First Field Findings and their Geological Interpretations at the Study Site Bello Oriente, Medellín, Colombia (Project Inform@Risk)

T. Breuninger

Chair of Engineering Geology, Technische Universität München, Munich, Germany

tamara.breuninger@tum.de

M. Gamperl

Chair of Engineering Geology, Technische Universität München, Munich, Germany

B. Menschik

Chair of Engineering Geology, Technische Universität München, Munich, Germany

K. Thuro

Chair of Engineering Geology, Technische Universität München, Munich, Germany

Abstract

The City of Medellín, Colombia, subject to the german-colombian project Inform@Risk, has suffered from multiple landslides in the recent past. Embedded in the Aburrá Valley in the Cordillera Central of the Andes, the region around the city consists of different triassic and cretaceous metamorphic rocks and magmatic batholites and plutonites. Especially the north-eastern slope is prone to landslides, as it is very steep and made up of a deep cover of soil over highly weathered dunite rock. During the first field trip, carried out in August 2019, former landslide areas were mapped and ERT-measurements were conducted at the study site Bello Oriente in the northeast of Medellín. After a first evaluation of the findings, the rock surface seems to be even deeper than expected, over 50 m in the middle of the slope, almost at the surface in the north and south of the study area. This indicates multiple faults and possibly also a deep-seated landslide, which might have been moving downhill very slowly for thousands of years. The more dangerous landslides however, which are much faster, are the shallow ones on the surface. These landslides can appear on top of each other and are distributed across the whole study area, but are most concentrated between and above the last houses of the barrio. All those findings are preliminary; The ERT-profiles have to be calibrated and complemented by drillings, the landslide map has to be completed and a geological map has to be created. A second field campaign in February/March 2020 will see to these tasks.

1 OVERVIEW

1.1 Inform@Risk

The project “Inform@Risk” is a collaboration of several German and Colombian institutions and universities that is developing an economically and regionally adapted early warning and evacuation system for informal settlements (see also Gamperl et al. 2020, this issue.). A key goal is to strengthen the resilience of residents against the risk of landslides that is rapidly increasing due to climate change, especially in the tropical regions. The project is funded by the German Federal Ministry of Education and Research in its program “Client II”, a promotion of international partnerships in science and research.

The barrio Bello Oriente (Comuna 3, Manrique) at the north-eastern slope of the city of Medellín, Colombia was chosen as a test site for the Inform@Risk project. It is an informal settlement located at the city border and the rural area surrounding the city in a landslide endangered area. The slope is up to 60 ° steep and consists of a thick layer (up to 50 metres) of residual soil covering the Dunite bedrock (Echeverri et al. 2012).

The first field trip, that included geological/landslide mapping and ERT (Electrical Resistivity Tomography) measurements, has been carried out in early August 2019. The results are presented in chapter 2 and 3, the interpretation of the findings in chapter 4. Further investigation methods are described in chapter 5.

1.2 Regional Geology

Medellín is located in the Aburrá Valley in the Cordillera Central of the northern Andes (fig. 1). The Cordillera Central consists of phanerozoic (mostly Mesozoic) metamorphic, igneous and volcanic rocks. The western and central part of the Cordillera Central is mostly made of Triassic and Cretaceous rocks, the Jurassic is predominantly visible at the eastern border in the north and in the south of the mountain range. Due to the general tectonic regime of the subduction zone in South America the faults in the Andes are mostly striking north-south (Cediel & Shaw 2019).

The region of Medellín is made of metamorphic rocks and plutonic structures. Figure 2 shows a geologic map of the city and its vicinity. The Triassic Medellín Dunite is exposed at the eastern city border. It follows a fault that strikes north-south at the edge of the slope. This dunite body is a former ophiolite complex that is now embedded in the metamorphic complex of the Medellín Amphibolite. The dunite also shows serpentinisation caused by high pressure and temperature during the orogeny of the Andes. Drillings show that the ophiolite also exists under the alluvial deposits in the city centre. South of the Medellín Dunite a Triassic plutonic rock, the Puente Peláez Migmatite, follows along the same fault. The migmatite was formed before the subduction began in the upper Jurassic (Restrepo et al. 2003).

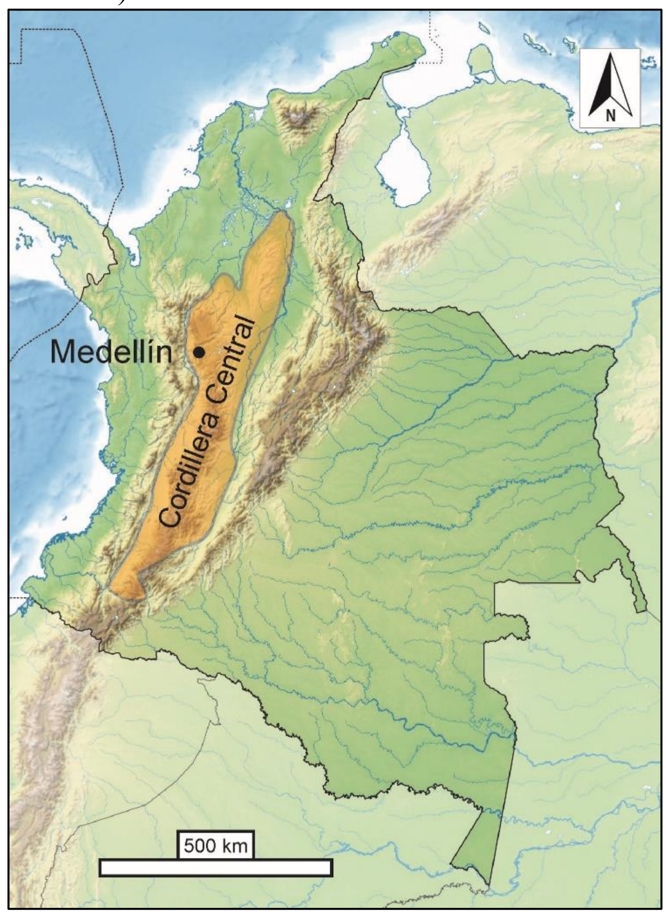

Figure 1: Position of the City of Medellín in the Cordillera Central.

In the north, west and south of the city the Medellín Amphibolite is exposed. This metamorphic complex is believed to be former oceanic crust, that was permeated by the ophiolite complex, that is now the Medellín Dunite. During the starting orogeny in the Jurassic and Cretaceous, different plutonic masses intruded in this amphibolite-dunite complex. The biggest of those plutons is the Antioqueño Batolite, which is exposed all around Medellín, in the city at the central eastern border. In the west of the city the Altavista Diorite is exposed in a large amount, in the east a gabbro-diorite complex (Restrepo et al. 2003).

Due to the tropical climate of the region, all rocks are severely weathered. The soil covering the rock is up to 40 metres thick, consists mainly of clay and iron-oxides and -hydroxides and can contain varying amounts of rocks and blocks of the underlying rock, which usually get bigger with increasing depth (Echeverri et al. 2012). In the valley this weathered material is deposited as colluvial (mostly gravitational transport) and alluvial (transport by fluids) deposits. The city of Medellín is built mostly on these deposits. Only the borders of the city are underlain by bedrock directly (Restrepo et al. 2003).

The Study Site Barrio Bello Oriente lies at the north-eastern border of the city in Comuna 3 (see fig. 2). The whole area is in a very steep slope of up to 60 ° inclination at some points. The most landslide prone areas are the ones to the sides of the quebradas (small creeks), as those have a high erosion rate. Small and creeping landslides have occurred in the area (Echeverri et al. 2012), the last of which in 2017.

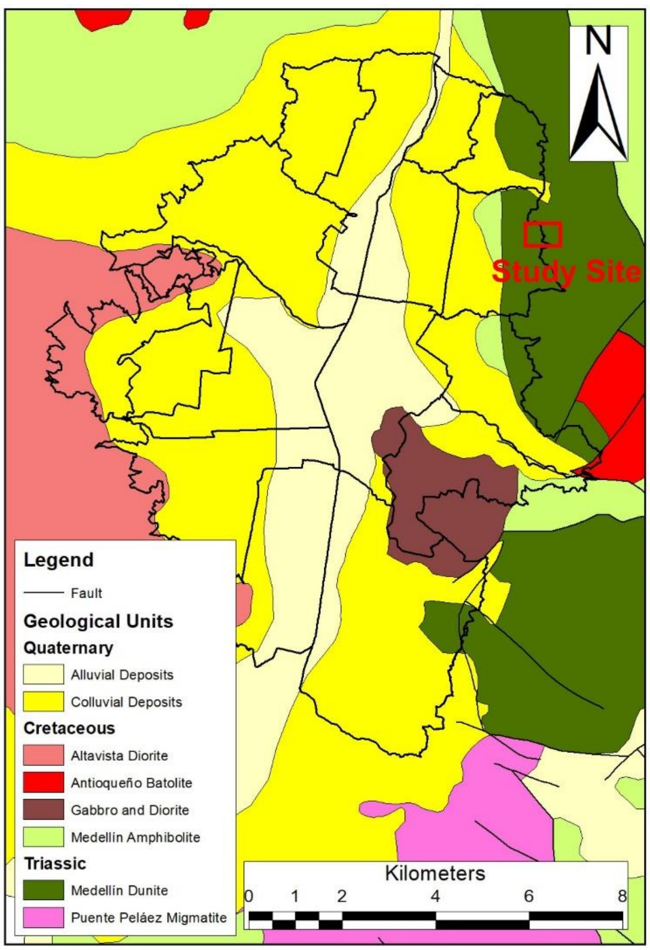

Figure 2: Geology of the city of Medellín (after Alcaldía de Medellín 2014).

1.3 Landslide Processes in Medellín

Medellín has suffered from multiple catastrophic landslides in the last 100 years, which have killed more than 1300 people (Corporacíon OSSO 2016).

Most of those landslides have occurred in the northeastern slope of the city, where the slopes are very steep and the deep weathering of the Medellín Dunite (see fig. 2) causes an up to 50 m thick layer of weathered rock and soil.

In this deeply weathered material rotational slides are predominant, whereas in the upper parts of the valley translational slides and rockfalls become more frequent, due to a thinner layer of soil and therefore a shallower rock surface. Additionally, in the deep channels of the quebradas, mudflows occur after heavy rainfall events (Alcaldía de Medellín 2014).

2 RESULTS OF THE MAPPING IN THE STUDY SITE BELLO ORIENTE

Figure 3 shows the preliminary landslide process map after the first field mapping in Bello Oriente. The left side of the figure is downhill, the right uphill.

Most landslides that were found during the mapping of the area are located right above or still in the last settlements of the barrio. All these landslides are rotational, except for the northernmost, which is one of the few translational landslides in the area (see also Gamperl et al. in prep.).

The depth of the landslides was estimated generally at 3 to 10 metres with a maximum of 12 metres. The observed age of the landslides is not older than 100 years, since older structures are not visible anymore due to the high weathering rate in the tropics. The oldest landslide that was found is the one that is crossed by ERT-profile BO-01. It is about 100 years old.

In addition to former landslides the map shows two detachment structures (fissures), one at the north-western border of the study site and one right to the south of the two landslides next to each other. Especially the southern structure indicates that a landslide is preparing at this fissure.

As visible in the map, there are some landslides that occur on top of another landslide. This indicates several detachments in different depths, not a single detachment layer.

In the uppermost part of the study area only two small landslide structures were found with no visible detachment. This lack of big landslides is

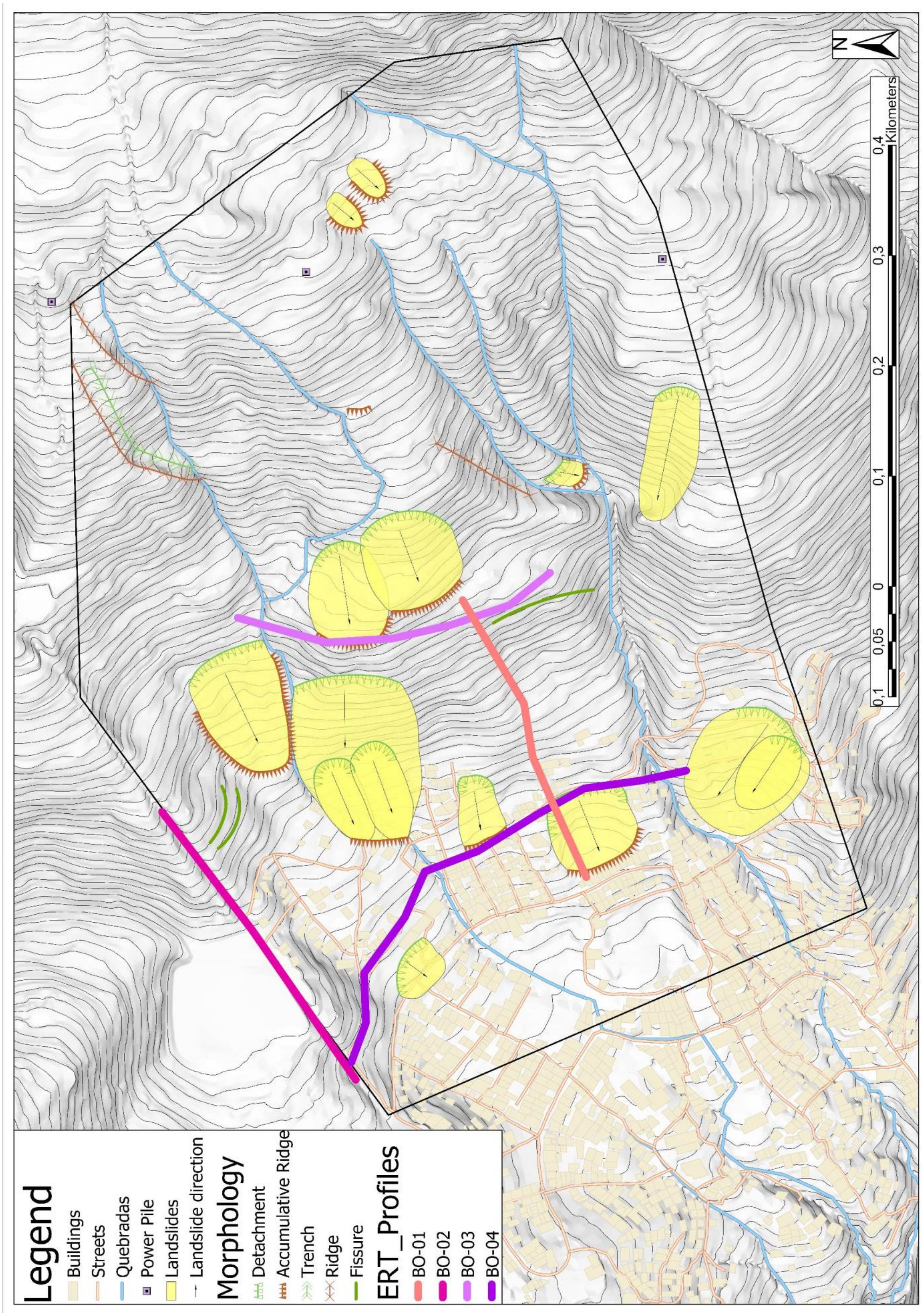

Figure 3: Result of the first field campaign in August 2019.

caused by the relatively flat morphology compared to the rest of the area.

The same part of the slope is also covered by rocks of a size of up to 10 m³. The origin of those rocks is most likely the steep slope above the two small landslides.

3 ERT-MEASUREMENTS

In order to find out more about the subsurface distribution of geological features, Geoelectrical measurements, specifically Electrical Resistivity Tomography (ERT) have been carried out on the site. The four transects BO-01 to BO-04 are displayed on the process map (fig. 3).

3.1 Methodology

The measurements were performed using an ABEM LS2 system (Guideline Geo) and two ABEM Lund cable sets. The electrode spacing is 5 m and with two 32 electrode cables, a total profile length of about 320 m can be achieved, with roll along measurements naturally yielding longer profiles.

An experimental measurement on a short transect was performed earlier in order to find out the most suitable electrode configuration. From this, it was observed that the Wenner-Array yields the best results, especially for the expected mostly horizontal geological features (Otto & Sass 2006). The power line frequency was adapted to the local value (60 hz for Colombia).

The inversion of the ERT-profiles was carried out using the software RES2DINV by Geotomo software. Due to high resistivity gradients on the surface, robust inversion was chosen and the mesh was refined to allow for more contrast in the inversion, resulting in an RMS Error of 5.9 % (BO-01) and 5.7 % (BO-03).

3.2 Results

Here, results for profiles BO-01 and BO-03 are shown (fig. 4 and 5). Both profiles show high variations of resistivity on the surface, followed by lower resistivity below. Underneath this, the resistivity rises again (fig. 4, right), indicating the soil-rock boundary.

3.3 Interpretation

As these measurements are preliminary and have not yet been complemented by drillings, it is difficult to make an exact statement on the structures in the subsurface. But with the current knowledge, it seems probable that the distribution

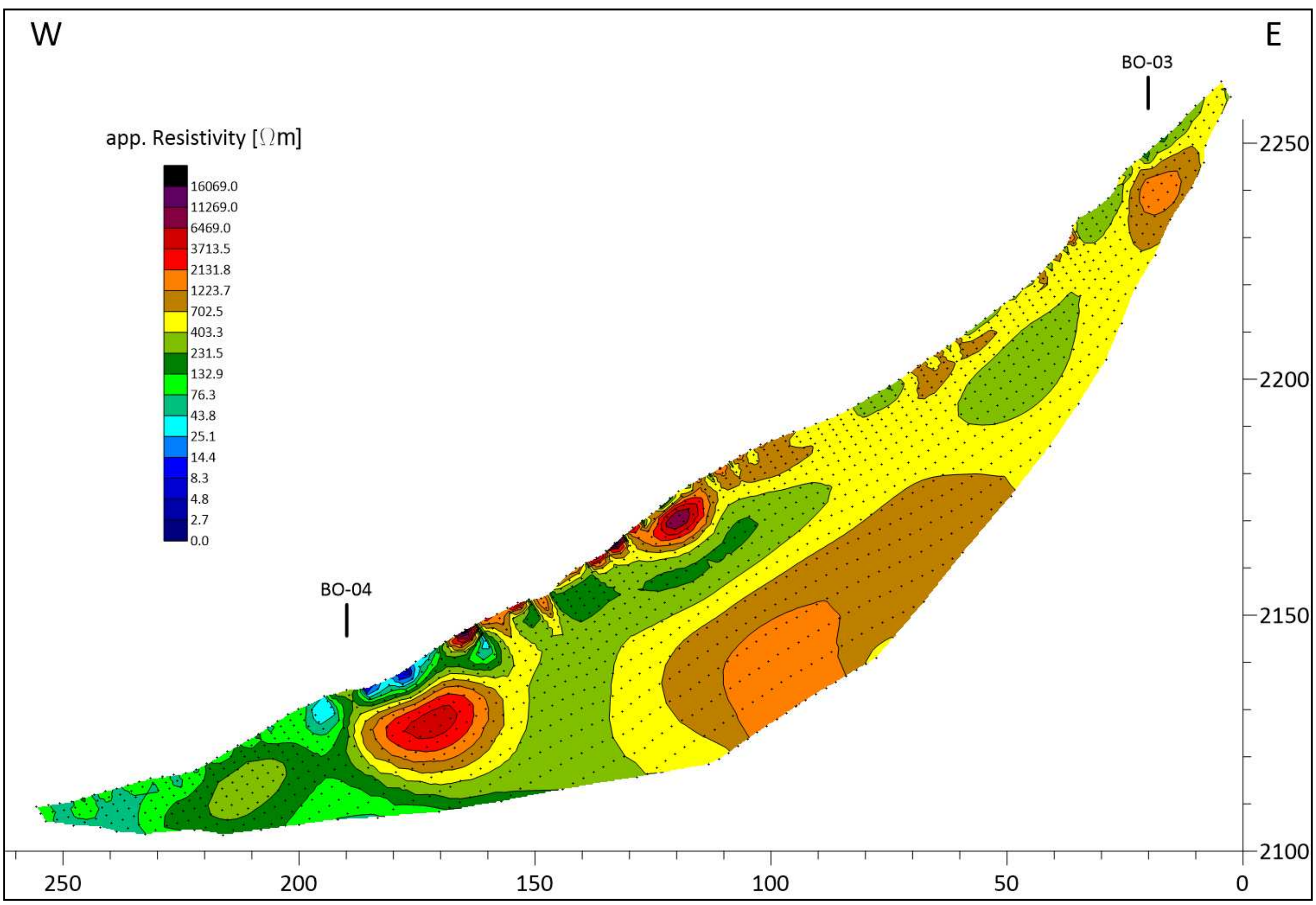

Figure 4: ERT-profile BO-01.

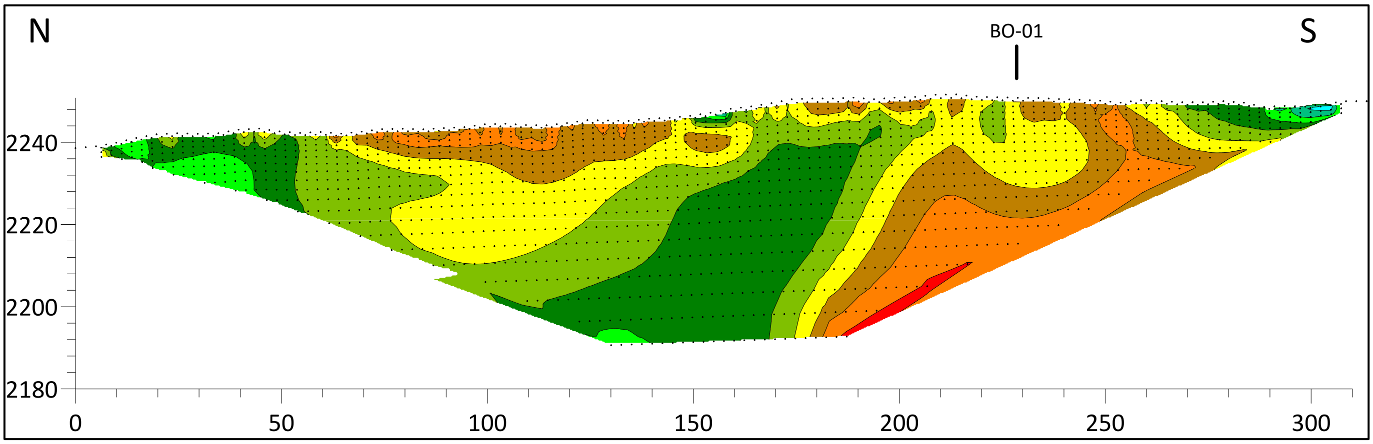

Figure 5: ERT-profile BO-03. The color scale is the same as in fig. 4.

of the Dunite in the subsurface is quite heterogeneous: Close to the surface in the south of BO-03 and very deep (up to 50 m) in the northern part of the transect.

4 GEOLOGICAL INTERPRETATION

The first field mapping and ERT-measurements indicate, that at some locations the Dunite can lie deeper (more than 50 m) than expected at first (30 m). Also the variation of the soil coverage is higher than described in the literature of the region (Echeverri et al 2012). As mentioned in chapter 3.3, the ERT-measurements are not yet calibrated. Still, the results show generally low resistivity in the first 30 to 50 m of the profile, which can only be achieved by soil or extremely weathered rock. Therefore, it can be assumed that the rock surface can lie in a depth of up to 50 m of even more.

Figure 6 shows a first draft of a profile of the barrio Bello Oriente from west to east. The profile line follows the ERT-profile BO-01 (fig. 4).

In the first 25 m (from the east) the rock surface is quite shallow. About 5 to 10 m of soil and weathered rock cover the solid rock. This area in

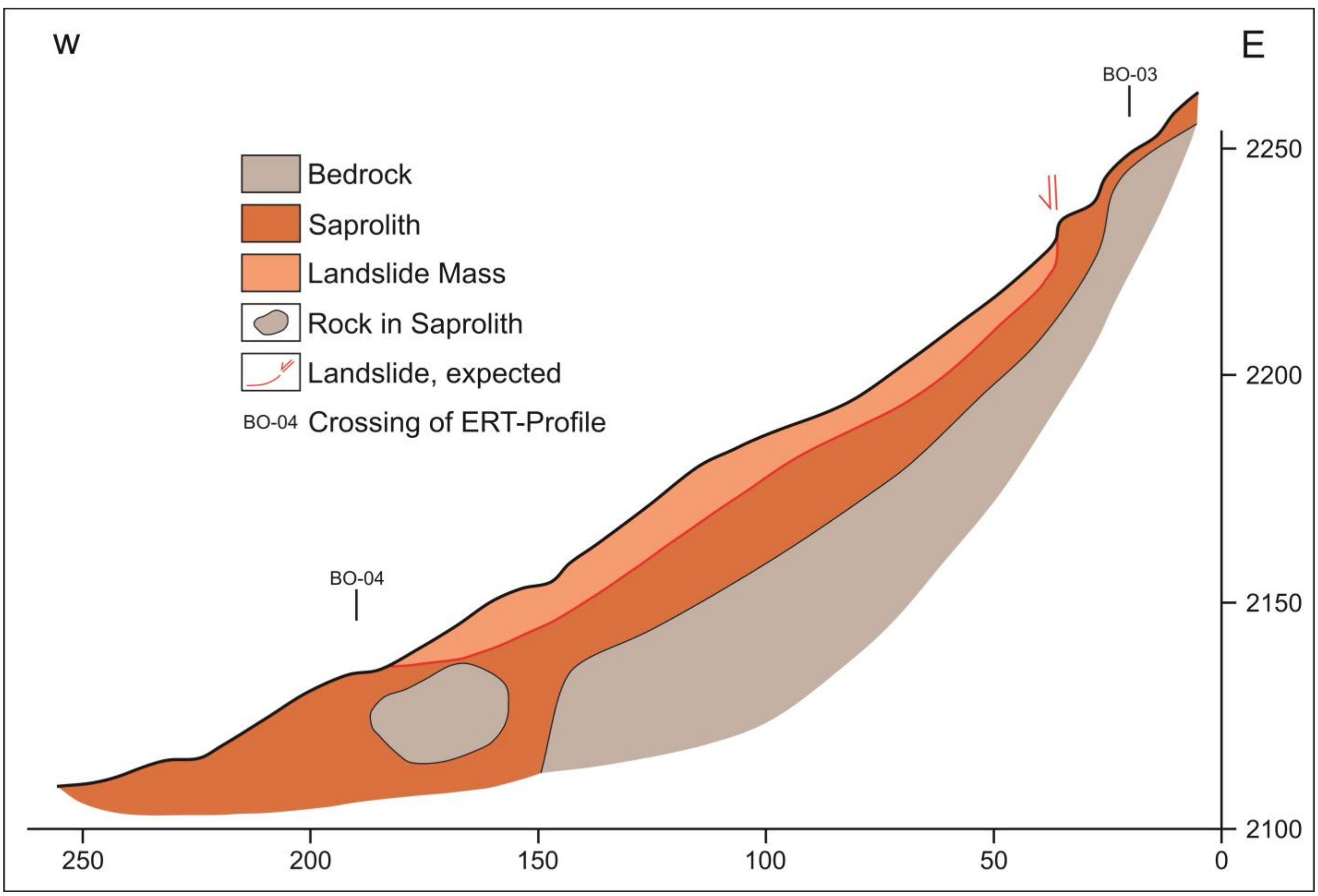

Figure 6: preliminary profile and interpretation of ERT-profile BO-01.

the slope is very steep, the soil coverage is washed off by rain and surface water. The rock is visible from the lower part of the slope. From 25 to 150 m the soil coverage is thicker, up to 30 m. Here, the slope is not as steep as above and the soil is not so easily removed by water. At 150 m the rock surface suddenly drops at least 20 m, leading to a soil coverage of up to 50 m. This sudden change in the rock surface might be caused by a fault striking north south or by a significant change in rock stability.

On top of the rock, the soil is made up of deposits of multiple landslides, as indicated by the varying resistivity at the surface (see fig. 4 and 5). The deepest possible detachment for future landslides is the rock-soil contact. There is no indication for such a deep seated landslide on the surface, but the deep soil coverage shown in the ERT-measurements indicates a mass movement that gathered this much material in this region. Some of the smaller landslides on top of the deep seated one have been mapped during the field trip (see also fig. 3).

ERT-profile BO-03 shows that the rock surface also varies from north to south. In this profile the resistivity is much higher in the south than in the north. This indicates that east-west striking faults are also to be expected.

These interpretations are preliminary as the ERT-measurements have not yet been complemented by drillings or other calibration methods.

5 FUTURE WORK

Due to the unexpected results of the first field trip more ERT-measurements and further landslide mapping will take place in February 2020. The first drillings are scheduled for May/June 2020, which will be used to calibrate the ERT-measurements and install sensors for the early warning system. During the drillings, samples will be taken and tested at the laboratories of the EAFIT University in Medellín and the Technical University in Munich. The tests will include for example compression tests (rock), determination of grain size distribution and shear parameters and XRD-analysis (soil).

6 REFERENCES

Alcaldía de Medellín (2014). *“Plan de Ordenamiento Terretorial (POT)”*. Medellín. – Alcaldía de Medellín.

Cediel, F., Shaw, R. P. (2019). *“Geology and Tectonics of Northwestern South America”.* Zürich, Springer.

Corporacíon OSSO (2019): *“Sistema de inventario de efectos de desastres – Medellin – Área metropolitana”*. Retrieved from: https://www.desinventar.org/en/database (24.07.2019).

Echeverri, A, Vélez Villa, A. E., Ward-Karet, M., Orbea Cevallos, S, Werthmann, C., O`Carroll, A., O’Shea, Conor (2012). *“Re Habitar La Ladera”*. Medellín, Lulu.

Gamperl, M., Breuninger, T., Singer, J., Garcia Londoño, C., Thuro, K., Menschik, B. (2020). “*Development of a Landslide Early Warning System in informal settlements in Medellín, Colombia”*. Proceedings of the 13th International Symposium on Landslides, Las Americas Convention Center, Cartagena, Colombia, 15th – 19th June 2020.

Otto, J.C., Sass, O. (2006). *“Comparing geophysical methods for talus slope investigations in the Turtmann valley (Swiss Alps)*”. Geomorphology 76: 257-272.

Restrepo, J., Rendón, D., Estrada, J., Toro, G.(2003). *“Guía de excursión geológica y morfología del Valle de Aburrá”.* Boletín de Ciencias de La Tierra 15: 73-84.