – potential difference between electrodes at position 78 and 84 m **(b)** Resistivity [Ohmm] – current injection between position 48–72, potential measurement between 78–84 both parameters versus time.

tus) are sent automatically every day via email to the data processing centre. Several software packages were developed for selecting appropriate measurement configurations, remote controlled operation, data conversion and data analysis. For the purpose of advanced interpretation, a special data base system was developed. One of the redesigned instruments was installed additionally in 2005, operating an electrode spread with 40 electrodes at 2 m spacing along the same profile. This line was replaced in late 2006 by a line with 20 m of electrode spacing perpendicular to the original layout.

The geoelectrical system was complemented with three soil temperature and soil humidity sensors, rainfall, snow and drainage recording points. Additionally three drillings, equipped with inclinometers, allowed correlation of movement rates with geoelectrical anomalies. To determine values of surface movements, high resolution geodetic surveys

were performed almost every two weeks. Selected results of self potential (Fig. 11a) as well as of resistivity time series (Fig. 11b) clearly showed the existence of pronounced anomalies at times of movements of the landslide (Fig. 10), whereas during periods of slowdown, hardly any anomalous values were registered. Unfortunately, due to the lack of permanent motion data, no direct correlation with triggering of movements could be derived.

3 Conclusions

Several methods were evaluated to design an improved interdisciplinary strategy for immediate measures to be applied in case of future landslide events. The strategy allows to quickly assess the prevailing hazard situation and to develop and recommend effective mitigation measures. The resulting optimised approach consists of the application of airborne electromagnetics, ground geoelectrical measurements and geoelectrical monitoring combined with hydrological and geological mapping and geotechnical modelling. Interdisciplinary communication and discussion was the primary key to access the complicated hazard situation in the case of the large-scale landslide event evaluated at Rindberg.

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