UNIVERSITÉ DE FRIBOURG
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4-PHASE MODEL SIMULATIONS GAMANJUNNI, NORWAY, 2018

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Content

1 Introduction

1.1 Purpose of the Study and Performed Work

The purpose of the study consisted of the characterisation of the general subsurface conditions regarding the potential occurrence of ground ice within the Gamanjunni rock slide, Northern Norway. The analysis was done with our in-house developed "4-phase model" (4PM, see Hauck et al. 2011, Pellet et al. 2016, Mewes et al. 2017), which estimates the subsurface ice-, water- and air content based on electrical and seismic data sets. The geoelectrical and seismic data sets from the area originate from several field campaigns along two profile lines, Gamanjunni 1 and Gamanjunni 2 (conducted by Geological Survey of Austria, NGU/Norway and GeoExpert ag/Switzerland) and were already described and analysed in several reports kindly made available by the data owners (GCA 2016, GeoExpert 2016).

The work conducted within this study comprised the following:

(1) Collecting and harmonising all necessary data from the different sources, including coordinates

(2) Inversion of geoelectrical raw data of profiles Gamanjunni 1 and Gamanjunni 2 using the software Res2dinv (Loke 2012)

(3) Matching and interpolating the inverted and exported specific resistivities to the same grid as the collocated seismic P-wave velocity distributions for both profiles

(4) Setting-up of the 4PM and defining adequate porosity models

(5) Running the model with different parameter combination to assess the potential uncertainties

(6) Interpretation of the 4PM results

(7) reporting

1.2 Structure of the Report

The report consists of the following parts:

- A very short introduction into the details of the **4PM modelling** (chapter 2)
- A description of the conducted **processing steps** as listed above (chapter 3)
- A presentation of the **obtained results** including their interpretation and discussion of individual uncertainties (chapters 4 and 5)
- A **summary and conclusion** (Section 6)

2 Ice Content Estimation - 4PM modelling

The 4-phase model (4PM, described in Hauck et al. 2011) was developed to determine the spatial distribution of the volumetric phase contents in the pore space (ice, water, air) of frozen or partly frozen ground based on collocated geoelectrical and refraction seismic tomographic surveys. These two geophysical techniques were chosen because their complementary nature, by addressing the electrical and elastic properties respectively, are suitable to distinguish between ice (high resistivities and medium P-wave velocities), water (low resistivities and P-wave velocities) and air (high resistivities, low P-wave velocities). This simple physically-based model is based on three main equations (see Hauck et al. 2011 for further details):

a) The well-known electrical mixing rule called Archie's law (found empirically by Archie 1942, and later theoretically confirmed by e.g. Sen et al. 1981),

b) An extension to a 4-phase medium of the seismic time-averaged approach for P-wave velocities by Timur (1968), and

c) The necessary assumption that the sum of all volumetric fractions of the ground is equal to one.

Among the free parameters of the model, the pore water resistivity (ρ_w) and the porosity Φ are the most sensitive for the calculation of the ice and water content (Hauck et al., 2011). While the pore water resistivity can be used as calibration factor if borehole or laboratory data are available, an estimation of the porosity of the subsurface has to be prescribed. Several approaches have been tested in the absence of borehole data on porosity (cf. Pellet et al. 2016), among them the explicit calculation from the geophysical results for unfrozen conditions, a homogeneous porosity and a gradient model.

In addition to the calculation of the absolute ice, water and air contents, which depend strongly on the available pore space and therefore on the prescribed porosity model, we analysed the modelled subsurface components as saturation values, i.e. relative to the available pore space. Sensitivity and field studies have shown that saturation values are much less depending on the porosity model and contain therefore less inherent uncertainties than absolute values (cf. Mewes et al. 2017). By this, the actual porosity value plays only a minor role for the 4PM results. Further, it has to be noted, that the 4PM cannot detect supersaturated conditions by itself, but a saturation of 100 % may indicate supersaturated layers.

3 Data processing

3.1 Available data

2-dimensional apparent resistivity data (from Electrical Resistivity Tomography, ERT) for the two profiles were kindly made available from the two sources, Geological Survey of Austria (horizontal cross profile, *Gamanjunni 1*) and NGU (vertical longitudinal profile, *Gamanjunni 2*) including corresponding electrode coordinates (Figure 1). These data sets were already pre-processed by the respective groups, meaning that some of the data with doubtful quality have already been filtered. However, due to the difficult terrain and in the absence of further quality criteria or reciprocal measurements, there is no absolute knowledge, which data should be retained and which data should be filtered. We conducted some analysis regarding differently filtered data sets and use data sets with not substantially different filtering as in the original report (GSA 2016).

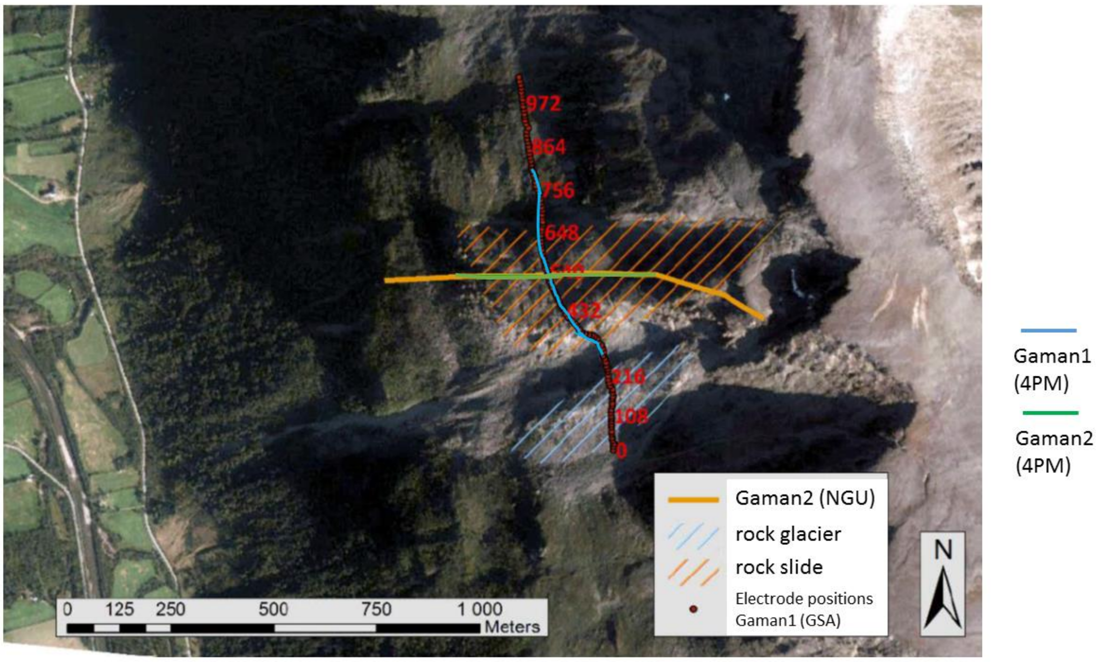

Figure 1: Location of profile lines Gamanjunni 1 and Gamanjunni 2 (taken and modified from GSA 2016) and corresponding 4PM modelled profiles.

2-dimensional refraction seismic data sets (Refraction Seismic Tomography, RST) were kindly made available as processed and already inverted P-wave velocity distributions by GeoExpert ag, Switzerland (GeoExpert 2016, Gamanjunni 1 and Gamanjunni 2). These data sets contain the P-wave velocity distributions on a 2-dimensional grid, which is the necessary input format for the 4PM. Consequently, we decided to use the seismic data grid, on which the inverted ERT data (see next sections) were interpolated. Hereby, it was found that coordinates between seismic and geoelectric data did not match, which was partly explained by the fact that the actual measurements were not conducted at exactly the same positions (cf. Figure 2). However, for the 4PM a joint 2D-model grid has to be assumed. In the following we tried to match the ERT and seismic data as best as possible, but this remains a source of uncertainty for the final interpretation.

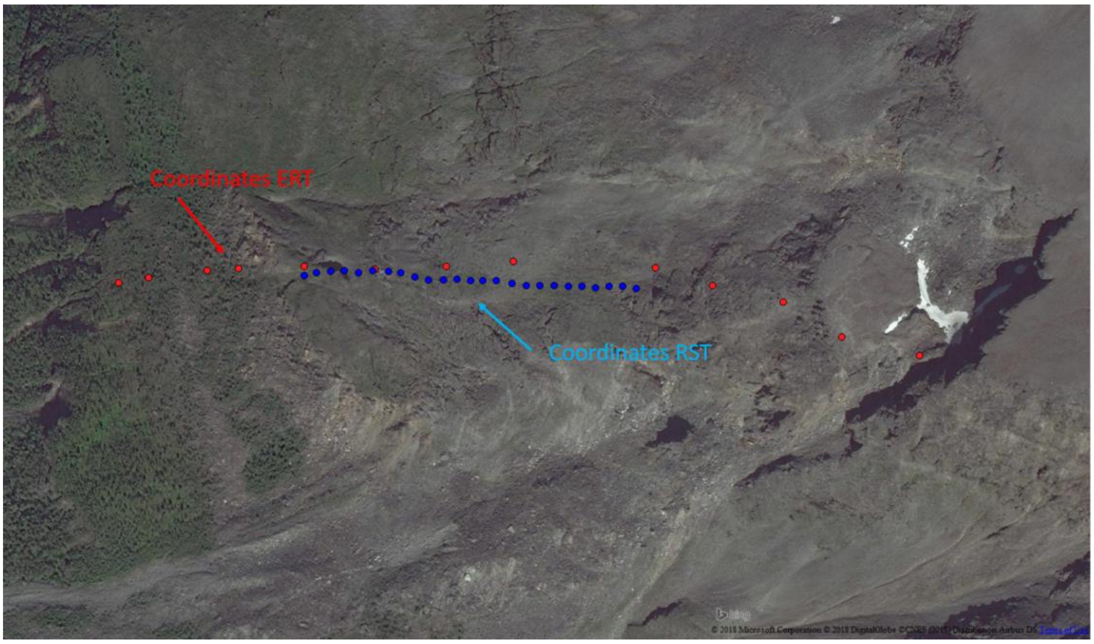

Figure 2: Coordinate mismatch between ERT and RST profiles for Gamanjunni 2.

3.2 Inversion of geoelectrical raw data

The inversion of the measured apparent resistivities (i.e. the calculation of the specific resistivity model of the subsurface) was performed using the Software *Res2DInv* (Loke 2012). For this, we used well-established methods to improve the accuracy and analysis of ERT inversions in high-resistive environments (such as coarse-blocky terrain and/or permafrost, cf. Marescot et al. 2003, Hauck & Kneisel 2008, Hilbich et al. 2009). Due to geometric reasons, the sensitivity of the measurements is highest near the surface and in the central part of the tomogram and decreases with depth and to the sides. Consequently, these areas have usually the highest reliability.

The resulting tomograms were afterwards compared with the tomograms presented in the existing reports for consistency. In general, major discrepancies between our tomograms and the previous tomograms can have three sources: (i) differences in model geometry; (ii) different filtering schemes of the raw data set and (iii) different inversion parameters (regularisation and convergence). Differences in model geometry originate from the need to interpolate the ERT data on the seismic grid as explained above. The resulting inconsistencies are considered acceptable for the overall interpretation. For detailed interpretation of specific ERT features, the original ERT tomograms as published in the relevant reports (Geological Survey of Austria, NGU) should be considered. Discrepancies due to filtering and inversion parameters are considered less problematic, as this ambiguity is a standard problem in ERT surveys due to the under-determined nature of the inverse problem and equivalence.

3.3 4PM setup and modelling

3.3.1 Matching of ERT and seismic data sets on the same grid

Figs. 3 and 4 show the resulting ERT and RST tomograms for Gamanjunni 1 and 2 after matching the ERT data sets on the grid of the seismic tomograms. Note also, that the plotted model area is restricted to model blocks where both, ERT and RST data are available.

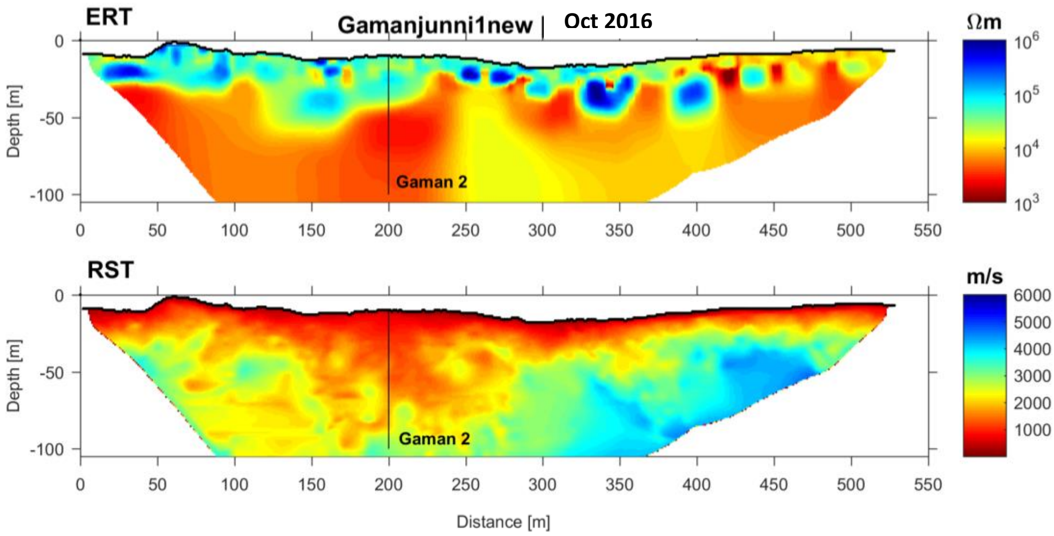

Figure 3: ERT and RST tomograms for profile Gamanjunni 1. The black vertical line marks the (approx.) cross-over point with profile Gamanjunni 2.

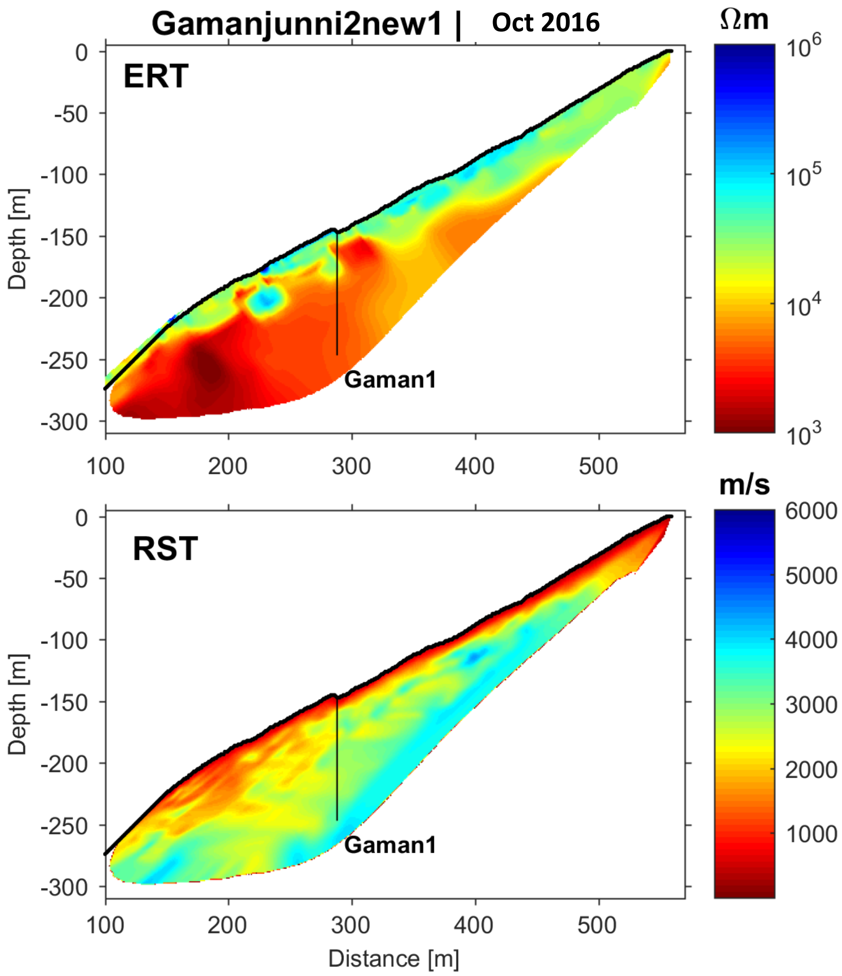

Figure 4: ERT and RST tomograms for profile Gamanjunni 2. The black vertical line marks the (approx.) cross-over point with profile Gamanjunni 1.

3.3.2 Porosity model

As mentioned in chapter 2, in the present version of the 4PM a porosity value has to be prescribed for each model block. We used a surface topography following gradient model (cf. Pellet et al. 2016). Surface porosity was chosen to be 60% with an decreasing gradient of 0.005/m (Gamanjunni 1) and 0.01 (Gamanjunni 2). This slight difference results from a manual optimisation process, which aims to generate physically consistent solutions for all model blocks. The resulting porosity distribution used as input for the 4PM calculations is shown in Fig. 5.

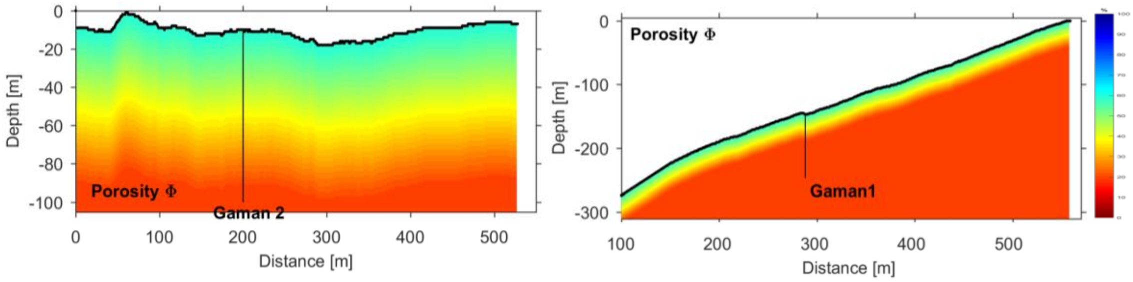

Figure 5: Porosity model for profiles Gamanjunni 1 (left) and Gamanjunni 2 (right). The black lines mark the (approx.) respective cross-over points with the other profile. Note, that the vertical scale is different for both profiles!

Without further a-priori knowledge about the porosity distribution, which could be very different in reality, this porosity model and the resulting absolute ice/water/air contents have to be interpreted with great care. However, the calculated *saturations*, i.e. the **composition of the available pore space** has been shown to be less dependent on the actual porosity values and may be interpreted with higher confidence (see chapters 4 and 5).

3.3.3 Specification of remaining 4PM parameter

The remaining parameter for the 4PM calculations are listed in Table 1. The P-wave velocity of the firm bedrock material was chosen consistent with the results of the seismic measurements, and the choice of the so-called Archie parameters ρ_w, n and m was based on own experience and aimed to optimise the number of physically consistent solutions for the full model domain.

Sensitivity studies with the 4PM have shown a strong dependence of the ice/water ratio on the choice of the pore water resistivity, ρ_w (e.g. Hauck et al. 2011). In the absence of direct measurements or a-priori knowledge of this parameter, borehole temperatures, active layer thickness or water contents for model calibration, the potential error linked with the pore water resistivity value is considered the largest uncertainty for the 4PM results.

Table 1: 4PM parameters used in this study.

Profile	Porosity model	Pore water resistivity [Ωm]	Archie m	Archie n	P-wave velocity ice	P-wave velocity air	P-wave velocity water	P-wave velocity rock
Gamanjunni 1	Surface porosity 0.6 Gradient 0.005/m	150	1.3	1.8	3500	330	1500	6000
Gamanjunni 2	Surface porosity 0.6 Gradient 0.01/m	100	1.3	1.8	3500	330	1500	6000

4 Results

4.1 Gamanjunni 1

Figure 6 shows the calculated ice-, water- and air contents, both as absolute (left) and saturation values (right), for the Gamanjunni 1 profile. Two striking characteristics can be seen directly: firstly, permafrost conditions are suggested by the considerable ice content values of 50-80% saturation, and secondly, large heterogeneities are seen, both, vertically and horizontally. This heterogeneity is largest close to the cross-over point with the Gamanjunni 2 profile, where a fracture zone at larger depth is suggested by the high subsurface air contents (horizontal distance 180-230). The validity of permafrost conditions is further supported by the presence of an unfrozen surface layer (ice contents ~ 0 in the uppermost 5-10m). Due to the large vertical scale, the exact extent of this unfrozen layer cannot be determined with certainty, but its variability may be realistic. It is also worth mentioning, that the results suggest a higher ice content in the right-hand (northern) part of the profile, and within the uppermost 30 meters.

The overall water contents are low, with the exception of the fracture zone near 200m horizontal distance. It is generally higher in the left-hand part of the profile. Air contents are high near the surface, suggesting dry conditions, and in the above mentioned fracture zone. It should be noted that this kind of high air contents at larger depths is very rarely seen, at least to our experience. From the viewpoint of the 4PM calculations, they have their origin in the low P-wave velocities encountered in this location (cf. Fig. 3). This region was also prominently discussed in the reports concerning the original seismic and ERT results of the area (GeoExpert 2016, GSA 2016).

The high-calculated ice saturations at depth in the right-hand side of the profile could be influenced by the presence of firm, low-porosity bedrock, which was described as outcropping at the very far end of the profile (GSA 2016). In this part of the profile, high P-wave velocities (significant for ice or firm bedrock) are coinciding with comparatively low resistivity values, which are more atypical for significant ice contents. As porosity values have been prescribed in a laterally homogeneous way, this potentially more firm bedrock conditions and its influence on the ice/water content in the right-hand side of the profile will not show up in the 4PM results.

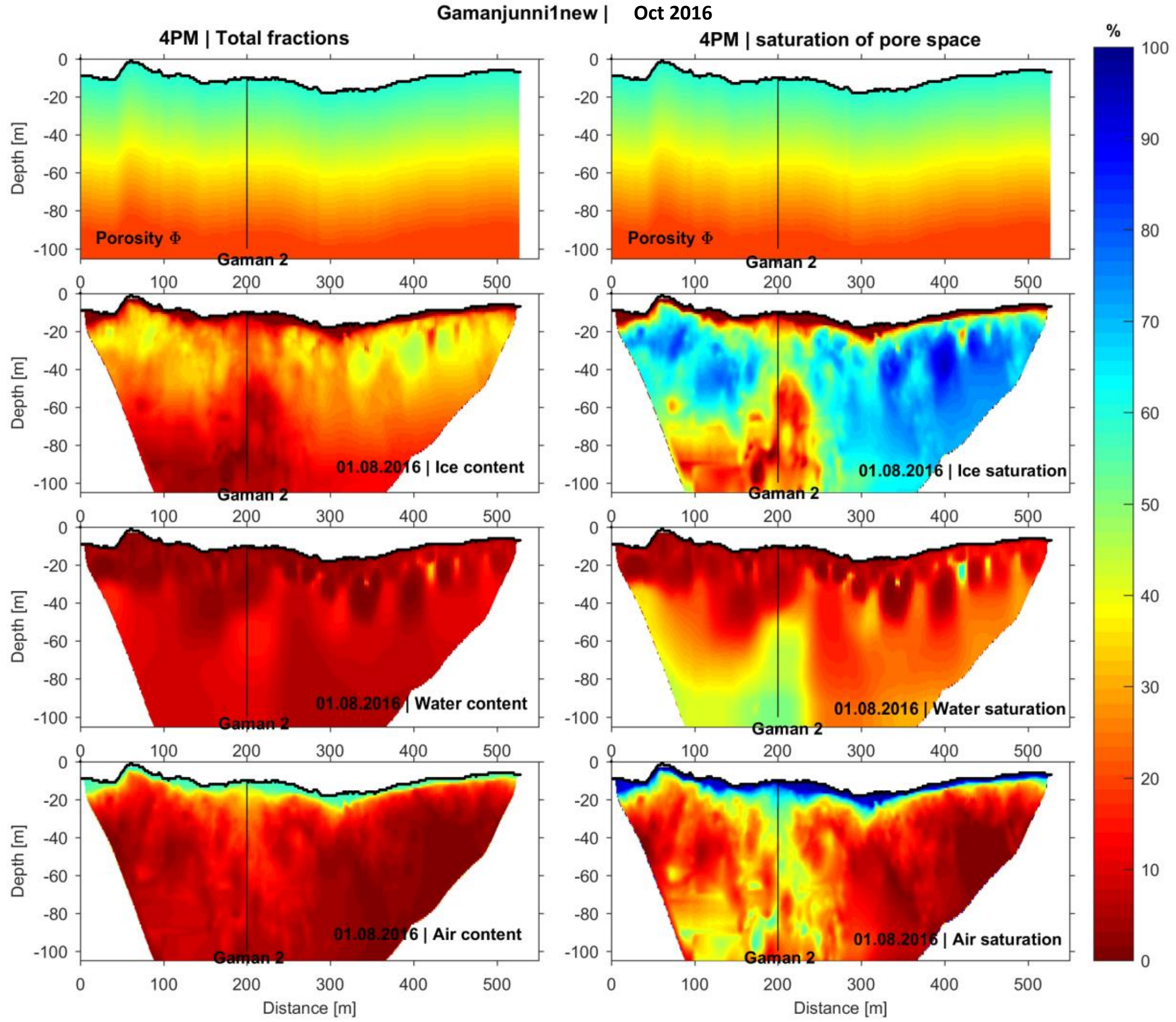

Figure 6: 4PM results for the horizontal cross profile Gamanjunni 1. The left column shows absolute ice-, water- and air contents, the right column shows the same results as saturation values that is relative to the available pore space. The porosity is given in the top row. The (approx.) cross-over point with the Gamanjunni 2 profile is shown as vertical black line.

4.2 Gamanjunni 2

In the same way as Fig. 6, Fig. 7 shows the calculated ice-, water- and air contents for the longitudinal Gamanjunni 2 profile. Here, the presence of a specific bedrock layer with different characteristics is more obvious (due to geometrical reasons) and has correspondingly been marked with grey shading.

Similar to Gamanjunni 1, the results suggest permafrost conditions, especially for the upper part of the profile. Due to the different geometry, the unfrozen surface layer is less visible, but similarly present as in Gamanjunni 1. A fracture zone, characterised by high air contents, is present at 150-280m horizontal distance, but a bit less pronounced than in Fig. 6. It is located close to the crossing with Gamanjunni 1, but does not seem to extend upslope of it. High water saturation values can be found at the foot of the profile (left-hand side) between 100-200m horizontal distance.

At the cross-over point marked with the black vertical line the results for the different saturations match well the corresponding values in Fig. 6. The transition between predominantly high ice saturations and high water saturations (which could be interpreted as the transition between frozen and unfrozen conditions) is in both cases around 40-50m depth. Whether this has any resemblance to the real word or is due to an abrupt (and not prescribed) change in porosity cannot be decided without additional data. However, the correspondence of the 4PM results of both profiles at the cross-over point can be seen as positive aspect regarding the reliability of the results.

Even considering the inherent uncertainties of the 4PM (see also Hauck et al. 2011, Mewes et al. 2017), which will be discussed in more detail in the next chapter, it can be stated that the 4PM calculates ice occurrences only in the uppermost 30-50 meters; which is best seen in the ice saturation sub-plot of Gamanjunni 2 (second sub-plot on the right, Fig. 7). Furthermore, ice content is decreasing with elevation, but seems to be still present at the lower end of the 4PM profile of Gamanjunni 2 (restricted by the seismic profile; the ERT profile by NGU reached lower elevations, see Fig. 1).

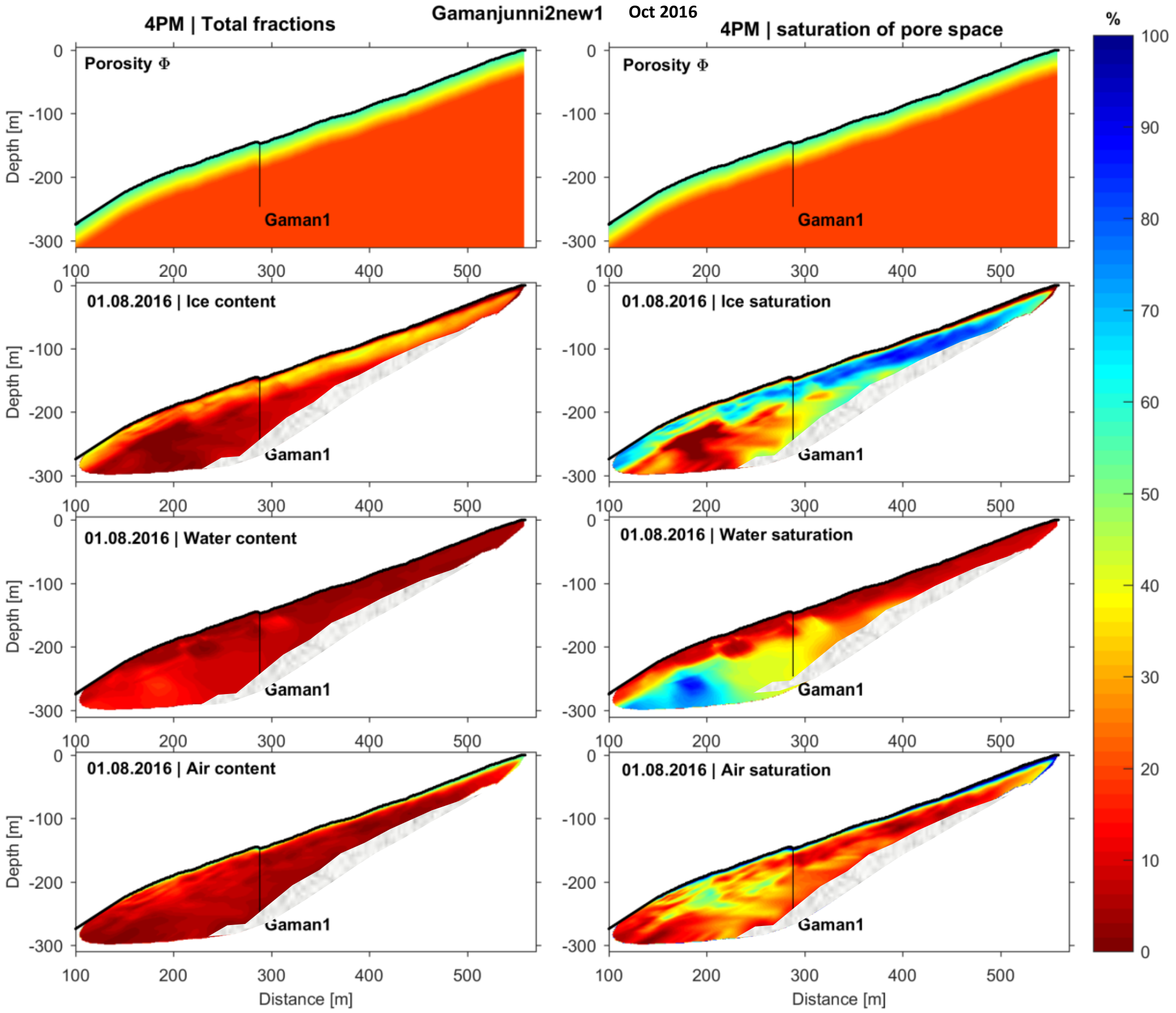

Figure 7: 4PM results for the longitudinal profile Gamanjunni 1. The left column shows absolute ice-, water- and air contents, the right column shows the same results as saturation values that is relative to the available pore space. The porosity is given in the top row. The (approx.) cross-over point with the Gamanjunni 1 profile is shown as vertical black line. The modelled firm bedrock layer (deviating from the prescribed porosity model) is shaded in grey.

5 Discussion

In this chapter, we discuss the correspondence of our 4PM results with the findings of previous studies in the area. These previous findings stem from the interpretation of the individual seismic and ERT profiles (reports by GeoExpert and GSA), temperature data (NORUT 2018) as well as additional ERT/laboratory data from the top part of the rock wall (data made kindly available by the groups of Prof. M. Krautblatter/TU Munich). In addition, the inherent uncertainties of the 4PM and their relevance for the interpretation of our findings are discussed.

5.1 Comparison with other available data

The 4PM results presented above suggest the presence of ground ice in both profiles with generally higher ice contents in the upslope parts and within the uppermost 20-30 metres below the surface. The active layer (here, the ice-free layer at the surface) is <5m, although difficult to estimate due to the resolution of the underlying data sets. This corresponds well with the findings of the NORUT (2018) report, which analysed probable permafrost conditions based on near-surface ground temperature measurements. For the upper part of the rock slope (not covered by the 4PM/geophysical results) the report states clear permafrost conditions; for the middle and lower parts of the rockslide (covered by the 4PM results), the report suggests that permafrost is probable or possible (based on measured BTS and near-surface ground temperatures values), except for the lowermost end of the rockslide (NORUT 2018).

The prominent decompaction zone as identified within the GeoExpert (2016) report corresponds to the zone with high air contents in the 4PM results of both profiles. It is also characterised by very variable (including high) resistivity values (cf. GSA 2016). In this area, also higher water contents are calculated at larger depths (Gamanjunni 1) which was also hypothesised in GSA (2016).

Finally, extensive ERT measurements in combination with laboratory measurements were conducted on the top plateau of the rockslide by the group of Prof. M. Krautblatter (TU Munich). The field and corresponding laboratory data, kindly made available by the TU Munich group, indicated permafrost conditions in this top part of the plateau, and ERT values > 10-50kΩm were identified for frozen conditions in the laboratory. The resistivity values for the transition zone between unfrozen and frozen conditions was estimated as 32-64 kΩm (M. Krautblatter, J. Leinauer & colleagues, personal communication). In the ERT results of Gamanjunni 1 and 2 (Figs. 3 and 4), this boundary would correspond to the orange to green colours indicating permafrost conditions down to ~50-60m (Gamanjunni 1) and ~30m (Gamanjunni 2) depth. This corresponds well with our 4PM results, which indicated permafrost conditions between 30-50m thickness depending on the location along and across the rock slide. Note however, that the 4PM takes also the seismic results into account (enabling for example the visualisation of the unfrozen surface layer (active layer) and the subsurface heterogeneities).

5.2 Uncertainty of 4PM results

The quantification of *absolute* ground ice contents by geophysical methods, i.e. by a combination of two indirect and surface-based methods, contains a series of uncertainties, which are partly described in section 3, and discussed more in detail in the relevant publications of the 4PM (Hauck et al. 2011, Schneider et al. 2013, Pellet et al. 2016, Mewes et al. 2017). However, in addition to an indication of the range between ice-rich to ice-poor conditions (and the absence of ground ice), the main advantage of the model is its ability to delineate the spatial heterogeneity of ground ice conditions, both, horizontally and vertically, as seen very clearly in the profiles where the 4PM has been successfully applied. The uncertainties of the patterns of ice saturation is hereby much lower than the uncertainties of the absolute ground ice contents.

Uncertainties arise from a series of factors including uncertainties of co-location of electric and seismic data sets, geometrical matching and interpolation of the two data sets on the same grid, the simplification of the prescribed porosity model, and the generally unknown Archie parameters and P-wave velocity of the rock material (Table 1). In the absence of borehole information for the calibration of the 4PM, the results have therefore to be interpreted cautiously as they give only indications of the subsurface composition rather than a prediction of their absolute values.

Finally, we have to mention that our results and their interpretation may suffer from the fact, that we have not visited the site ourselves. The geotechnical/geomorphological significance of our 4PM results are therefore best analysed by people familiar with the specifics of the site. Corresponding modifications/adaptions to the 4PM input parameters (Table 1) and subsequent re-modelling can easily be conducted, if needed.

6 Summary and Conclusions

Calculations with the so-called 4-phase model (4PM) have been conducted based on available electric and seismic data sets along two profiles at the Gamanjunni rock slide site. The results indicate permafrost conditions in both profiles, which may amount to of at least 30-50m thickness. In addition, strong heterogeneities especially regarding decompaction and fracture zones have been found, including significant air contents at larger depths, which is seldom found at mountain permafrost occurrences.

The inherent uncertainties of the method have been described in this report. Although they may be significant due to the fact, that a 4-phase modelling has not been planned from the beginning of this study, and relevant information/preconditions are therefore partly absent, we consider the results reliable with respect to the above described main features, i.e. the permafrost conditions and the significant heterogeneities/air contents in the subsurface.

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