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SDRUŽENÉ INTERPRETACE GEOFYZIKÁLNÍCH MĚŘENÍ JAKO KLÍČ K POCHOPENÍ VÝVOJE RELIÉFU

JOINT INTERPRETATIONS OF GEOPHYSICAL MEASUREMENTS AS THE KEY TO UNDERSTAND LANDSCAPE EVOLUTION

autoreferát doktorské disertační práce

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Abstrakt

Užitá geofyzika představuje rychlý, efektivní a nedestruktivní způsob získávání informací o složení a stavu horninového prostředí, jakož i o studovaných geologických či geomorfologických procesech. Kombinování různých metod geofyzikálního průzkumu přináší ve srovnání s použitím pouze jedné geofyzikální metody výrazně širší rozsah měřených fyzikálních parametrů, což umožňuje získání mnohem podrobnějších informací o zkoumaném geologickém prostředí. K interpretacím geofyzikálních dat je vždy potřeba přistupovat obezřetně, protože jde mnohdy jen o jedno z pravděpodobných, nikoli však jediných možných řešení. Předkládaná disertační práce na několika vybraných případech ilustruje, jak snadno může dojít k nepřesné, nebo dokonce mylné interpretaci. V řadě případů přitom nemusí jít o problém kvality dat nebo chybného nastavení parametrů výpočetního modelu. Problém nastává při interpretaci výsledků, kdy dochází k přiřazení určité geologické kvality ke konkrétní měřené nebo modelované hodnotě nebo pozorované anomálii. Sdružené interpretace geofyzikálních metod (ideálně doplněné informacemi „negeofyzikálního“ charakteru) mohou nejen přinést zásadní informace o studovaných geologických či geomorfologických fenoménech, ale také přispět metodickými poznatky, a to jak k metodám jednotlivým, tak zejména k jejich kombinacím. Disertační práce hodnotí aplikační potenciál vybraných geofyzikálních metod, použitých v rámci prezentovaných případových studií, jakož i praktické možnosti využití kombinovaného geofyzikálního průzkumu při řešení konkrétní geologické problematiky. Vedle samotného posouzení vhodnosti jednotlivých geofyzikálních metod, práce hodnotí zejména přínos jejich vzájemných kombinací na základě sdružených interpretací výsledků. Velký důraz byl kladen zejména na reinterpretace výsledků, které ze společného zpracování metod vzešly.

Klíčová slova: užitá geofyzika, geoelektrický průzkum, seismický průzkum, gravimetrický průzkum, sdružená interpretace, reinterpretace, vývoj reliéfu

Abstract

Applied geophysics represents fast, efficient and non-destructive way of acquiring information on the composition and conditions of the rock environment as well as on the investigated geological or geomorphological phenomena. Compared to the use of a single geophysical method, the combination of various geophysical surveying techniques provides significantly wider range of measured physical parameters which allows much more complete information on the studied geological environment. We have always to be careful when dealing with interpretations of geophysical data as the final result can represent just one of many possible solutions. Using several selected case studies, the presented Ph.D. thesis illustrates how easily we can achieve an inaccurate or even incorrect interpretation. In many cases, there is no problem with data quality or erroneous settings the of computational model parameters, but the error arises during the interpretation of the results when we assign specific geological quality to certain measured or modelled value or observed anomaly. Joint interpretations of geophysical methods, ideally further supported by additional information of "non-geophysical" nature, can provide crucial information not only on the studied geological or geomorphological phenomena, but also contribute to the methodological know-how, both concerning the individual geophysical methods as well as especially their combinations. This thesis evaluates the application potential of selected geophysical methods as illustrated by the presented case studies, but also analyses the practical concerns of using combined geophysical survey in solving specific geological issues. In addition, the benefits of the combinations of various geophysical methods are evaluated, based on the combined interpretations of the results. The contribution of the joint processing on the newly emerged interpretations of the results are emphasized.

Keywords: applied geophysics, geoelectrical survey, seismic survey, gravity survey, joint interpretation, reinterpretation, landscape evolution

1. Introduction

The use of applied geophysical methods has a relatively long tradition. Initially, a utilization of the field geophysical methods by the broad geoscience community was considerably limited by the complexity and size of the devices, by the slow and often manual measurement, and last but not least, by the laborious, mostly manual data processing, requiring prior experience because there was no computer technology available. Later, from the 1980s and especially the 1990s, the rapid development of computer science (IT) led to a very rapid development of instrumentation and the first data processing software. Applied geophysics became a fast, non-invasive and relatively cheap way how to acquire information on the situation below the Earth's surface (including lithological composition, structural, tectonic, geotechnical, and hydrogeological properties of the rock environment or sedimentary layers).

Geophysical (*hereafter referred as GF*) methods were thus beginning to find applications in other geoscience and engineering disciplines. The new millennium brought an introduction of a new generation of instruments. The instruments already represented (and further represent in their later versions), complex devices that are as compact as possible, have sufficient power, are sophisticated, yet relatively simple to operate. They are fully controlled by an internal microprocessor, have sufficient storage capacity, and they are even capable of sending data to remote storage. Measurement is often fully automated following a programmed scheme and data is stored in the built-in memory or sent to a remote device or stored on a remote storage (server) via mobile networks and the Internet.

In many cases, these devices have only minimal demands on the user in terms of operation and often no longer require complex technical settings. These steps are already performed by the instruments themselves and are fully automated, or can be calibrated relatively easily. GF instruments have thus gradually become so-called user-friendly and do not require a deep knowledge of the instrument and the measuring principle and often not even significant previous experience with the instrument. This is a great advantage over older GF devices, but on the other hand, it can pose problems in data processing and interpretation of results, where some insight and prior experience are necessary.

Applied geophysics is nowadays a relatively fast, efficient, non-destructive and relatively cheap way of obtaining information on the composition and condition of the bedrock (by condition is meant, for example, the intensity of fracturing or weathering), the thicknesses and courses of sedimentary bodies, geological structures, tectonics, and shear surfaces, or the presence of voids, the thicknesses of collapsed masses or water saturation of the rock environment, etc. Especially when using a combination of several GF methods, geophysics can provide crucial information on the environment or a particular natural phenomenon or process under investigation.

The dissertation focuses on the application potential of selected GF methods used in the solution of the presented geological and geomorphological phenomena, as well as on the evaluation of the utilization of a complex of GF methods in solving the given problem. In addition to the applicability of the individual methods, the thesis evaluates in particular the benefits of combining different methods, including the joint interpretation of the data.

2. Motivation and aims of the dissertation

In the last 20 years, there has been a large increase in the number of studies that - although primarily geomorphological - use an interdisciplinary approach, including the use of shallow geophysical survey methods. A significant increase in the number of such studies has occurred especially in the last decade, when geophysical devices have gradually become a part of the instrumentation of many different geoscience research institutes, departments or research teams and is no longer the "prerogative" of geophysical departments alone. However, the presented interpretations are not always correctly performed.

The present thesis therefore focuses on the last step in the sequence "measurement design - measurement implementation - data processing - measurement interpretation". In spite of the fact that GF measurements can be wrongly "grasped" already in the design phase, it is especially the final interpretations of the results that are subsequently presented. Erroneous or at least misleading interpretation can compromise any research in fact. This dissertation discusses examples of interpretations and suggests some solutions.

The main objective of the thesis is therefore to assess the applicability of individual GF methods used and their mutual combinations in solving various geological problems (structural geology, fault tectonics, effect of lithology, slope processes, etc.), using a joint interpretation of the results.

3. Joint interpretation of geophysical data

The mutual comparison of results from different GF methods can help to understand the geological situation below the surface more comprehensively and, within the integration of results and their joint analysis, to refine the resulting geological (geomorphological) interpretation.

This joint data analysis is also called "*integrated analysis*" or "*integrated interpretation*". The established procedure is to combine the outputs of separately processed and interpreted methods, based on visual comparison of results, looking for associations or anomalous manifestations of specific structures, and then combining them. This approach is referred as "*joint interpretation*" (sometimes also as "*combined interpretation*").

The joint interpretation of GF data consists in the creation of a conceptual geological model based on all available direct and indirect data, including the results from geophysical measurements, and their mutual verification.

Although the primary goal is not to "fit" the data or partial results to the combined model, but rather to adjust the resulting model to fit all partial results (inputs) and the knowledge derived from them, it often happens that the results of some of the partial methods need to be reinterpreted when solving such a model (and thus the resulting interpretation). By interpretation, we mean the attribution of a geological quality to a particular value of the interpreted measured physical parameter, or a change in that value (Reynolds 2011).

The combined interpretation often yields findings that lead to adjustments in the model parameters. A typical example is the gravimetric model, where the values of bulk density are given only on the basis of knowledge of the geological (lithological) conditions, and the model can thus have infinitely many solutions.

Kvamme (2006) considers the separate processing of data from individual geophysical methods and the subsequent manual marking of recurring anomalies as a joint interpretation. This author also presents an interesting possibility of working with datasets. He states that data of a discrete nature (e.g., clearly distinguishable separate occurrences of anomalies) allow the use of various algebraic operations or classification even for large numbers of imaging datasets without losing the predictive power of the output. The procedure uses the conversion of the input data into a binary form and leads to a simple standardisation of the data into a bipolar distribution with values "0" (anomaly not present) or "1" (anomaly present). Similarly, Piro et al. (2000) also report on the possibilities of such normalization and scaling.

3. Methodology

Due to the relatively large number of different combinations of GF methods used at 6 different sites, presented in the dissertation as case studies, the description of the methodology is divided as follows. Chapter 4 Methodology describes the different GF methods used. This is not a complete list of GF methods; this is certainly not the aim or purpose of the present dissertation. It is a brief description of only those methods that have been directly used in the case studies in this thesis, with a focus on the parameters and practical aspects of the measurements. These include electrical resistivity tomography, GPR, dipole electromagnetic profiling, audio-magnetotelluric measurements, gravity and seismic surveys.

First, the principles of individual GF methods are briefly described, or the methodology is elaborated for a group of GF methods if they share a physical basis. The chapter then presents some typical variations of the measurement method, as well as typical applications, depth ranges, as well as generally known advantages and disadvantages of the methods, limitations, etc. A more detailed description of the specifically applied GF measurements is then given separately for each study site (case study) (Chapter 5), especially with regard to the geological and research context (e.g. structural and lithological conditions, purpose and scale of the survey, resolution of the measurements, etc.).

Considering the focus of the present thesis on the interpretation of data and results and the limited extent of this summary, the PhD student does not consider as useful to present here the detailed methodology, which is, moreover, standard, established and described in a number of professional books (textbooks), scripts and other professional publications (Gruntorád et al. 1985; Karous 1989; Mareš et al. 1990; Telford 1990; Milsom 2003; Reynolds 2011), listed in the dissertation on 30 pages in the list of references used.

5. Case studies

The use of combined GF measurements has been carried out at a number of sites within the dissertation project, not only in the Czech Republic. However, a selection of only six of these sites is presented within the dissertation (Fig. 20). The research sites have been carefully selected, particularly with respect to (i) their realized or currently forthcoming publication in peer-reviewed journals, (ii) the illustrative nature of the presented examples of reinterpretations (made on the basis of combined interpretations), (iii) the reasonable extent of the dissertation.

At the same time, the case studies were selected to best represent the different applications of GF methods in geomorphology and geology, from the study of fluvial sediments (fluvial geomorphology/hydrology) to the study of block accumulations (periglacial geomorphology), slope deformations (slope geomorphology / speleology) or Hranice Abyss (karst geomorphology / hydrogeology / geology) to tectonics research, both on a small scale (deep fault zone exploration) and on a large scale (detailed GF measurements for palaeoseismological research).

An overview of the basic information on the presented sites is summarized in Table 2.

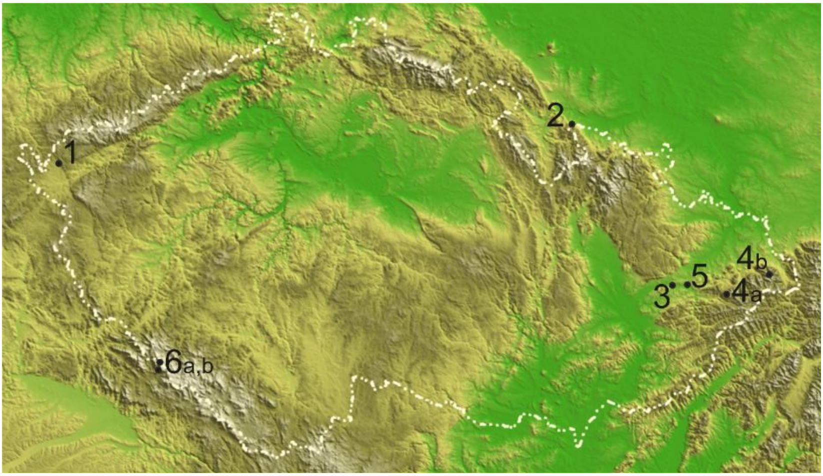

Fig. 20: Situation of the study sites within the Czech Republic: (1) Kopanina (Cheb basin/Krušné hory Mts), (2) Bílá Voda (Rychlebské hory Mts/Przedgórze Paczkowskie hilly-land), (3) Hranice abyss (Podbeskydská pahorkatina - Malenická vrchovina hills), (4a) Záryje (Moravskoslezské Beskydy Mts - Radhošt' ridge), (4b) Ropice (Moravskoslezské Beskydy Mts. - Ropická rozsocha), (5) Bečva river (Podbeskydská pahorkatina hills - Valašsko-meziříčská basin), (6a) Skalka Mts (Šumava Mts- Kvilda plains), (6b) Slunečná Mt (Šumava Mts – Kochánov plains).

(Relief map of the Czech Republic based on SRTM, Farr et al. (2007); own elaboration)

As case studies, the individual research sites are presented as sub-chapters using the following structure. First, the research objectives and a basic introduction to the issues under study are presented. This is followed by local geological, geomorphological and other selected characteristics relevant to the research. Further, the research methodology, in particular the geometry of geophysical measurements used (supplementing the basic methodological overview in Chapter 4), is introduced or specified, and the basic results of the research are presented, using references to publications listed in the dissertation appendix. Each of the publications (technical papers) is listed as a numbered appendix. Thus, when a specific figure or table in a particular scientific article is referred to in the text of the dissertation, the figure number is also preceded by the number of the appendix (e.g. see Appendix P1 - Figure 3, abbreviated Fig. P1 - 3). A list of appendices is given on **page 227** of the dissertation.

In the description of the methodology used for each study site, in addition to listing the specific GF methods used and the basic measurement parameters (e.g. profile lengths, sensor spacing, depth ranges, etc.), it is also stated which equipment was used for the measurements and how the data were subsequently processed and interpreted (in which software package).

The author of the thesis emphasizes at this point that this is certainly not a single or universal procedure for processing GF data, but the way how the data were processed within the case studies (not only by the author, but also by his colleagues within the joint research, cited in publications in the appendices of the thesis) with regard to the research objectives and specific local conditions of the studied sites. It is therefore only one of the possibilities of data processing, not a universally valid procedure. It also has to be note here that the author of the thesis performed and interpreted only some measurements, i.e. mainly the ERT and DEMP measurements. Other measurements were performed by collaborators - co-authors of the papers included in the thesis.

Tab 2: Summary of selected information on the study sites, including relevant publications of the author.

	LOKALITA (GEOMORFOLOGICKÝ CELEK)	VÝZKUMNÉ TÉMA	CÍLE GF PRŮZKUMU (GF ÚLOHA)	GEOLOGIE	ERT	DEMP	GPR	AMT	MRS	GM	DALŠÍ INFORMACE	PUBLIKACE
1	**Kopanina** *Chebská pánev* *X* *Krušné hory – Jindřichovická vrchovina)*	**Hluboký GF průzkum zlomové zóny (malé měřítko)** strukturní geologie / tektonika / seismologie	zjištění lomu, sledování jeho průběhu a geometrie do hloubky, stanovení strukturně-tektonických podmínek a litologie, rozlišení sedimentárních a krystalických hornin	Český masív / Saxothuringikum / Podkrušnohorské pánve (miocenní sedimenty) X Český masív / Saxothuringikum / Krušnohorské krystalinikum	*	x	x	*	*	*	průzkumné paleoseismologické rýhy, vrty, seismologické studie	**Blecha et al. (2018) - P1** Tábořík et al. (2016) - P2
2	**Bílá Voda** *Rychlebské hory – Hřibovská hornatina* *X* *Przedgórze Paczkowskie – Paczków Graben (Vidnavská nížina)*	**Detailní tektonický a paleoseismologický výzkum zlomu (ve velkém měřítku)** strukturní geologie / tektonika / tektonická geomorfologie / paleoseismologie	zjištění zlomu, stanovení strukturně-tektonických podmínek a litologie, studium sedimentárních forem spojených se zlomem, určení objemu proluviálních sedimentů	Český masív / Lugikum / krystalinikum orlicko-sněžnické klenby X Masyw Czeski / Blok przedsudecki / Paczków Graben (Vidnavská pánev) / miocénní sedimenty	*	x	*	*	*	x	průzkumné paleoseismologické rýhy, kopané sondy	**Štěpančíková et al. (under review) - P3,** Tábořík et al. (in prep.-A)
3	**Hranická propast** *Podbeskydská pahorkatina - Malenická vrchovina*	**Výzkum krasu** obecná geomorfologie / krasová geomorfologie / pohřbené povrchy / hydrogeologie	sledování průběhu propasti do hloubky, určení litologie a strukturně-tektonických podmínek, zón oslabení (krasověním, hydrotermální působením), identifikace pohřbených povrchů	Český masív / Karpatská předhlubeň / kra Maleníku / vápenec a neogénní sedimenty	*	x	x	*	**1)	*	vrty, speleoprůzkum	**Klanica et al. (2020) - P4** Kadlec et al. (2021) - P5
4	**Záryje (Radhošť) a Ropice** *(Moravskoslezské Beskydy – (Radhošťský hřbet) a Ropická rozsocha)*	**Hluboký gravitační rozpad hřbetů a související morfologické formy** (geomorfologie svahů / výzkum svahových deformací / rozsedlinové jeskynní systémy)	určení litologie, strukturně-tektonických podmínek, vnitřní struktury a distribuce projevů svahových deformací, včetně tahových zón a rozsedlin	Vnější západní Karpaty / Slezská jednotka / Godulské vrtsvy / flyšové horniny (pískovce a jílcovce)	*	x	*	x	*	*	geomorfologické mapování, detailní speleoprůzkum	**Tábořík et al. (2017a) - P6**
5	**Bečva** *Podbeskydská pahorkanita – Valašskomeziříčská kotlina*	**Výzkum říčních sedimentů** (fluviální geomorfologie / hydrologie / hydrogeologie)	určení mocností, distribuce a vnitřní struktury fluvialních sedimentů	Vnější Západní Karpaty / Slezská a Podslezká jednotka / flyšové podloží překryté fluviálními sedimenty	*	*	*	x	*	x	vrty, hladina podz. vody ve studni, ruční vrtané sondy	Tábořík et al. (in prep.-B)
6	**Skalka a Slunečná** *Šumava – Kvildské a Kochánovské pláně*	**Bloková pole a blokové akumulace na svazích** (geomorfologie svahu / periglaciální geomorfologie)	určení mocnosti, distribuce, vnitřní struktury a typologie blokových polí	Český masív / moldanubikum / granity a metamorfované horniny (pararula, kvarcit)	*	*	*	x	*	x	geomorfologické mapování, ruční sonda	**Duffek et al. (under review) - P7**
					1) reflexní seismický průzkum							**Px - číslo přílohy**

Similarly, for the joint interpretations of the GF methods and possible reinterpretations of selected results (in particular, the determination of interfaces, the modified geophysical-geomorphological interpretation, or in several cases, modifications of the resulting model) it apply that they were carried out - despite the obvious effort to be as objective as possible - with a certain amount of subjectivity, at least in terms of the routine procedures and experience of the team members who participated in the processing and interpretations. The author of the thesis points out that this is by no means a generally valid interpretative procedure, but rather a very specific approach, closely related to the local conditions of the particular study site.

The results section is then discussed in the Discussion, which summarises the main results of the research carried out, and in particular the joint interpretations that are the main focus of the present thesis, with a reinterpretation of the results for each of the sites, which are analysed and discussed in the Discussion section.

A graphical example of the reinterpretations of the results performed within the thesis:

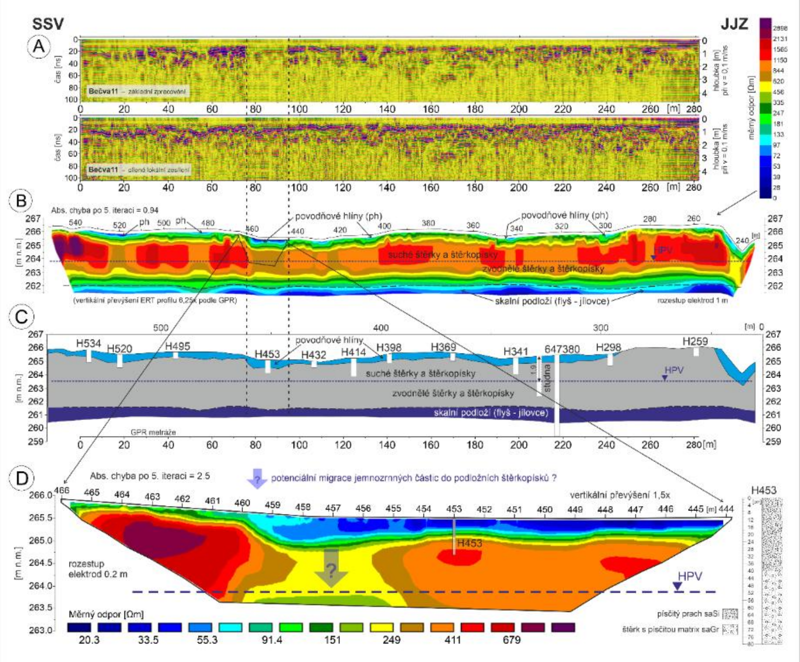

Fig. 39: Joint interpretation of GF data on profile P1 at Bečva site: (A) top: original GPR data processing with an anomaly with significant attenuation, bottom: processing with targeted anomaly amplification; (B) ERT measurements identifying anomaly below the conductive sedimentary infill of the old channel (vertical exaggeration according to GPR); (C) exaggerated interpreted geological section, the thickness of fine-grained floodplain clay interpreted based on ERT and shallow manual boreholes; (D) detailed ERT measurements (with 0.2 m electrode spacing) across the filled palaeochannel, the final inversion model shows decreased resistivity values in the gravels beneath the sedimentary infill.

(reinterpretation, own elaboration, partly based on Stacke 2013)

6. Discussion

The joined interpretations, presented in the previous chapter, provided a lot of interesting information not only on the studied geological or geomorphological phenomena, but also a number of methodological knowledge, which enriched the author of the thesis and his colleagues with further valuable experience, especially with the processing and interpretation of GF data.

6.1 Interpretations and their ambiguity

Although the presented dissertation aims at evaluating the practical applicability of combined GF surveying in the research of lanscape evolution, including the assessment of the applicability of individual GF methods and their mutual combinations in solving different geological problems (using the combined interpretation of results), it is not a purely methodological or even theoretical work. On the contrary, the work is mainly based on the practical application of GF methods. The evaluation of the applicability of individual methods in solving a specific problem includes - besides the evaluation of practical benefits - also a certain degree of evaluation of methodological approaches used both in the design of measurements (technical solution) and in data processing and interpretation of results. The thesis is based on the author's own research and data, or on research in which the author was actively involved from the design of the measurement methodology to the final interpretation and publication of the results.

The thesis describes the use of GF methods in other geoscientific disciplines (geology, geomorphology sedimentology, engineering geology, etc.) and thus targets not only geophysicists, but brings - as its author firmly hopes - useful experience, insights or inspiration for the general scientific community. For this reason, commonly available (e.g. also for commercial companies) GF methods and standard methodological procedures based on well-known physical principles have been used in this work. The aim of the work is not to create new approaches that would thus require further testing and validation, but rather to use established methodological procedures that have been proven by years and practice.

It can certainly be argued at this point that a contribution could be made, for example, by experimental measurements or a novel way of processing the data, which could further develop or even advance the methodology. On the other hand, any such experimental measurement is burdened with a relatively high level of uncertainty and would require validation at many other sites with different geological conditions to verify the general validity of such an approach. Similarly, for a new method of data processing applies the same. Although the author of the thesis greatly appreciates such efforts and is himself frequently and happily involved in experimental measurements, he does not consider such innovative approaches to be very suitable for the main purpose and objective of the present thesis, due to the aforementioned need of validation of such procedures.

However, even with the use of standard methodological procedures and commonly (commercially) available apparatuses and processing programs, great care must be taken in the interpretation process. Errors in interpretations can occur very easily, even assuming that the interpreter has previous experience, as illustrated by the six case studies in the results and discussion sections of this thesis.

The correct geophysical-geological interpretation of GF measurements has been previously addressed by some authors (Piro et al. 2000; Kvamme 2006; Drahor 2011; Doetsch et al. 2012; Fischer et al. 2012; Simon et al. 2015, etc.), but there is apparently no work that describes this issue in a comprehensive and systematic way. Given the wide range of GF methods, their different modifications, different instrumentation and software, and especially the myriad different types of applications of GF methods for different targets, this is probably not even possible. For example, it is not possible to apply the same measurement procedure for detailed exploration of shallow depths and for deep exploration of macrostructures.

For example, it is difficult to apply the same approach to detailed GF measurements in palaeoseismological research (Fischer et al. 2012) as in the verification and monitoring of a tens of metres wide fault zone down to depths of several hundred metres (e.g. Blecha et al. 2018). Yet, both of these studies deal with essentially the same location and the same fault, and can in principle be included in the common category of tectonics research (however, at two completely different scales). In other cases, however, the objectives of the research are already so different that it is indeed difficult to seek any generally valid rules.

Moreover, the whole problem is fundamentally complicated by the diversity of local geological (lithology, structure, tectonics), hydrogeological and geomorphological conditions, and each studied site is thus very unique and specific. For simplicity, these local aspects can be called 'environmental properties' and include all of the above mentioned aspects, including more general physical-geographic aspects. This is because different developments may occur, for example, on north-facing slopes and different ones on south-facing slopes - in particular, hydroclimatic conditions such as insolation intensity, precipitation intensity, snow cover duration or frost weathering intensity (e.g. Křížek 2016; Uxa et al. 2019; Hrbáček et al. 2021). These local subsurface properties then need to be taken into account in qualitative interpretations, where some geological property (= quality) is attributed to the measured GF data, or to the already processed data in the form of GF curves or sections respectively.

In addition to incorporating all available information that can help or refine interpretations (e.g. information from boreholes, excavated probes or exploratory trenches, rock outcrops or geological/geomorphological mapping), such interpretations often require considerable experience, especially in methods where neither the processing nor the subsequent interpretation is intuitive and often unambiguous, e.g. GPR (Simon et al.).

The author of the dissertation, however, distances himself from the claim that "geophysics measured by a non-geophysicist" must necessarily pose a problem. In a number of cases, it is not so much a question of an inappropriate method of measurement, but rather a misinterpretation of the resulting data or models in terms of attributing the aforementioned geological properties. Thus, it is not so much a geophysical problem as a (lack of) knowledge of local geology, including lithology and structural properties, and geomorphological processes. The author of this dissertation, based on his own experience of studying peer-reviewed publications, as well as his experience of many peer-review processes (either as an author or as a reviewer), acquires the knowledge that mistakes are made "on both sides".

In many cases, it is indeed an inaccurate understanding of the physical principles and behaviour of the studied parameter in a particular physical field by the geologist/geomorphologist and as a result, the results may be misinterpreted. As an example, we can state the dogmatic observation of a selected isoline, e.g. a "wavy" isoohm in a resistive section, and its subsequent interpretation as an observed boundary, where the course of this line may differ (even quite significantly) when using altered model parameters (Bláha et al. 2017; Taborik et al. 2017b).

In some cases, (e.g., Sherrod et al. 2014), such an interpretation may even contradict other physical principles, such as soil/rock mechanics, as critically analysed and evaluated by Bláha (2017) in his practice-oriented publication on the application of geophysics to landslides. Therefore, structural geology, engineering geology and other aspects need to be taken into account when interpreting these geological/geomorphological forms. Of course, geophysical surveys can be seen as a very useful exploration tool, but one still needs to keep in mind an important fact, namely that in most cases it is only indirect information conveyed by the measured geophysical field, or a certain parameter of a particular field (e.g. resistivity or seismic wave propagation velocity, etc.) (Mareš et al. 1990; Milsom and Eriksen 2011, etc.).

However, there are also cases when the results of GF surveys were desinterpreted by a geophysicist (*the author of the dissertation does not* *quote here on purpose*), and these interpretations completely lacked "basic geological logic", or it was obvious that the author of these interpretations had very little knowledge of geology or geomorphological processes. It follows from the above that the ideal interpreter is either a geophysicist with considerable overlap with other geological disciplines, or a geologist (geomorphologist) with extensive experience with geophysical methods. This is, however, a somewhat simplistic statement that suggests the idea of some kind of "super-powers" of the individual. A far more effective solution - also preferred by the author of the thesis - is of course to work in a team, composed of experts with different specialisations and then discuss the results together in a joint interpretation.

The joint interpretation of geophysical data can then be viewed similarly. The author of this dissertation in no way claims that the results of "just" one method are necessarily misleading and misinterpreted. However, in a number of cases, it appears that the use of a combination of GF methods and their subsequent combined interpretations leads to significantly more accurate final interpretations (conceptual geological models), where often the original result - based on a more comprehensive approach using other GF survey methods (even "non-geophysical") and subsequent combined interpretation - is reinterpreted, as illustrated by the selected case studies presented in chap. 5 of the present dissertation.

A separate topic is then the data processing, which of course always depends on the "skills" and experience of the interpreter. If the interpreter has only basic knowledge of the interpreting program and cannot use all the tools offered by the software, then one cannot expect any advanced data processing. Especially for problematic datasets (with high measurement error or uneven coverage by the data, etc.), it is possible to achieve a result (model) with an acceptable error, for example, by a suitable type of inversion, appropriate filtering of erroneous data or adjustment of other parameters (e.g. smoothing), without "artificial" anomalies resulting from outliers and subsequent errors in the calculation (McNeill 1980; Loke 2019a). However, this often requires optimization of a number of parameters (statistical pre-processing of data, level and type of data smoothing, type and parameters of filtering, etc.), and often no generally valid rule or specific value of a given parameter can be used and its setting simply needs to be tested. Even so, this does not necessarily mean that the same values of the parameter being set will "work" equally well for a different dataset.

However, using different versions of processing software can also be a problem when processing GF data. And this does not mean a different program (software product of another manufacturer), but only a different version of the same program. In the study by Taborik et al. (2017b), three versions of Res2Dinv (Geotomo software), namely versions 3.54, 3.58 and 4.04, were tested on identical datasets to compare the resulting inverse resistivity models (inverted sections). Since a number of parameters can be changed during the calculation (inversion) setup and thus cannot be simply set up identically, a basic processing with default parameters was used. Moreover, this is the way of processing the data that is most likely to be applied by a beginner-interpreter. Unfortunately, even the basic ("default") settings of the program do not ensure identical results when different developer versions are used (Taborik et al. 2017b), which of course complicates the verification of the correctness of the calculations and subsequent interpretations.

Thus, qualitative interpretations of data should always be approached with caution, bearing in mind that in many cases this is one of the likely, but not the only, possible explanations. It means that a given interpretation - however highly probable - is always only one possible solution. The presented dissertation uses a few selected cases to demonstrate how easily an inaccurate or even misleading interpretation can occur. Also, it may not only be a problem of setting the parameters of calculations, but a problem of qualitative geophysical/geological/geomorphological interpretation, where a certain geological quality (e.g. rock type, differentiation of sedimentary cover from bedrock, delineation of tectonics, etc.) is assigned to a certain measured or modelled value.

There is probably no need to argue about the fact that the quality of the result is fundamentally affected by the quality of the input data in addition to the processing. Repeated measurements can make a significant contribution to quality control and confirmation of data consistency. An example is the repeated GPR measurements in the Bečva floodplain. Looking at the resulting GPR sections Bečva11 and Bečva12 (Fig. 40, chap. 5.2.5.5), which represent two measurements on an identical P1 profile, only in the opposite direction, it can be stated that both sections are surprisingly similar, including the position of the described anomaly.

Nevertheless, the measurement of the Bečva12 control profile was carried out under practically the same conditions, moreover, exactly in the line (track) of the Bečva11 measurement set. Obviously, the measurement on the snow contributed significantly to the unchanging conditions, which ensured that (i) the GPR antenna was guided in the exact track of the previous measurement, (ii) the measurement was free from random tilts or jumps of the antenna, e.g. on stones or clods, (iii) the same "level" of measurements was maintained, because the snow cover more or less compensated for any terrain irregularities.

It follows from the above that not only the combination of several different GF methods or different variations of one method (e.g. antennas with different frequencies, different electrode geometries or the use of different seismic sources), but also repeated measurements can significantly contribute to the verification of both the data quality and the correctness of the result.

6.2 Joint interpretation, reinterpretation and evaluation of the methods used

Within the study of river sediments in the Bečva floodplain (Chapter 5.2.5), very important and interesting results were achieved using GF methods. Probably the most important methodological finding was that in trying to remove the effect of the attenuating conductive overburden within one particular localised anomaly, the research team deprived themselves of quite useful information that attenuation, or the anomaly caused by it, carries (at least in the context of river sediment research). Indeed, the question should not have been how to "get rid of" the anomaly in the resulting section, but rather to ask what might have caused the anomaly and what information it might provide about the environment under study.

According to van Heteren (1996), attenuation is crucial for GPR measurements because it significantly affects the skin depth of the emitted EM waves. The attenuation of the EM signal fundamentally limits the use of GPR in some sedimentary units ('facies'), especially those that are saturated with groundwater or have a high proportion of salts or clay particles. High conductivity, together with the predominant fine-grained nature of the rocks, is also cited by Annan (2009), Cassidy (2009a) and Słowik (2012) as the most common cause of signal attenuation.

Van Heteren (1996) specifically states attenuation values for dust (silt) in the range of 1-100 dB/m. Although this is a slightly wide range of values, if we compare it with sand or gravel (0.1-2.3 dB/m), the average attenuation values for dust are several orders of magnitude higher, with not much difference between saturated (0.03-2.3 dB/m) and dry sands (0.01-0.14 dB/m), and for gravel the difference is even smaller - saturated (0.03-0.5 dB/m vs. 0.01 - 0.1 dB/m). This is based on the general conductivity characteristics of sands and gravels (Milsom and Eriksen 2011).

At the Bečva site, a certain analogy with the above-mentioned sedimentary facies can be considered, where a significant part of the measured environment is partly saturated and partly is formed of dry gravel in the river floodplain. The fine-grained sedimentary infill of some local depressions (paleo-channels) is then made of dust (silts), forming the main component of floodplain clays, which tend to be very fine-grained and often contain some clay particles (Miall 2006), as confirmed by samples collected from shallow hand drilling (Stacke et al. 2014).

If we apply the mean values of attenuation reported by Van Heteren (1996) to the sediments present at the Bečva site, then it is quite clear that areas with a higher content of fine-grained particles will experience a higher attenuation of the EM signal. The zone of EM signal attenuation manifested on the GPR sections is also manifested on the resulting resistivity section (ERT) as a local decrease (vertical band) in resistivity directly below the fine-grained paleochannel infill, in otherwise relatively high-resistivity gravels. The fine-grained overbank clayey deposits at this particular site were confirmed by both direct exploration, including hand boring and sample analysis (Chap. 5.2.5, Fig. 39C), and indirect exploration using ERT (Chap. 5.2.5, Fig. 39B,D) (Stacke et al. 2014; Tábořík et al. in prep.-B). Even though the thickness of these fine-grained sediments is not significantly larger (roughly 1.5 - 2 times) compared to the surrounding areas of overbank deposits, this larger volume of conductive material greatly affects the energy and amplitude of the penetrating EM signal, which is thus intensely attenuated (Annan 2009; Cassidy 2009a; Słowik 2012). The signal attenuation zone is repeated in both measurement directions and on all 3 antennas (Chap. 5.2.5, Fig. 40A-C). The attenuation is most pronounced at the 500 MHz antenna and least at the 100 MHz antenna. This is clearly related to the wavelength of the antenna (Neal 2004; Cassidy 2009a).

In many cases, however, there may be situations where the original channels and their fine-grained infill are not distinguishable on the surface. This is also the case at the study site in the Bečva floodplain, where the majority of the study area is used as arable land. In addition, at the time of the measurements, the entire study area was covered with a continuous layer of snow. In such a case, the EM wave attenuation identified as an anomaly on the GPR sections (radargrams), despite its negative effect on the data quality, can instead provide very useful information about the location of some attenuation layer (or lens), which can then be interpreted as e.g. the above-mentioned fine-grained infill of a buried paleochannel (oxbow/abandoned meander), or - as evidenced by the research at the Ropice locality in the Moravskoslezské Beskydy Mts (Tábořík et al. 2017a, fig. P6 - 3B) - as a result of intensive disturbance of the massif, when tension cracks below the surface continue to expand gravitationally and are probably gradually filled with conductive clays and other fine-grained material, which is subsequently saturated with water. Again, significant agreement was observed with the ERT section, which in areas of intense EM wave attenuation displayed prominent low-resistivity lenses in an otherwise relatively high-resistivity flysch environment dominated by Godula Unit sandstones.

If we take a closer look at the results of ERT and measurements in the Bečva floodplain, the vertical band of reduced resistivities below the fine -grained paleochannel infill (Chap. 5.2.5.5, Fig. 39B,D) continues down to the groundwater table level, but this zone of lower resistivities passes further through the coarse-grained gravels, which are located below the sediments of the fine-grained fraction. It is a fairly well-known fact that, for example, the Res2Dinv program tends, in the case of highly conductive near-surface anomalies, to model high resistivities in close proximity to a low-resistivity anomaly within the resulting section (e.g., Tábořík et al. 2017a,b), or, in the case of a layered environment, thus typically beneath the anomaly. For gravels above the water table, extremely high resistivities would probably not surprise us too much. In the case of Bečva and the filled channel, however, the opposite was rather the case, raising the question of whether the relatively significant local reduction in specific resistivities in the gravels might be related to "infilling of the gravels by loams" and the washing of fine-grained particles deeper into the bedrock. Unfortunately, the borehole (H453) was carried out a few metres aside, already outside the zone of significant resistivity reduction, so it does not support the above hypothesis.

The above-mentioned "modelling" of often extremely high resistivity values in close proximity to a low-resistivity anomaly is also related to the experience of the author of the thesis, obtained during the interpretation of gravitationally relaxed zones of the massif at the localities Záryje and Ropice in the Moravskoslezské Beskydy Mts. (Tábořík et al. 2017a). Here, the authors were faced with the fact that high-resistivity anomalies, which should be a typical manifestation of free, air-filled voids, did not correspond in their position in the ERT section to the actual position of tension cracks or crevice-type caves, which are relatively common on Carpathian flysch slopes affected by deep gravitational deformation (Figs. P6-2). However, the conclusion of the joint interpretation, which also included the methods of shallow seismic refraction (SSR) and gravity survey (GS), was that at the anomaly locations on the ERT section (i.e. where a cavity could be assumed), the other two methods showed, on the contrary, high values of measured gravity (even a maximum on the Bouguer gravity anomaly curve) or high P-wave propagation velocities. Both methods thus pointed to a rigid rock block (Chap. 5.2.4.5, Fig. 35) rather than to a deficit of density and missing mass. Nevertheless, the methods also suggested that some form of slope disruption and relaxation occurs a little further downslope.

This led the authors to consider whether the sought discontinuity in the massif might not be depicted on the ERT section as a region of extremely high resistivity, but instead as a strongly contrasting transition between regions of high and low resistivity. Thus, that the discontinuity in the massif (fracture, cave) manifests itself as a pronounced horizontal gradient in the resistivity distribution beneath the surface. To support this reasoning, they reinterpreted ERT sections that have been previously carried out in the flysch Carpathian region (Pánek et al. 2010; Lenart et al. 2014). Both of these studies were summarizing and dealt with deep-seated slope deformations at several sites in the Outer Western Carpathians. A number of these sites showed typical manifestations of deep-seated mountain ridge failure, including identifiable tension cracks, double ridges and known caves. Fig. 46 then presents a selection of ERT sections within which these zones of sharp transition (contrast) between conductive and non-conductive environments were clearly identifiable, with many of these being well-known and speleologically-mapped caves with exact locations known. In virtually all cases, these cracks (crevices), located in deformation zones of deep-seated slope deformations and rockslides, have manifested the sharp resistivity gradient mentioned above. It is already evident from the slope morphology that gravitational movements and massif relaxation (lateral spreading) are occurring at the site.

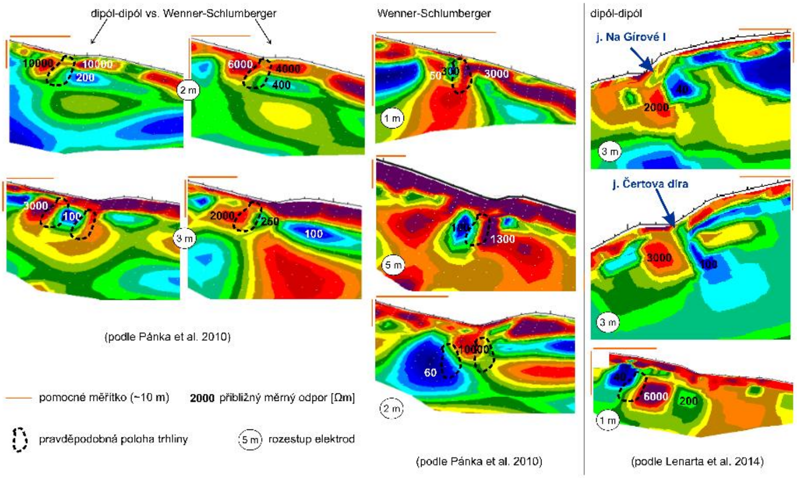

Fig. 46: Reinterpretation of tension cracks manifestations in the area of the flysch Western Carpathians. Based on the joint interpretation with the SSR and GS survey results, it was hypothesized that tension cracks manifest themselves as subvertically dipping, sharp resistivity interfaces between high and low resistivities in the flysch rocks. In a number of cases, the existence and exact location of the fracture has been confirmed by speleological survey. The slope morphology also shows that these cracks (crevices) are located in deformation zones of deep-seated slope deformation and rockslides.

(adapted from Tábořík et al. 2017a, Lenart et al. 2014 and Pánek et al. 2010)

The gravimetric survey occupies an interesting position in the framework of the joint interpretations. This is probably due to the way how the gravimetric data are commonly presented, where the optimal density model of the environment is constructed using visual comparison of measured gravity anomaly curves with theoretical gravity curves calculated as the model response (as discussed in Chap. 4.1.1). Within the case studies (Chap. 5), gravity survey was used as part of the combined GF measurements at three sites and was always an "active participant" in subsequent reinterpretations.

In the first case (Kopanina site, chap. 5.2.1), the direct gravimetric model was adjusted according to the ERT resistivity section, which revealed the existence of a wide fault zone along the fault plane, and after adding this zone to the direct gravimetric model, the agreement between the curves of measured ("observed") and modelled ("calculated") gravity values was significantly higher than in the case of the original model, where the fault was modelled only as a thin interface between two adjacent lithological units (Blecha et al. 2018).

In the second case (Beskydy site, chap. 5.2.4), the results from gravimetric measurements combined with the final inverse P-wave velocity section from the shallow refraction survey led, on the contrary, to a reinterpretation of the ERT. The original hypothesis interpreting the high to extreme resistivities (>5000 Ωm) as potential open space/void (e.g., a crevice-type cave) (Pánek et al. 2010; Margielewski and Urban 2003, 2005; Lenart et al. 2014) proved to be incorrect, and the most likely explanation for the anomaly is instead a rigid massive block of thick-bedded Godula Unit sandstones wedged (“subsided”) into a tension zone of a deep-seated gravitational slope deformation. Given the gravimetric measurements and the relatively high modelled rock densities (>2500 $kg.m^{-3}$) and high seismic wave propagation velocities in the zone of this block (>2200 $m.s^{-1}$), the sandstone is unlikely to be much disturbed (by fractures and tension cracks) despite being located in the tensile zone of gravitational slope deformation.

In the last case (Hranice site, chap. 5.2.3), based on the results from reflection (reflection boundary) and refraction seismics (velocity model, refraction boundary), both the gravimetric and ERT models were modified. The gravity model again resulted in a better fit of the "observed/calculated" curves and, in particular, the ERT section was reinterpreted and the overall geological situation and subsequent geophysical-geological interpretation was reassessed (Klanica et al. 2020).

However, it is not only about modifying the interpretation of gravimetric measurements based on other methods (ERT, MRS), or reinterpreting ERT based on the results of seismic and gravimetric surveys, but especially about the overall refinement of the resulting conceptual geological model that is the result of these combined interpretations. Indeed, the matter can be viewed in two ways. If it were only a matter of confirming or refuting the hypothesis of, for example, the existence of a cave, the result can be viewed as simply that the theory of a crevice-type cave has not been confirmed. As for the correctness of the interpretation of the GF measurements by the ERT method, then we have to look at the problem more critically, because if we use the original interpretation (without further verification), it would be a clearly erroneous and misleading interpretation. Nevertheless, by combining the interpretation of the measurement results from several GF methods, the original hypothesis (interpretation) was rejected as unconfirmed (wrong) and a new interpretation was created that is already consistent with the results of all the methods used.

The role of the seismic survey within the studied sites, presented in chap. 5, was also quite specific. The method has always yielded quite interesting information on the environment studied. As P-wave propagation velocities in different environments and rocks are quite well known (e.g. Barton 2007), the distribution of P-wave velocities below the surface can be used to interpret e.g. lithological units, sedimentary cover, or to determine the depth of an intact massif based on increasing velocities (e.g. Sass 2007; Owoc et al. 2019). On the other hand, the method did not yield much information about the internal structure of the block fields at the Slunečná and Skalka sites (Figs. 43 and 45) or the fluvial sediments in the Bečva floodplain (Fig. 37). It was not even able to distinguish between the sandy-clayey Miocene sediments of the Paczków Graben and the weathered crystalline rocks of the Rychlebské hory Mts at the Bílá Voda locality (Fig. 25), where both lithological units showed practically the same P-wave propagation velocities. In contrast, ERT measurements were able to distinguish both lithological units very reliably on the basis of the sudden change in resistivity (Štěpančíková 2022; Tábořík in prep.-A).

However, the seismic survey was able to determine - quite convincingly - the interface between the block field accumulations and the bedrock in Šumava (Duffek et al. under review) and thus determine their thickness. Similarly, at the Bečva site, it contributed to confirmation of the thickness of fluvial sediments (Stacke et al. 2014). Moreover, at the Hranice Abyss site (Fig. 32) and also in Šumava, seismic interfaces according to the t_0 method or selected P-wave velocity isolines were taken as a reference in relation to other methods, which were reinterpreted according to them. In particular, this involved the redetermination of interpreted boundaries, and in the case of gravimetric survey, the direct model was also modified) (Klanica et al. 2020). At the Ropice site (Figure 35), the hypothesis of a large cavity within the collapsed rock block was then rejected on the basis of seismic (and gravimetric) measurements, as already described a few paragraphs earlier (Tábořík et al. 2017a). Thus, seismic surveys also had, or have, an indispensable role in the combined GF measurements and combined interpretations.

Regarding the evaluation of the benefits of the AMT method, its greatest advantage is clearly its great penetration dept. In applied geophysics, there are several types of methods that can look deeper below the Earth's surface and investigate the crust on the order of km to tens of km (Mareš et al. 1990), but from a practical point of view (e.g., due to the lack of a seismic resource for deep exploration at most sites), the use of these methods is often complicated. Of the commonly used methods employed by geophysicists, MT sounding probably has the greatest potential for exploring "shallow" depths (on a planetary scale) of the Earth's crust. From the perspective of the research topics presented in this paper, then, the measurements are instead relatively "deep".

The AMT method, which was used at two sites (Kopanina and Hranice abyss), has contributed significantly to the understanding of the studied phenomenon, especially in terms of its depth manifestation or even geometry. In the case of the Hranice Abyss, the method helped to estimate the potential total depth (<1 km) of this unique vertical karst system (Klanica et al. 2020). At Kopanina, it was then able to follow the studied fault (MLZ) to depth and contributed significantly to the determination of its dip (up to ~80°), including a gradual change in near-surface parts of the measured profile up to ~50°. Such a dip is confirmed by ERT and gravity survey (Blecha et al. 2018). Especially when combined with another geoelectrical method, ERT, it is then possible to combine the results and essentially integrate them into a single section, as the authors of the cited paper demonstrate, i.e. in terms of the distribution of resistivity values below the surface, AMT picks up where ERT "leaves off", or conversely, ERT adds detailed information for the near-surface region (the first hundreds of m) where AMT lacks sufficient resolution.

Combining different GF methods is therefore possible, although in most cases the physical parameters measured by different methods cannot be compared directly. Even so, there are of course attempts to directly integrate the data into one combined model. This works to some extent within the individual methods, where it is possible to combine, for example, geoelectric survey data measured using different electrode arrangements. For example, for the Slunečná site, a joint inverse model was created from data measured using two different arrays (W-S and Wα), combining data from both configurations. Technically, this is a joint inversion of the data (including the fact that it is an inverse problem). However, it is also a fact that despite the different measurement geometry, the values are still of the same physical parameter, namely the (apparent) electrical resistivity.

An interesting way of solving how to compare the results of the different methods with each other without "mixing" the individual physical parameters together has been proposed, for example, by Piro et al. (2000) or Kvamme (2006). They state that if the data are more or less discrete in nature (i.e., clearly definable, separated occurrences of anomalies), various algebraic operations or classification can be used even for a large number of imaged datasets without losing the predictive power of the output. Within this approach, they convert the input data into a binary form, resulting in a simple standardization of the data into a bipolar distribution with values of "0" (anomaly is not present) or "1" (anomaly is present).

In the case of the results presented in this thesis (chap. 5), such an approach would probably be possible (at least hypothetically), e.g. by combining GPR and resistivity sections. It would be relatively straightforward to specify that **0** = conductive zone on the ERT section (or in the data representing the resulting inverse model) = significant signal attenuation on the GPR slice (quantified presumably by signal amplitude in dB), while at the same time it would be apply that **1** = higher resistivity = significantly higher EM signal amplitude and energy. The question, of course, would be how to set limits on amplitudes or resistivity values. On the other hand, for such well-defined anomalies, such as the vertical band with "attenuated" signal amplitude on the radargram in the Bečva floodplain (chap. 39 and 40) or zones of strongly "attenuated" EM signal corresponding in position and range to low-resistance "lenses" in the ERT section at Ropice (chap. 5.2.4.5, fig. 35), it would be possible to process the data using appropriate statistical tools and determine these thresholds empirically.

Of course, it is not always possible to proceed in this way. The described binary model will probably work reliably only with certain data and assuming clearly definable anomalies. EM signal attenuation is strongly dependent on the conductivity of the environment (van Heteren et al. 1998; Cassidy 2009a). In any case, it is an interesting possibility to combine data from different geophysical methods in specific cases where we are able to clearly define certain anomalies physically and spatially.

7. Conclusions

Interpretations of geophysical data should always be approached with caution, as they are often just one of the likely, but not the only, possible solutions. The present work, using a few selected cases, illustrates how easily inaccurate or even erroneous interpretations can occur. In many cases, it may not be just a problem of data quality or incorrect setting of the parameters of the computational model. The problem arises in the qualitative geophysical-geological (/geomorphological) interpretation of the data, when a certain geological quality (rock type, determination of sedimentary cover thickness, determination of bedrock or landslide slip plane, etc.) is assigned to a specific measured or modelled value, or a certain observed anomaly is explained in this way.

A combination of different geophysical survey methods offers much wider possibilities in terms of application in different natural conditions and in terms of the number of measured parameters of the geological environment. The joint interpretation of GF methods (often together with other information of a "non-geophysical" nature) can provide a range of fundamental information not only about the geological and geomorphological phenomena studied or other geoscientific and environmental problems, but also a range of methodological insights, both about the individual methods and especially about their combinations.

The thesis evaluated the practical possibilities of using combined geophysical surveying in the research of landscape evolution, including the assessment of the applicability of individual geophysical methods and their mutual combinations based on the joint interpretation of the results. In particular, great emphasis was placed on the reinterpretation of the results that emerged from the joint processing of the methods.

The conclusions of the thesis, summarized in the Discussion chapter, as well as the presented individual studies do not only target geophysicists, but on the contrary - as the author hopes - bring useful experience, insights or inspiration to the broader scientific community, especially in geosciences such as geology, geomorphology, sedimentology, hydrology or engineering geology, etc. Therefore, commonly available geophysical methods and standard methodological procedures based on well-known physical principles have been used in this work.

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