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TARTALOMJEGYZÉK

Foreword

The Eötvös Loránd Geophysical Institute (ELGI) of Hungary celebrated its 100th anniversary in 2007–2008 with several programs. The most significant event was an international conference on the co-operative research results of the Institute on 28th February, 2008. In this issue we are publishing the short or partly extended abstracts of the papers presented at the conference in their unedited form – as usual in similar abstract books.

Six topics were covered at the conference representing the wide spectrum of the investigated fields in geophysics:

CO_2 storage
Contamination detection
Paleomagentic studies
GEOMIND Geophysical Database Services
Advanced Seismic Acquisition and Processing
Lithospheric studies

We wanted to demonstrate above all that members of ELGI, as successors of the great Hungarian scientist, Loránd Eötvös, are strong in field survey as well as in pure scientific topics. Palaeomagnetic results or deep seismic investigations were equally present at the conference. We are proud of our results and hope that our readers will find new and interesting information on the subsequent pages. With this issue ELGI hopes to give insight into the wide spectrum of its scientific activities and also to demonstrate its distinguished place in the international world of geophysical research.

We also have to make the announcement that this is the last printed issue of our journal. Our regular readers are likely to have noticed that there has been more and more delay in the publication of issues in recent years. We hope to be able to solve our problems by switching over to electronic publishing. We will be announcing the new electronic issues of the journal on our website: *www. elgi.hu*. We hope our readers will find the electronic issues also interesting and worthwhile to read. As a result of electronic publishing we expect the number of papers per issue to increase in a short time. We will continue the policy of publishing first and foremost the papers of our researcher colleagues at ELGI, but we would also like to give an opportunity to other prominent Hungarian authors to publish their results on these pages. International contributions are also welcome if the authors work in collaboration with Hungarian institutions.

Thank you for your continued interest in our journal in the past, and we hope you enjoy reading this issue as well.

Budapest, December 8, 2011

Tamás Fancsik
director

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Vol. 45. No. 4. pp. 185–191

CO_2 storage

Geological storage of CO_2: a viable solution to mitigate climate change? Storage options, potentials and obstacles in Hungary

G. György FALUS*, Kálmán TÖRÖK*, Mária HÁMOR-VIDÓ*, Endre HEGEDŰS*, Ágnes SZAMOSFALVI*, Henrietta JENCSEL*

Carbon dioxide storage is better and better concerned on international level as a viable option to mitigate climate change. However, for a site being acceptable for CO_2 storage some basic, geological related criteria has to be fulfilled.

Hungary has annual stationary point source CO_2 emissions around 23 Mt, of which more than 70% is related to the energy sector. According to recent assessment of storage potential, more than 4000 Mt of CO_2 could be stored in the subsurface.

Keywords: hydrocarbons, coal, climate change

1. General issues

Increasing awareness of climate change attracts more and more economic and political stakeholders to think about carbon dioxide capture and geological storage (CCS) as a possible option to effectively cut greenhouse gas emissions. Current studies univocally state, that drastic changes have to be made in our energy systems to mitigate the effects of climate change. This means, that besides considerably increasing energy efficiency, fossil fuels would have to be replaced by renewables in a very short time period. Although the necessity of this replacement is indisputable the very short time period does not seem realistic from technological and economic viewpoint. Consequently, the only available bridging methodology in the next few decades to fulfill ambitious goals in drastic emission cuts is the application of CCS technologies.

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Injection of CO_2 to saline formations in sedimentary basins is one of the most promising methods of geological storage of CO_2 for the long-term sequestration of the gas. This is because saline formations are very common in sedimentary basins, they have enough capacity to store large amounts of industrial CO_2, and there are shorter distances between most large CO_2 point sources and saline formations, which can minimize CO_2 transportation costs. The injected CO_2 is stored by three trapping mechanisms in saline formations:

— CO_2 can be trapped as a gas or supercritical fluid in a formation, commonly called hydrodynamic trapping.

— CO_2 can dissolve into the groundwater, referred to as solubility trapping. The dissolution of CO_2 in groundwater increases the acidity of water and affects the dissolution of minerals composing the host rock matrix.

— CO_2 can react directly or indirectly with minerals in the geologic formation leading to the precipitation of secondary carbonates. This process is called 'mineral trapping', which could immobilize CO_2 for long-time scales, and prevent its return to the atmosphere.

For a site being suitable for CO_2 storage some basic, geological related criteria has to be fulfilled [CHADWICK et al. 2006]. These are:

a) Sufficient depth of reservoir to ensure that CO_2 reaches its supercritical dense phase but not so deep that permeability and porosity is too low.

b) Integrity of seal to hinder CO_2 escape.

c) Sufficient CO_2 storage capacity to hold the CO_2 expected to be released from the source.

d) Effective petrophysic reservoir properties to ensure CO_2 injectivity to be economically viable and that sufficient CO_2 can be obtained.

Fulfillment of these basic criteria depends on the values of several geological and physical parameters. In the search for suitable sites for CO_2 storage it is therefore important to estimate if the basic criteria listed above and their associated geological and physical parameters are fulfilled. The first step in a site selection process, which has been carried out by the Eötvös Loránd Geophysical Institute of Hungary in national and FP6 EU projects is the screening of sedimentary basins in Hungary for CO_2 storage potential.

2. Carbon dioxide emission in Hungary

Having a view on the emission statistics of 2005, the largest CO_2 emission in Hungary is related to the energy sector (*Fig. 1*), which is responsible for 33% of total emissions (~80 Mt) and almost 73% of the emissions by large point sources. Cement industry and oil refineries also represent important emission sources being responsible for around 13% of point source related emissions.

In the short and medium term no cuts in emission are expected in Hungary. In fact, in certain scenarios, emissions in some industrial sectors may even show an increase in the medium term. The demand for an alternative solution for decreasing the emissions, namely carbon dioxide capture and geological storage are expected in this field.

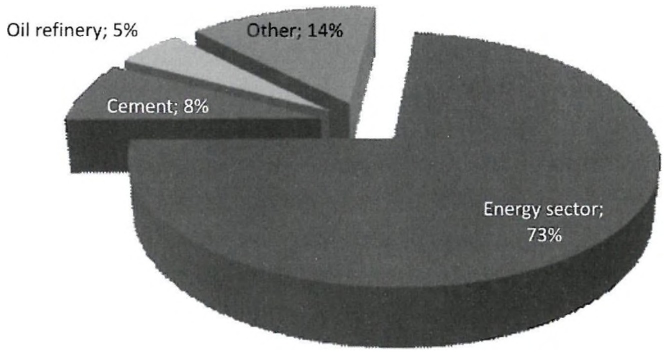

Fig. 1. Carbon dioxide emission in Hungary (2005)
1. ábra. Széndioxid kibocsátás Magyarországon (2005)

3. General storage options

Carbon dioxide, after being captured from an emission source, can be either stored or re-used. Because of limited market use, the majority of extracted CO_2 needs to be stored. CO_2 can be stored in geologic formations (including depleted oil and gas reservoirs, deep saline aquifers and unminable coal seams). CO_2 can also be fixated in the form of minerals. Geologic formations offer a huge storage capacity. Despite the broad ranges in the storage capacity, it can be concluded that the capacity is sufficient to store worldwide man-made CO_2 emissions for tens and possibly hundreds of years.

Oil and gas reservoirs, which generally have been well researched, are considered to be safe sinks for CO_2 storage, since these reservoirs have held oil, gas and often CO_2 for millions of years. CO_2 injection in some of these reservoirs will enable further production of oil/gas remaining in the reservoir. The revenues from this additional oil/gas could be used to offset the cost of CO_2 storage. This process, referred to as enhanced oil/gas recovery (EOR), has been performed in the USA using CO_2 for some years, not with the purpose of CO_2 storage, but to increase oil production. In Canada, injection of acid gas (a residual product of natural gas refining consisting of mainly CO_2 and H_2S) into oil/gas fields and deep saline aquifers has been practised for many years.

Deep saline aquifers are underground formations, typically sandstones, containing saline water. These formations offer enormous storage potential: they are present in most countries, often close to industrial CO_2 sources, are usually very large, and so have a very large CO_2 storage capacity. The injection of CO_2 into these formations is similar to injection into oil and gas fields. The Norwegian Sleipner project, the first commercial CO_2 injection project in the world, where annually circa one million tons of CO_2 is injected into an aquifer under the North Sea, demonstrates that CO_2 can effectively be stored in large quantities.

Underground coal layers sometimes cannot be mined, being too thin or too deep. They usually also contain certain amounts of methane gas. When injecting CO_2 in a coal seam, it has been shown that CO_2 'sticks' better to coal than methane does, so it sets the methane free. This means that the coal layer becomes a producer of natural gas, which can be sold to offset the costs of CO_2 storage. Coal seams have held methane for millions of years, so it is quite probable that they will retain CO_2 for at least thousands of years. This storage technology is being tested in the EU RECOPOL project, with a field experiment in Poland.

4. Storage options in Hungary

According to preliminary studies, carried out in the frame of EU-funded CASTOR and GeoCapacity and national projects, Hungary's potential in geological storage of carbon dioxide is remarkable. Potential formations are similar to those, discussed above, namely depleted hydrocarbon reservoirs, deep saline aquifers and unminable coal seams. In case of hydrocarbon reservoir and coal layer storage of carbon dioxide there is an option to extract additional oil or methane stored in the layers, respectively. This could offset high costs related to CO_2 capture.

In the following section an estimation of the storage capacity of potential storage sites is given:

Hydrocarbon reservoirs

Public data used for the preliminary estimation of storage capacity of hydrocarbon reservoirs is derived from the Hungarian Bureau of Mining and Geology. Distribution of hydrocarbon fields is shown below in *Fig. 2*. The estimations are based on production data of the 10 largest oil and gas reservoirs which provide about 80% of the total production. The reservoirs are mainly Upper Miocene sands, however, karstic and metamorphic reservoirs also exist.

The estimated amount of CO_2 that could be theoretically stored in the hydrocarbon reservoirs is about 470 million tons.

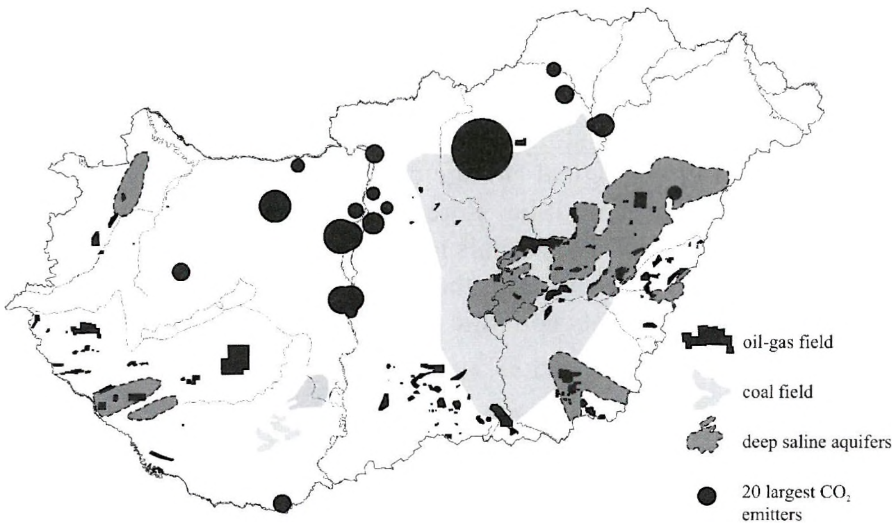

Fig. 2. Cumulative storage capacity in Hungary
2. ábra. Tárolási kapacitás Magyarországon

Coal seams

The minimum depth required to store carbon dioxide in coal layers is 400 meters. Based on this limiting factor, there are three coal fields in Hungary that are potentially available for CO_2 storage: the Mecsek Coal Formation with Lower Jurrasic age, in southern Hungary and the Toronyi and Bükkalja Lignite Formation in western and central Hungary, respectively, with upper Miocene age. The bulk storage capacity of the coal formations is between 60–600 million tons depending on, whether lignites are capable of permanent CO_2 storage or not.

Deep saline aquifers

Deep saline aquifers represent the largest carbon dioxide storage potential worldwide. Storage can be realized below 800 m depths in aquifers that contain water which is not suitable for drinking, or any other purposes (i.e., geothermal applications, etc.).

Concerning the deep aquifers in Hungary, only a very preliminary database exists and more detailed study is necessary to have a clearer view on storage capacity in this type of geological formations. Based on the preliminary estimations the storage capacity in Hungarian deep saline aquifers is estimated to be 3000 to 5000 million tons.

Cumulative storage capacity in Hungary

The first estimation of storage capacity demonstrated that Hungary has a large potential in geological storage of CO_2. The results show that the amount of CO_2 that could be stored in the subsurface amounts to 4000–6000 million tons. This equals to 100–200 years of all point-source emissions in Hungary and indicates that carbon dioxide storage in Hungary could become a significant economic potential of our country.

Acknowledgements

This research was enabled by participating in the CASTOR and EU GeoCapacity EU FP6 projects, and by the financial support of a national project of Hungarian Academy of Sciences and Hungarian Prime Minister's Office.

A CO_2 földtani tárolása: a klimaváltozás csökkentésének életképes megoldása? Tárolási feltételek, potenciál és akadályok Magyarországon

FALUS G. György, TÖRÖK Kálmán, HÁMOR-VIDÓ Mária, HEGEDŰS Endre, SZAMOSFALVI Ágnes, JENCSEL Henrietta

A széndioxid tárolását egyre inkább a klimaváltozás csökkentésének lehetséges megoldásának látják nemzetközileg. Azonban a széndioxid tárolására alkalmas tárolónak néhány alapvető, földtani vonatkozású feltételnek meg kell felelnie.

Magyarországon az éves stacionárius pontforrásból eredő széndioxid kibocsátás közel 23 Mt, melynek több, mint 70%-a az eneregiaszektorból ered. A tárolási kapacitás legfrissebb felmérése szereint a föld alatt több, mint 4000 Mt CO_2 tárolásra van lehetőség.

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CO_2 storage

CCS actions and storage options in Croatia

Bruno SAFTIĆ* and Iva KOLENKOVIĆ*

Construction of the Carbon Capture and Storage (CCS) systems might help Croatia to meet the Kyoto targets in the next decade already. There are various reservoir formations in the southern Pannonian Basin and in the Adriatic off-shore that could be prepared for this permanent, geological storage. Not only favourable natural conditions exist, but also the pipeline transport system and potential of the developed upstream part of the oil industry. Depleted oil and gas pools might be used in the beginning, particularly in the initiated EOR operations, but by far the largest potential is seen in the regionally extending deep saline aquifers.

Keywords: carbon capture and storage (CCS), storage capacity, hydrocarbon fields, saline aquifers, Croatia

1. Introduction

Republic of Croatia became a party to the United Nations Framework Convention on Climate Change (UNFCCC) in 1996 and accepted to maintain the emission of greenhouse gases to the 1990 level, the 'base year'. Croatia has also signed and later ratified the Kyoto Protocol and thereby took the obligation to reduce the greenhouse gas emission by 5% in the 2008–2012 period.

Croatia is among the European countries with the lowest total emission of greenhouse gases as well as per capita emissions of both greenhouse gases (CO_2) and acid gases (SO_2 and NO_x). Nevertheless, the CO_2 released into atmosphere exceeds the amount allowed by Kyoto protocol steadily in the last four years. The major part of CO_2 emissions in Croatia is related to energy sector. This includes emissions from fuel combustion in thermal (coal, gas, oil) power plants related to electricity production (5478 kt CO_2/yr in 2003), municipal/district heating plants, and oil indus-

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try activities (2800 kt CO_2/yr) as well as other industrial processes [EKONERG 2005].

The largest concentrated stationary sources ('point sources') of CO_2 in Croatia are the seven coal, gas and/or oil power plants operated by the national power supply company HEP. Mainly due to the increased economic activity, their emissions were constantly rising in 1990–2003 period. The locations of these facilities are shown in *Fig. 1*. Total power plant emissions in 2003 were 5478 kt CO_2/yr which is 24% of total CO_2 emissions in Croatia.

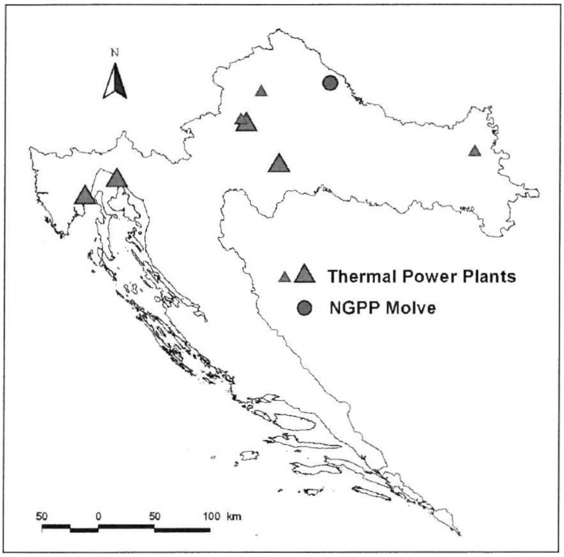

Fig. 1. Locations of CO_2 point sources in Croatia
1. ábra. CO_2 pontforrások helyzete Horvátországban

There is also one large point source in the national oil industry. This is the natural gas processing plant 'Molve', located in the western part of the Drava river valley, close to Hungarian border (Fig. 1). In 2004 a total of 684 kilotonnes of CO_2 are separated there from the natural gas streams and released in the atmosphere. Presently, this plant is the primary candidate for the carbon dioxide capture and subsequent use in EOR (Enhanced Oil/gas Recovery) operations. The fact that the emissions from point sources in Croatia amount to 26% of total CO_2 emissions, actually allows significant reductions to be made by carbon capture and storage system.

2. Geological composition in the subsurface

Subsurface geological relations are the first critical factor to estimate the geological storage potential. These relations have been defined in the course of petroleum-geological exploration mainly in the last 60 years. It soon became known that there are three parts of the Croatian territory that have some common characteristics regarding the generation and accumulation of oil and gas. These large units are called hydrocarbon-bearing provinces – Pannonian Basin, Dinarides and Adriatic offshore. Only the first and the third province can offer locations with favourable conditions for geological storage of carbon dioxide, the Dinarides can largely be ruled out due to several reasons. Firstly, this mountain region is in Croatia largely composed of Mesozoic carbonates that are karstified to depths exceeding 1000 m. Karst hydrogeological system and its groundwater resources effectively prevent any type of geological storage in that region. The other reason is the high neotectonic (and seismic) activity which would put installations and subsurface storage objects at risk. This means that looking for the favourable natural conditions should be directed both to the southern part of the Pannonian Basin and to the Adriatic off-shore.

2.1. Pannonian Basin

Due to the complex geological history of the SW part of Pannonian Basin, the structure of the basement is complex. Elongated basement highs and narrow depressions developed during the Mid-Miocene rifting [ROYDEN, HORVÁTH 1988] were refigured by several phases of basin inversion prior to, during and after the subsequent thermal subsidence [PRELOGOVIĆ et al. 1998, TOMLJENOVIĆ, CSONTOS 2001, CSONTOS et al. 2002]. Most of the sedimentary succession accumulated in these depressions which are separated by uplifted and partially eroded tectonic units. The mentioned depressions (subbasins, or structural depressions) – the most northern Mura depression, Drava depression, Sava depression and Slavonija–Srijem depression – are filled with the Neogene rocks where source rock formations and various reservoir rocks were found. Some of the basement highs are exposed as Palaeozoic–Mesozoic mountains (e.g. Mt. Papuk, Mt. Psunj etc.) while others are still covered by 1000–2000 m thick Neogene and Quaternary sediments.

A generalised stratigraphic column of the southern Pannonian Basin is given in *Fig. 2.* Basin fill contains some volcaniclastics (and volcanic rocks as well) but is mostly composed of sediments reaching maximal thickness of e.g. 5000 m in Sava depression or over 6000 m in Drava depression. This large sequence of lacustrine–marine–lacustrine–fluviatile environments contains major unconformities – the Base Neogene, the Base Pannonian

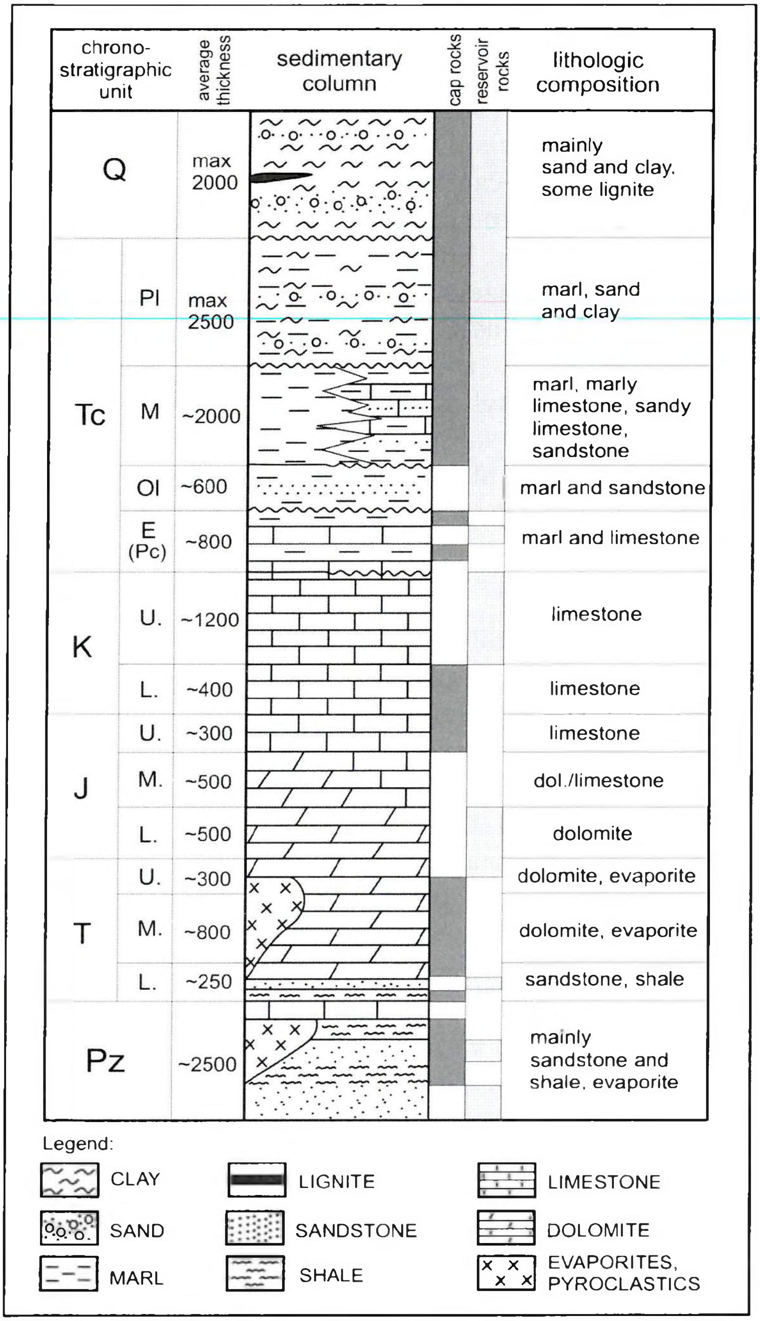

Fig. 2. Stratigraphic column of the Neogene basin fill of southern Pannonian Basin

2. ábra. A dél-Pannon medence neogén medencekitöltésének rétegoszlopa and the Base Pliocene unconformities, which usually separate the onlapping deposits from uplifted, tilted and eroded older rocks. These uplifts interrupting basin subsidence reveal compression events in association with inversion tectonics [LUČIĆ et al. 2001]. Even a fifth, Quaternary unconformity exists, as the reflection of the youngest uplift in the marginal part of depressions.

The oldest Neogene sediments are of Early to Middle Miocene age and comprise syn-rift and early post-rift sediments [SAFTIĆ et al. 2003]. Terrestrial sandstones, subordinate coal seams, sedimentary bodies of talus breccia (mainly Lower Miocene), reefs (mainly Badenian), coastal and shallow marine sandstones (Karpatian, Badenian) are interlayered with volcaniclastics/volcanics, marls and clayey limestones (Fig. 2). The end of Middle Miocene is characterised mostly by fine-grained deposition in the starving brackish-water basin.

Late Miocene age is characterised by the post-rift thermal subsidence of the Pannonian Basin [SAFTIĆ et al. 2003]. Lake Pannon deposits were formed in brackish (Pannonian) to freshwater environment (Pontian). Apart from local variations due to pre-Pannonian topography the sedimentary succession begins with littoral limestones and nearshore transgressive lag overlain by hemipelagic calcareous and clayey marls basinwide. The deepest depressions were filled by lacustrine turbidite lobes and channel fills of considerable thickness; thus initial basin floor topography gradually became levelled. Turbiditic successions are overlain by shale-prone delta slope and sandy delta front to coastal plain sediments. After the northern part of the Drava depression in Hungary was filled to lake level and the youngest Miocene deposits were formed in fluvial environments, to the south in Croatia deposition continued on the delta front and in the prodelta region. Deltaic sand bodies or turbiditic sand lobes of this unit are interlayered with silty marls and make the majority of HC pools discovered in the area.

Pliocene and Quaternary rocks are sediments which were deposited in the remnants of Lake Pannon and in the subsequent fluvial systems [SAFTIĆ et al. 2003]. These are mostly sands and sandy gravels with some clay and silt that have the largest thickness of 1000–1500 m in areas of continuous subsidence (Fig. 2). At that time Lake Pannon occupied only the southernmost part of the Pannonian Basin where basin fill up to fluvial deposits continued in similar manner as previously. The largest number of oil and gas reservoirs was found in the Upper Miocene sandstones interlayered with silty marls, but the largest single reservoirs were much deeper, either in the Lower to Middle Miocene coarse clastic bodies, or in the Mesozoic and Palaeozoic basement rocks.

2.2. Adriatic offshore

The oldest formations reached by wells in the Adriatic offshore are of Permian age. They are of heterogeneous lithologic composition. Mostly clastic sediments were deposited, mainly sandstone and shale, but carbonate formations are also present, and particularly evaporites. Early Triassic was characterised by intensive tectonic movements and volcanism followed by clastic sedimentation, and that is why Lower Triassic sequence consists of both siliceous and carbonaceous sandstones with subordinated tuff and dolomite indicated shallow water conditions. Middle Triassic unit was affected by the beginning of the Alpine orogenesis and both the shallow water and deep water carbonates are found, frequently with andesite and pyroclastics. In the basal part of the Upper Triassic (Karnian) evaporites can be found but their occasionally diapiric bodies are much more frequent in the Central and Southern Adriatic, while dolomites prevail in the Northern Adriatic. Generally, shallow water carbonate sedimentation (mainly dolomites) in platform conditions began in Late Triassic and continued in more-less similar platform conditions throughout Early and Middle Jurassic (mainly dolomites), Late Jurassic and Cretaceous (limestones), till the Palaeogene or occasionally Middle Eocene. Towards the end of Cretaceous the platform gradually disintegrated. The thickness of carbonate deposits amounts to 5000 m at most. During the Middle Eocene, Late Eocene and Lower Oligocene, intensive tectonic movements caused opening of the future Adriatic basin [PRELOGOVIĆ, KRANJEC 1983]. Tectonic movements were accompanied by sedimentation of marl, sandstone and subordinated limestone. Miocene was characterised by hemipelagic marl in the central parts of deep basins and turbidites close to their margins – marl, calcareous and marly siltites interbedded with sandy limestones and sandstones. Pliocene sediments resulting from the subsequent transgression include clays, marls and sands. There is a lithologic continuity with Quaternary deposits composed of sands, silts and clays with lignite interbeds. Pliocene–Quaternary deposits can reach the thickness of 2000 m in places and the thickness of Neogene deposits together with Quaternary deposits can amount up to 4000 m in the deepest subbasins. Thickness of this sequence in the Northern Adriatic reaches 1000 m.

Several gas fields were discovered in the Northern Adriatic with reservoirs within Pliocene–Quaternary deposits. Traps were formed by differential compaction resulting in small structural closures and there are numerous isolated sand bodies. They are characterised by intergranular porosity and markedly irregular distribution of reservoir properties. [ZELIĆ et al. 1999].

3. Prospective geological storage objects

There are several types of geological formations suitable for permanent storage of carbon dioxide. Most of the regional studies performed indicate that sedimentary basins worldwide could offer significant storage potential roughly distributed in the three orders of value – deep regional saline aquifers are by far the largest, usually ten times less can be found in depleted hydrocarbon reservoirs, and 100 times less in deep unmineable coal seams. Coal layers in Croatia are both too shallow or too thin to result in significant storage potential and it is best to direct attention to the other two types.

Out of the 60 hydrocarbon accumulations that were discovered, around 30 are now in production. Some of them are near depletion, particularly the oil fields and they might be candidates for the early application of the CCS concept. EOR pilot studies are on the way and it is to be expected that the first industrial CO_2 injection will be done in one or two oil fields in the western part of the Sava depression. The so far obtained results [DOMITROVIĆ et al. 2005] prove that it can be done and that there is significant CO_2 retention potential already in the phase of enhanced oil recovery. Regarding the stratigraphy of the potential reservoirs in the southern Pannonian Basin (Fig. 2), Upper Miocene sandstones are the most frequent type that might be used because they are numerous, reliably correlated and usually in the convenient depth range (1000–2500 m). At some locations, large capacity is estimated in the base Neogene breccia-conglomerate bodies, and particularly where those reservoirs are hydraulically connected with the underlying Mesozoic or Palaeozoic rocks. Prospectivity of these reservoirs might prove to be somewhat hindered by their large depths and consequently high pressure and temperature, and also by the extensively developed fracture porosity. As for the off-shore possibilities, only northern and central Adriatic are geographically/economically reachable and three types of reservoirs are worth investigating – Pliocene/Quaternary sands/sandstones that are documented to be gas-tight but these gas pools are at the marginal depth (750–850 m), Upper Cretaceous limestones with secondary porosity covered with impermeable Miocene or Pliocene sediments and Miocene formation that is locally developed between the first two, especially in the deep depressions like the Dugi Otok basin (*Fig. 3*).

A number of **hydrocarbon fields** were screened out, namely those that appear more promising due to the reservoir conditions and they are shown by groups in *Table I*.

Basin (no. of fields)	**Stratigraphic unit**	**Lithological composition**	**Depth** (m)	**Capacity** (Mt)
Drava (2)	Miocene	carbonate breccia/sandstone	1950/750	12.30
Sava (5)	Miocene/ Palaeozioc	sandstone/ granite	1580–825	23.20
			Σ Oil fields	35.50
Drava-deep (4)	Miocene/ Mesozoic/ Palaeozioc	breccia/ carbonates/ metamorphic rocks	3200–900	83.15
Drava-shallow (2)	Miocene	sandstone	1600	17.75
Sava (2)	Miocene	sandstone	2000–1850	20.20
N. Adriatic (3)	Quaternary/ Pliocene/ Mesozoic	sand/ sandstone/ carbonates	900/1300	32.10
			Σ Gas fields	**153.20**
			ΣΣ	188.70

Table 1. Estimates of storage capacity in hydrocarbon fields
1. táblázat. Szénhidrogéntelepek tárolási kapacitásainak becslése

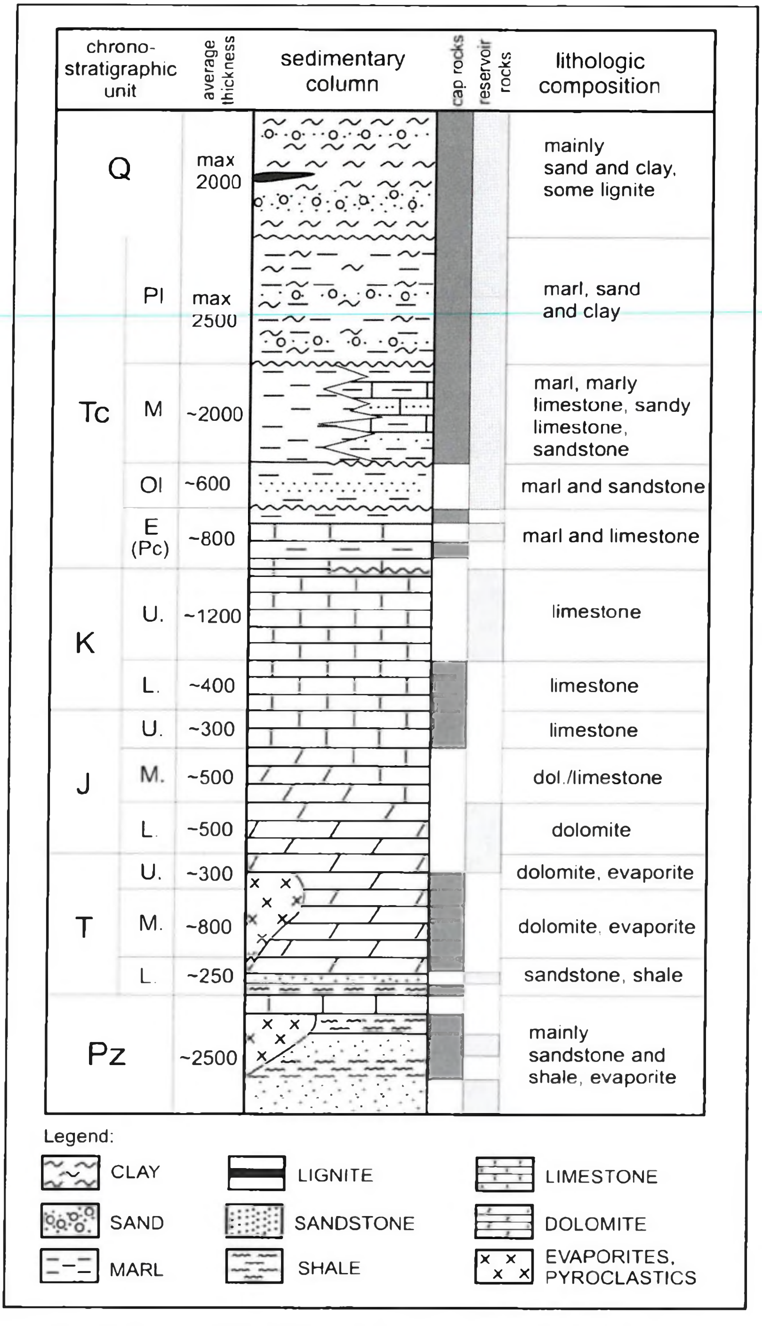

Fig. 3. Stratigraphic column of the northern Adriatic offshore

3. ábra. Az északi Adriai offshore rétegoszlopa

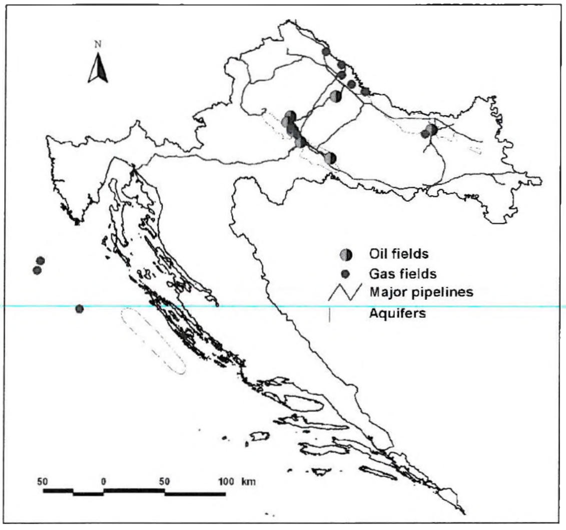

Fig. 4. Major aquifers, oil and gas fields and pipelines in Croatia

4. ábra. Fő rétegvíztároló rendszerek, olaj- és gázmezők, távvezetékek Horvátországban

Calculations were performed for altogether 15 fields in the Pannonian Basin and three fields in the Northern Adriatic off-shore. Locations are given in *Fig. 4.* Storage capacity is calculated based on the volume of the already produced hydrocarbons, considering that all of it can now be safely filled with pure CO_2 and mass was calculated based on the pressure and temperature of the reservoir at its average depth. The listed capacity in gas fields greatly exceeds the one in oil fields, but gas fields are still far from depletion and will not be converted to storages very soon. This especially refers to the three gas fields in the Northern Adriatic. As for the oil fields, the obtained total capacity is approximately five times smaller, but at least some among them are 'ready to be used', firstly for EOR and subsequently for permanent CO_2 storage. Their geographical distribution is favourable — close to the major point sources in continental Croatia and only limiting factors are seen in the size of their reservoirs and occasionally large number of old wells that will have to be plugged and monitored.

Trying to estimate the capacity in *deep saline aquifers,* major problem lies in the fact that the available data are usually not detailed enough. Even in the mature petroleum provinces deep aquifers were simply not drilled through enough and there are just a few analyses of their reservoir properties. That is why even in the cases where the geometry of the reservoir rock formations can be delineated based on the regional subsurface data, other parameters — effective thickness, porosity, temperature have to be extrapolated from the existing hydrocarbon fields in that region. This inevitably burdens the storage capacity estimates with a lot of uncertainties. Even more so knowing that adequate trapping conditions in parts of these regional aquifers will only later be confirmed by targeted surveys.

That is why these storage estimates are regarded as theoretical capacity only and are usually declared as the total pore space volume to make it clear that only part of it can eventually be used for CO_2 storage. Pore space volume listed in *Table II* is actually total pore space volume multiplied by a displacement coefficient which is only roughly estimated to be 3%, meaning that only such a small proportion of available pores might probably once be filled with carbon dioxide (at several locations they are still to be found). In conclusion, if the estimated cumulative volume within aquifers is multiplied with CO_2 density at estimated average depth and temperature, which is 500 kg/m^3 it sums up to 4829 Mt which is a far more respectable number. This capacity might be prepared for use only after the deliberated exploration of these objects not only to fully investigate their reservoir properties, but also to confirm the integrity of their cap rocks.

Aquifer	**Area** (m^2)	**Depth Top** (m)	**Depth Base** (m)	**H** (m)	**Hef** (m)	**Porosity**	**Pore space volume** (m^3)
Dugi Otok	1135546278	930	2100	1170	234	0.10	797153487
Drava	1353234016	900	1900	1000	600	0.25	6089553071
Osijek	41085959	1000	3500	2500	1750	0.20	431402566
Sava West	314735506	800	2300	1500	500	0.17	802575539
Sava Central	517134191	1000	2700	1700	550	0.18	1535888547
						ΣΣ	9656573210

Table II. Estimates of theoretical storage capacity in deep saline aquifers
II. táblázat. Mély sós akviferek elméleti tárolási kapacitásának becslése

Storage capacities listed in Table II are mostly on shore, within the sediments of the Pannonian Basin. Due to more than 700 exploration wells in this area, regional subsurface maps allow the geometry of deep Miocene aquifers to be delineated and porosity was taken from the oil and gas fields in the area. Margins of these aquifers were defined based on the two criteria – extension of the Upper Miocene sandstones and thickness of the overlying Pliocene and Quaternary sediments more than 1000 m. Capacity declared for the Dugi Otok aquifer in the Adriatic off-shore is really a preliminary and rough estimate because its reservoir rock properties are based only on the data from three wells, and its outline follows the contours of the entire sub-sea Dugi Otok basin.

4. Conclusions and recommendations

Several conclusions can be drawn based on the explained screening. Failing to consider those carefully might have significant impact to the country's development of the energy sector in the future:

1. Republic of Croatia will be very soon facing the challenge of reducing CO_2 emissions. One of the ways to achieve significant reductions on a national level is to equip large industrial 'point sources' with adequate capturing facilities, and to build a transport system capable of safely conveying CO_2 streams to the 'sinks' – geological storage objects situated deep in the subsurface (under 1000 m).

2. There are favourable natural conditions for geological storage of carbon dioxide in some parts of Croatia – in the deep structural depressions of the southern Pannonian Basin, and in the Adriatic off-shore as well. It is also important that significant human and technical resources of the national oil industry can be fully used to that purpose.

3. The most prospective objects in the near future are the depleted hydrocarbon fields. In one of the oil fields in the Sava depression, the pilot CO_2 injection has already been done as a part of an EOR project. In the long term, though, it is possible that the cumulative storage potential in oil and gas reservoirs will not offer the largest capacity in the end. There are two reasons for that. The first is that old oil fields usually have a large number of old wells drilled through multi-storey reservoirs, and those wells significantly increase the risk of leakage to the atmosphere or at least cause additional costs for plugging and monitoring. The other reason is even more obvious – since the prices of crude oil are so high (and, at least to the opinion of authors, are not going to be drastically reduced in the near future) the remaining reserves in partly depleted reservoirs are so valuable that EOR projects have to be optimised on maximum recovery, not on maximum CO_2 storage. This hinders the large-scale utilisation of oil and gas reservoirs in the near future.

4. Significantly larger capacity is estimated in the deep saline aquifers – porous and permeable regional formations deeper than 1000 m. There should be no conflict of use to define and equip underground storage sites in a part of this waste pore space, but the subsurface data available are too scarce to allow anything but generalised regional estimates to be made. That is why it will be necessary to develop research projects targeted specifically to the better definition of their geological composition and reservoir properties.

5. Capacity for geological storage of carbon dioxide in coal seams in Croatia is too small to be significant.

It is worth emphasising that preparations will have to be really quick in order to fully develop the carbon capture and storage system in time to achieve significant reduction of CO_2 emissions. In light of the international commitments made by Croatia, this could really have grave impact on the price of energy in the near future. Also, there is a potential benefit of improving one country's image as an economy that uses its fossil energy sources in environmentally friendly way.

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Széndioxid befogás és tárolás lehetőségei Horvátországban

Bruno SAFTIĆ és Iva KOLENKOVIĆ,

Lehet, hogy már a jövő évtizedben segíti Horvátországot kyotoi vállalásainak teljesítésében a széndioxid befogási- és tárolási rendszer (CCS). A Pannon medence és Adria partszegélyi területén különböző tárolásra alkalmas formációk találhatók, amelyeket hosszú idejű tárolásra át lehet alakítani. A megvalósításhoz nem csak a kedvező természeti adottságok vannak meg, de a szállítási rendszer és az olajipar fejlett kutatási és termelési részlege is rendelkezésre áll. Kezdetben a letermelt olaj- és gáztelepeket lehetne hasznosítani, különös tekintettel a növelt hozamú kőolaj-termelésben (EOR) bevezetett üzemeltetéssel, de mindezeken túl a legnagyobb potenciál a regionálisan elterjedt mély sós rétegvíztároló rendszerekben látszik.

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CO_2 storage

CO_2 perspectives and storage potential in unmineable coal seams in Hungary

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The present study provides a review on the state of art in CO_2 geological storage or carbon storage (CS) studies, with special focus on unmineable coal deposits. An introduction to the characteristic conditions and factors for long-term storage in unmineable coal seams is given. Upon a short presentation of the coal geology of Hungary an assessment of the coal formations and coal fields is made from the CS point of view.

The Mecsek Coal Formation (MCF) and the Újfalu Formation (UF) coals are considered to be perspective geological host reservoirs for the long-term CO_2 storage and disposal. A preliminary evaluation of the CO_2 storage capacity potential of the two formations is presented.

Key words: coal seams, CO_2 storage capacity, enhanced coalbed methane recovery (ECBM)

1. Introduction

Among other geological storage possibilities coalbeds represent a potential option for long-term storage of CO_2. Coalbeds can be used for the storage of CO_2 where it is unlikely that the coal will be exploited in the future and provided that effective permeability is sufficient. It is widely recognized that CO_2 preferentially adsorbs onto coal or organic-rich shales replacing gases such as methane. In these cases, CO_2 will remain trapped as long as pressures and temperatures remain stable. These processes would normally take place at shallower depths than CO_2 storage in hydrocarbon reservoirs and saline formations.

Although the storage capacity of coal is much less than other options, like depleted oil and gas fields and saline aquifers, its consideration is important in the potential estimation. The estimates of the technical potential for geological storage option for Hungarian coals are discussed

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using the calculation methodology developed in the frame of the Geo-Capacity project of EU–FP6 program.

2. Physical and geological preferences for CO_2 storage potential in coal seams

All coals have varying amounts of methane adsorbed onto pore surfaces, and wells drilled into unmineable coalbeds usually recover coalbed methane (CBM). Unmineable coal seams are those parts of the coal field where the resources are located too deep or their thickness is too thin to be mined economically. Initial CBM recovery methods, dewatering and depressurisation, leave a fair amount of CBM in the reservoir, which can be achieved and replaced by sweeping the coalbed alternatively with CO_2. It preferentially adsorbs onto the surface, where CO_2 molecules are immobilized or trapped at near liquid like densities on micropore wall surfaces of the coal, while methane releases from the host rock. Two or three molecules of CO_2 are adsorbed for each molecule of methane released, thereby providing an excellent storage sink for CO_2.

The hydrostatic pressure in the formation controls the gas adsorption process. With physical adsorption, the adsorbed CO_2 is essentially immobile. However, the intermolecular attraction forces between a CO_2 molecule and a solid surface are relatively weak, and the adsorption process is reversible. Thus pressure must be maintained at or above the gas desorption pressure in order for the adsorbed CO_2 molecules to remain immobile.

The other criteria for CO_2 storage are the physical and chemical properties of coal. It depends at the first place on the isolation from other formations avoiding leakage of CO_2 to the surface. Other criteria are the maceral composition, the rank and well-developed cleat system, the permeability and the tectonically controlled strain system in the coal seam.

Coals with high vitrinite content are favourable for CO_2 storage because the adsorption surface of telinite walls in the micropore range is the biggest among the three maceral groups. The coexisting gases generating during coalification and CO_2 to be disposed are adsorbed in this micropore space [RADNAINÉ GYÖNGYÖS 1990; CROSDALE at al. 1998; CLARKSON, BUSTIN 1999]. The higher is the rank the higher is the generated gas content in the coal and the storage capacity for CO_2 (*Fig. 1*). Experimental results of CHALMERS and BUSTIN [2007] proved that the

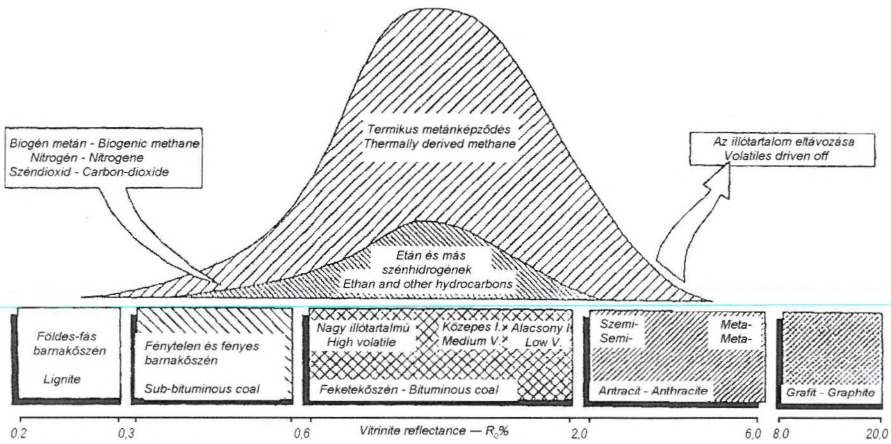

Fig. 1. Intensity and volume of hydrocarbon generation during coalification
Modified after DOW [1977]

1. ábra A szénhidrogén képződés intenzitása és relatív mennyisége a szénülés során.
DOW [1977] nyomán

highest storing capacity has anthracites and low volatile bituminous coals, while natural cokes' and low rank coals' adsorption capacity is low. In these later ones the meso and macro pores are dominant.

It is well known that during coalification hydrocarbon gases generate from the coal, which start to migrate in the source rock. Later, due to the confining pressure of the generated gases fissures appear forming cleat systems in the coal. This meso- and macro-porosity help the movement of generated hydrocarbon and CO_2 to be disposed. There is linear correlation between the cleat system development and the permeability of coal.

Currently there are many discussions concerning CO_2 storage and enhanced coalbed methane (ECBM). It has been observed that when coal adsorbs CO_2, it swells in volume. This swelling reduces the effective permeability and injectivity of gases. Additionally, many coal bodies have extremely low matrix permeability, and gases flow in the meso and macro pore cleat system. Cleat structures are extremely difficult to map, and their response to pressure transients from injection is poorly understood. The other difficulty for the CO_2 storage in coals is that CO_2 plasticizes and alters the physical properties of coal.

At present level of knowledge it is unclear what the risk of leakage is in long-term and in a short time. Gas desorption and leakage to the surface is a potential risk because the hydrostatic pressure in the coal formation can change due to uplifting over geologically long time periods. During coal mining it was observed frequently that there were dramatic floodings of the galleries due to the man-made disturbance of the natural hydrodynamic patter of the coal seams and the fresh water aquifers. This phenomenon might have consequences on the CS, causing contamination and leakage risk.

3. Geological setting coal resources and storage capacity of unmineable coal seams in Hungary

In Hungary there are nine distinct coal basins representing coals of various rank from Mesozoic to Tertiary age (*Fig. 2*). Their quality is ranging from lignite to low volatile bituminous rank from Upper Miocene to Jurassic age. Due to the requirements of the present project, coal fields and basins, which are located at depth less than 1000 metre below the surface, were not considered. Another screening condition was that former

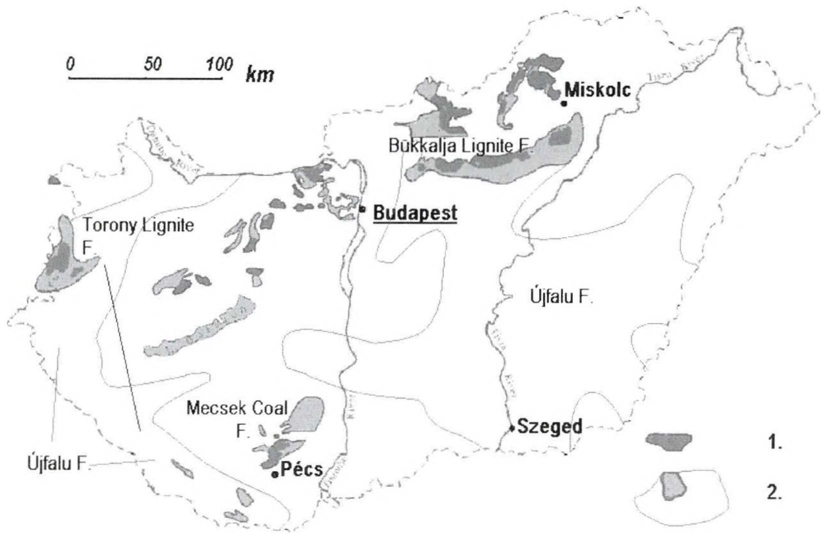

Fig. 2. Location and distribution of coal fields and related formations.
Legend: 1—Explored coal resources and mining plots; 2—Occurrence of Mecsek Coal Formation and Újfalu Formation

2. ábra. A kőszén előfordulások elterjedési térképe.
Jelmagyarázat: 1— Földtanilag megkutatott, készletben nyílvántartott terület. 2—Reménybeli terület, a Mecseki Kőszén Formáció és az Újfalui Formáció elterjedése

calculations on coal resources contained the mining activity areas between 150–1000 m depth depending on the exploitation technology. These data are figured in brackets in *Table I*. In the case of Mecsek Coal Formation (MCF) coal resources represent 70 km^2 areas of the 350–400 km^2 extension of the coal basin, which is indicated by seismic profiles in the deeper basin extending to a depth of 2000 metres.

Practical experiences generated during the mining operation show that gas sorption capacity of coals is very limited above 400 m depths because the gas is migrating, due to low sealing effect of the cover sediments. Coal resources of MCF, and Bükkalja–Újfalu Formations (UF) were calculated in the interval between 1000–2000 m, however these latter one occurs below 2000 m depths in dipping sequences in the southern part of their occurrences and in depressions. Differences between the published data and estimated coal resources proved by former geological and geophysical studies in basic stratigraphic wells and seismic logs are shown in Table I, where the underlined data correspond to the referred interval.

4. CO_2 potential of the Mecsek Coal Formation (MCF)

In MCF two-third of the resources is situated in synclinal position, below 1000 m and the bottom section of the formation reaches 2600 m. MCF is humic coal with more than 85% vitrinite content of the organic matter from high volatile (HVB), to low volatile (LVC), bituminous coal rank. The ash content is relatively high 20.1%; the sulphur content is 1.3% in average. The coal porosity is ranging between 1–15%, but it is emphasized that coal seams are practically impermeable. The moisture content in the coal seams and partings is 0.5 to 2.0%; however, water is penetrating into abandoned gob** areas in the mine continuously.

Methane sorption capacity is 50 m^3/t, where 92–98% of the methane content is adsorbed and only 2–8% occurs in the free gas phase. The exploitation of this type of methane content requires special methodology and techniques. Industrial carbon dioxide sequestration can be a tool for storage and enhanced methane production at the same time. Producible gas in place reserves of MCF is 18.9 and 62.3 billion m^3 as well as carbon

** gob: that part of a mine from which the mineral has been partially or wholly removed; the waste left in old workings

Coal Basin, Subbasin, Region	Formation	Age	Rank ASTM	Formation thickness (m)	Coal seams total thickness (m)	Depth interval (m)	Coal resources >1000 m in place (Mt)	Gross calorfic values (MJ/t)	CO_2 storage capacity (Mt)
1 Mecsek Mts., Pécs	Mecsek Coal F. MCF	J_1	HVB-LVC	1000–1200	23	300–2000	2400* 8000	19387	68 (224)
2 Bakony Mts, Ajka	Ajka Coal F. AF	Cr_2	Sub-bit.A	50–100	12	300–500	(450)	10277	–
3 N-Transdanubia Tatabánya-Oroszlány	Dorog Coal F. DCF	E_2	Sub-bit.B	15–60	30	300–500	(1000)	12436	–
4 N-Transdanubia Oroszlány	Mány F. MF	O_2	Sub-bit.C	30–50	5	0–300	(80)	15026	–
5 N-Hungary. Miskolc-Salgótarján	Salgótartján Brown Coal F.	M_1	Lignite A	30–300	15	0–400	(1350)	10618	–
6 Bakony Mts. Várpalota	Hidas Brown Coal F.	M_2	Lignite A	50–70	8	0–100	(320)	8560	–
8 N-Hungary. Visonta-Bükkábrány	Bükkalja BL Lignite F. (Újfalu F. UF)	M_2	Lignite B – Sub-bit A	250–1000	15	0–2000	(5800**) 90000	7419	– (394)
9 SW –Hungary Szombathely	Torony Lignite F. TLF (Újfalu F. UF)	M_2	Lignite B – Sub-bit C	200–800	10	20–2000	(5800**) 7400	7281	– (33)
Total									68; (651)

Table I. Summary of coal formations, quality and CO_2 storage capacity from 1000 to 2000 m depths; Hungary. See explanation in the text. *Legend*: ASTM—American Society for Testing and Materials; HVB—high volatile bituminous coal; LVC— low volatile bituminous coal; Sub-bit A—sub-bituminous coal A. * Published data by the Hungarian Geological Survey (HGS) and FODOR [2007]; ** HGS data for the two occurrences. These data are calculated to the mining quarries

I. táblázat A magyarországi kőszén formációk tulajdonságai és CO_2 tárolóképessége az 1000 és 2000 m közötti mélységben. A további magyarázatot lásd a szövegben. *Jelmagyarázat:* ASTM — Amerikai Szabványügyi Társaság; HVB — nagy illóanyag-tartalmú feketeszén; LVC — alacsony illóanyag-tartalmú feketeszén. *A Magyar Geológiai Szolgálat (MGSZ) és FODOR [2007] közzétett adatai; ** az MGSZ adata a két formáció összes földtani készletére, mely a bányatelekkel lefedett területekre esik dioxide storage capacity 68 and 224 Mt in the mining area and the deepbasin occurrence, respectively.

5. CO_2 potential of the Újfalu Formation (UF)

The Pannonian (Late Miocene–Pliocene) sequences were studied in detail in outcrops of basin margin areas and in thousands of deep hydrocarbon exploratory wells and shallow boreholes drilled in search for solid minerals and water resources, as well as from hundreds of seismic profiles. The Pannonian formations in Hungary occur more than three fourth of the country's area (about 75,000 km^2), mostly covered by the Pleistocene. Lignite formations of delta facies with several seams of lignite to sub-bituminous rank represent 200–1000 m thick measures, which are getting thicker to the direction of S–SE and S–SW in the Great Plain and in the Dráva Basin, respectively. Sequence stratigraphy of Bükkalja Lignite Formation (BLF) and Torony Lignite Formation (TLF) in basic stratigraphic wells by the Geological Institute of Hungary compared to hydrocarbon exploration wells data show that their heteropic facies Újfalu Formation, UF also has similar development of coal formation in deep basins like their surface or near surface lignite occurrences. It has a gentle dip of two to three degrees to the direction of thickenings.

The number of economic seams is five to seven in the Dráva Basin and Great Plain, respectively. The organic matter of lignite consists of more than 80% vitrinite from lignite B to sub-bituminous C rank. The average moisture content is about 49% at the surface and decreases to 30% at 2000 m depths. The ash content is high, ranging between 15 and 35%, and the sulphur content is 1.32%. Methane sorption capacity is 2 m^3/t in the deep basin areas [FODOR 2007]. Former studies on $\delta^{13}C$ carbon stable isotope ratio changes strengthen that high portion of the hydrocarbon gas resource in the Pannonian Basin derives from biogenic origin of UF lignite as a source rock [HOLZHACKER et al. 1981; FEDOR 2004].

Although methane adsorption capacity of lignite is low, some former studies on lignites and bituminous coals showed that low rank coals have higher CO_2 sorption capacity, which is at least 8–10 times of the methane content, while in bituminous coals the ratio is two in average. [GLUSKOTTER et al. 2002]. Based upon this experimental result we calculated nine times sorption capacity factor determining the carbon dioxide capacity, which is 394 Mt for the Great Plain and 33 Mt for the Dráva Basin.

6. Summary and conclusion

In the last decade there were some CO_2 ECBM pilot projects and raised several criteria and technological problems discussed above. These concerns limit the immediate attractiveness of unmineable coal seams for CO_2 storage. However there is strong interest in this mechanism, which might produce profitably ECBM in the future reducing the costs of capture and storage.

In Hungary there are two candidate coal formations the Lower Jurassic MCF and the Late Miocene UF. Due to preliminary results the CO_2 storage capacity of Hungary is 651 Mt CO_2 in total. To give a better storage capacity potential we need further investigation to get more detailed information on the distribution of coal formations in the deep basins and characteristics of coals. Additionally we need to get more precise data on permeability, tectonics, and hydrogeology of the candidate coal basins as well.

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Széndioxid tároló kapacitás lehetőségek és képesség a magyarországi le nem bányászott kőszéntelepekben

Mária HÁMOR-VIDÓ

A cikk röviden összefoglalja a témában folyó kutatások eredményeit. A kőszéntelepekben való széndioxid tárolást befolyásoló tényezők ismertetése után bemutatja a magyarországi előfordulásokat és minősíti azokat.

Két perspektivikus előfordulás, a Mecseki Kőszén Formáció (MCF) és az Újfalui Formáció (UF) földtani felépítése és fizikai tulajdonságai alapján vázolja a két formáció széndioxid tárolókapacitását.

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Contamination detection

Application of geophysical methods for environmental diagnostics on two contaminated test sites

Zsuzsanna NYÁRI*, Boriszláv NEDUCZA*, Péter SZŰCS**

A consortium with three partners from different fields of environmental sciences (geophysics, hydrogeology, geotechnics) was formed for a three-year-long project to improve hydrogeophysical methods in order to detect and characterize special subsurface contaminants. Different contaminated sites were chosen in Hungary as study-areas to improve and calibrate special geophysical methods to provide remediation experts and hydrogeologists with necessary information for reliable transport modelling. A strong collaboration between the geophysicists and hydrogeologists evolved protocols and techniques to carry out successful site assessment and remediation schemes of contaminated lands.

This study presents the diagnostic works on two of these test sites: one with ionic and the other one with hydrocarbon contamination. At both sites high resolution geophysical methods were applied in order to give reliable information for site diagnostics and for further hydrogeological investigations. The results of the geophysical measurements were validated by geotechnical methods.

Keywords: resistivity, contamination, hydrogeology, transport modell, non-invasive methods, remediation

1. Introduction

Chlorinated organic compounds and hydrocarbons are among the most serious soil and groundwater contaminants because of their mobility and persistence in the subsurface, their widespread use, and their health effects. Developing and applying reliable and accurate geophysical methods and transport models is greatly needed to assess the risk posed by the plumes of these compounds to the subsurface.

The geophysical investigations had dual purposes: high resolution reconstruction of the underground structure and reliable detection and

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characterisation of the contamination. There was a serious expectation from the applied method: they should give reliable and understandable information for hydrogeologyists for further examinations and geotechnical experts for planning the remediation. To fulfil these expectations development of conventional measuring methods was necessary. This development concentrated on geoelectrical and IP methods and included improvement both in survey techniques and data processing.

As an advantage of the consortium's structure the geophysicists got directly the expectations from the end users. The results were immediately applied in further examinations and tested by the environmental expert partncrs.

This study presents the application of 2-D and 3-D resistivity surveys and ground penetrating radar (GPR) profiling on the test sites.

2. Test Site 1

Site description

The test site is located in Northern Hungary at the bank of river Danube. The area is an abandoned aluminium works. The contamination is concentrated in the gravel aquifer of the ground water. The vertical distribution of the contamination is inhibited by thick clay layer at the depth of 5–6 m. The extreme high conductivity of the contamination refers to high chloride concentration of the ground water. Beside the salt content (mostly natrium, sulphate, chloride, phosphate, and ammonium ions) there is significant toxic metal content as well. The pH value of the ground water is also high: 8–10. The presence of the contamination causes strong increase of conductivity of the upper gravel layer so the application of resistivity measurements was obvious.

Reconstruction of geological structure

At the beginning a 250 m long, 2-D geoelectric profile with inverse Schlumberger array was measured in order to get familiar with the geologic structure. After the interpretation a 3-D resistivity survey was planned on the area. According to the interpretation results the contamination was accumulated in a buried old watercourse and it moves preferably along it (*Fig. 1*).

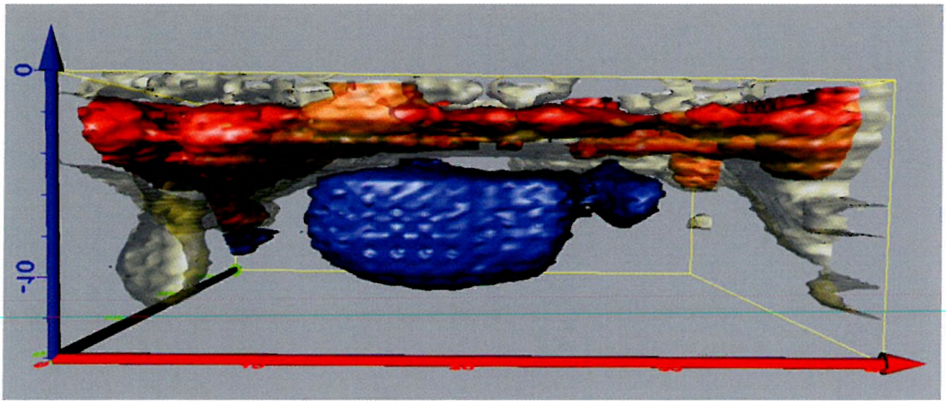

Fig. 1. 3-D Resistivity image on Test site 1. The shape of the buried river bed can be recognized (low resistive, light blue) where the conductive acidic contamination accumulates. The resistive uncontaminated gravel is marked with red, the intermediate resistive upper layers are yellow

1. ábra. 3-D ellenállás kép az 1. tesztterületről. A betemetett folyómeder alakja felismerhető (kis ellenállás, világos kék szín) ahol a jólvezető savas szennyeződés felhalmozódott. A nagyellenállású szennyezetlen kavicsot piros színnel, a közepes ellenállású felső rétegeket sárgával jelöltük

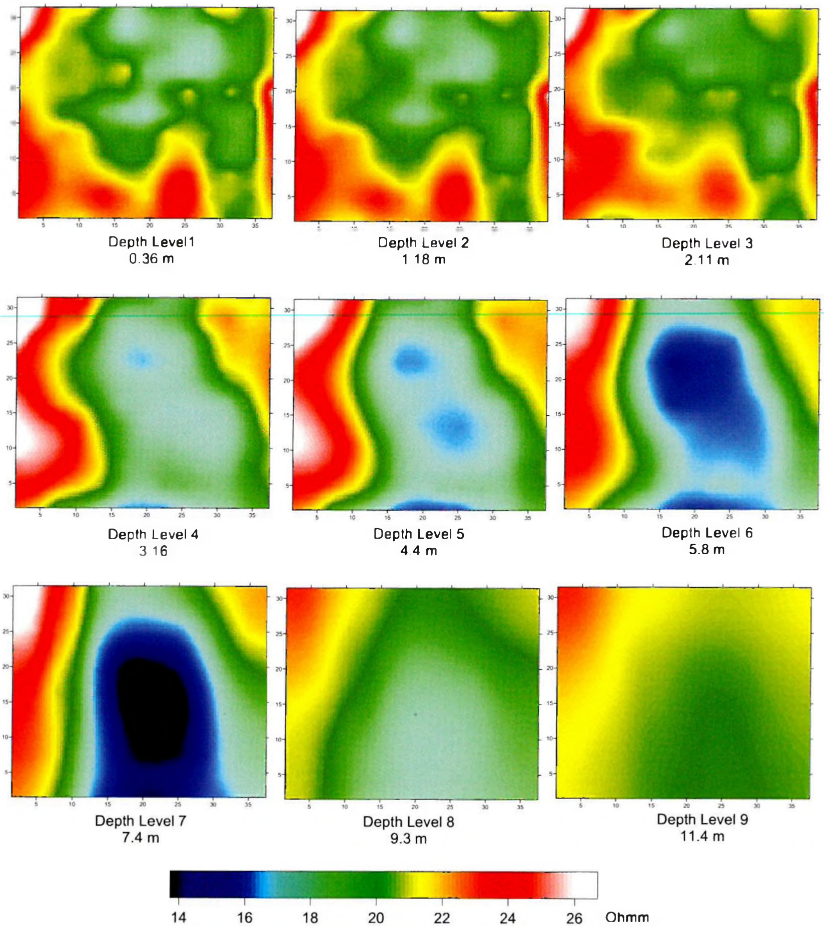

Fig. 2. Depth slices of a 3-D resistivity image on Test site 1.
The low resistive contamination appears at Depth Level 4. It reaches its maximal concentration at Depth Level 7. The aquifer is free from contamination from Depth Level 9 downwards

2. ábra. Mélységmetszetek az 1. tesztterület 3-D ellenállásképéről. A kisellenállású szennyeződés a 4. mélységszinten jelenik meg. Maximális koncentrációt a 7. szinten ér el. A vízadó réteg a 9. szinten és attól lefelé szennyeződésmentes

Contamination delineation in 3-D

Consultations with geologists and analysing the geotechnical information of the area the theory of the buried watercourse filled with ionic contamination were proved. At the next phase detailed information was needed from the extension of the contaminated aquifer. From the dataset of combined interpretation of surface 3-D and borehole geoelectric surveys the delineation of the contamination was done in both horizontal and vertical directions. Creating depth slices from the 3-D resistivity images the vertical change of the contamination accumulation in the ground water can be defined: the contamination accumulates in the lower part of the aquifer (*Fig. 2*).

3. Test site 2

Site description

Test site 2 is located in a flatland in Southern Hungary. The geological structure of the contaminated zone does not show much diversity: sand layers with thin clay intercalations. A damaged pipeline crosses the area causing seriously chlorinated, organic and hydrocarbon contamination either in the subsurface formations or in the groundwater. After an unsuccessful remediation process the spread of the contamination and its compounds were defined from the data of observation wells in 2004. Then a new system of monitoring wells has been implemented in 2006. The monitoring data started flowing in the middle of 2007. Applying all these data a hydrogeological transport model was created to be used during the remediation process.

Hydrogeological investigations

As a first step, a hydrodynamic model was created to describe the main hydrogeological properties of the investigated site. Then, a transport model was elaborated in order to characterize the time movement and the behaviour of the contamination plume. It was revealed that mainly BTEX compounds (Benzene, Toluene, Ethylbenzene and Xylene) were found in the TPH (Total Petroleum Hydrocarbons) contamination. The Processing Modflow Pro program package was used for our simulation activity. The MOCD and RT3-D modules were applied for transport modelling. The initial contamination concentrations in the model were based on the site assessment results from 2004. The measured concentrations from 2006 and the monitoring data of 2007 were involved to calibrate accurately the transport model. The results of the geophysical interpretations were also utilized to refine the flow as well as the transport model. The derived transport model is able to predict accurately the movement of the investigated contamination plume in space and time for different scenarios. Based on the transport model simulation, *Fig. 3* describes the BTEX concentrations at the investigated site in 2008.

Reconstruction of geological structure

Among the non-invasive geophysical methods GPR profiling and 3-D resistivity imaging were applied on the area during the summer of 2006. Eleven parallel GPR profiles were measured in order to reconstruct the underground geological structure. The shielded 250 MHz antennas provided detailed geological information. The structure of the lower regions was mapped after 3-D geoelectrical images.

Contamination detection

The detection of contaminated zones had to be divided into two phases. In phase one the contaminated earth was investigated above the water table. Then in phase two the delineation of the contaminated groundwater was done. The CH contamination caused low resistive anomaly either above or below the water table. In both cases the geophysical results were compared with the data of ground sampling and groundwater analysis (*Fig. 4 a, b*).

4. Conclusions

Investigations on two test sites proved that applying non invasive geophysical methods the reconstruction of the near surface geological structure and 3-D delineation of contaminated zones can be reliably executed.

The obtained pieces of information provided by the geophysical methods were included into the transport models to predict the behaviour and future movement of the investigated plumes. The advantages and applicability of this new approach are well illustrated by means of theoretical investigations and geophysical and hydrogeological case studies.

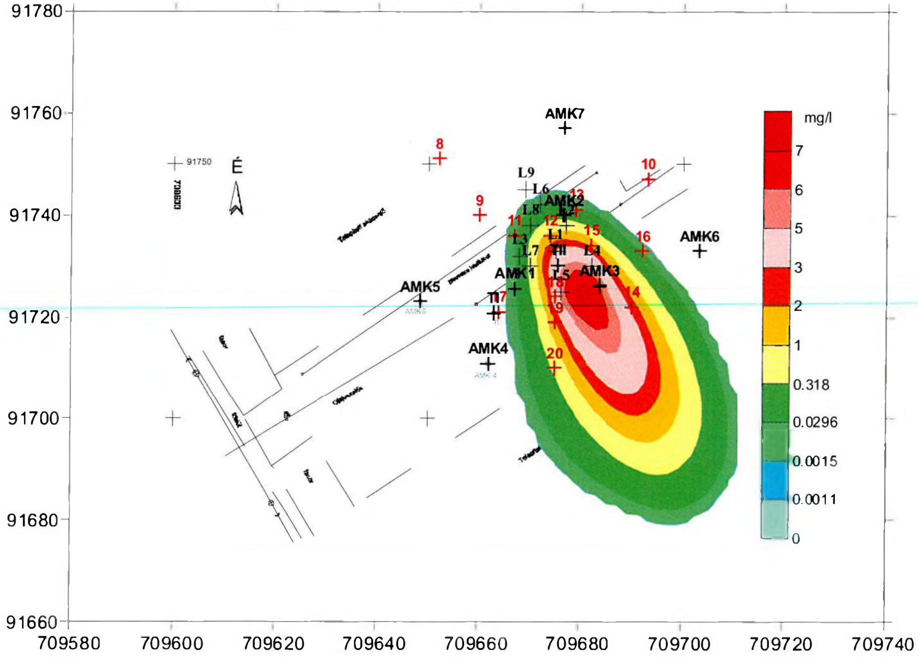

Fig. 3. The expected distribution of BTEX by the end of 2008 based on hydrogeological modelling

3. ábra. A BTEX becsült eloszlásképe 2008. végén a hidrológiai modellezés alapján

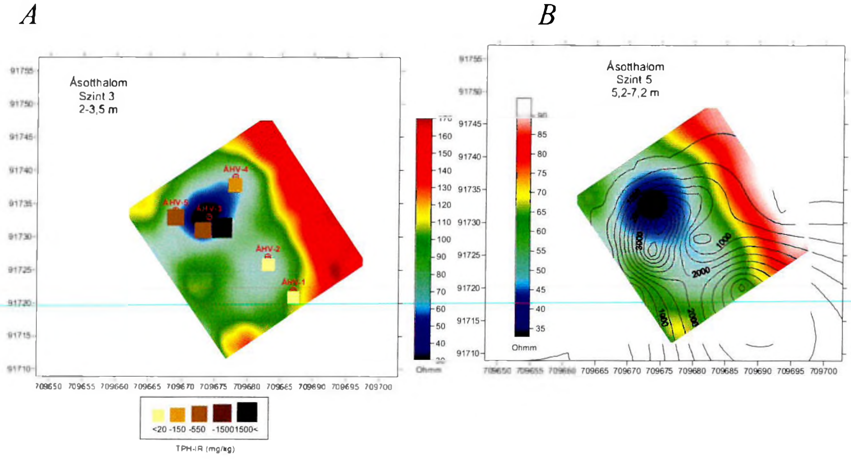

Fig. 4. Resistivity depth slices above (*A*) and below (*B*) the water table. In both cases the contamination accumulation causes low resistive (blue) anomalies. In the case of *A* geophysical results are compared with chemical analysis of ground samples. At *B* the isoclines indicate the BTEX distribution based on the data of monitoring wells.

4. ábra. Ellenállás mélységszeletek a talajvízszint felett (*A*) és alatt (*B*). Mindkét esetben a szennyeződés felhalmozódás kisellenállású anomáliákat okoz. *A* esetben a geofizikai eredményeket összehasonlítottuk a talajmintavétel vegyi elemzésének eredményeivel. *B* esetben az izovonalak a BTEX eloszlását mutatják a monitoring kutak adatai alapján

Acknowledgement

The authors gratefully acknowledge the Bolyai János Research Scholarship program of the Hungarian Academy of Sciences, the Hungarian Research Fund (OTKA T 048329) and the GVOP (GVOP-3.1.1.-2004-05-0187/3.0) for support of this work.

Geofizikai módszerek alkalmazása két szennyezett terület környezeti diagnosztikájához

NYÁRI Zsuzsanna, NEDUCZA BORISZLÁV, SZŰCS Péter

A környezettudományok három szakterületét (geofizika, hidrogeológia, geotechnika) képviselő tagokból álló konzorcium jött létre abból a célból, hogy végrehajtson egy három éves projektet, melynek célja a hidrogeofizikai módszerfejlesztés volt bizonyos felszín alatti szennyeződések kimutatására és jellemzésére. Különböző magyarországi teszt területeken zajlott a speciális geofizikai módszerek fejlesztése és kalibrálása abból a célból, hogy a hidrogeológusok és kármentesítési szakemberek megbízható folyadéktranszport modelljeikhez szükséges adatokat kapjanak. A geofizikusok és hidrogeológusok közti erős együttműködés eredményeként eljárások és technológiák kerültek kidolgozásra, melyek sikerrel alkalmazhatók a terepi felmérésekben és a kármentesítésben.

A tanulmány ismertet két teszt területen folyó diagnosztikai munkát: az egyik ionos anyaggal, egy másik pedig szénhidrogénnel szennyezett terület. Mindkét helyszínen nagyfelbontású geofizikai méréseket végeztünk annak érdekében, hogy megfelelően megbízható adatokat tudjunk nyújtani a későbbi kármentesítéshez és hidrogeológiai modellezéshez. A geofizikai mérések eredményeit geotechnikai módszerekkel hitelesítettük.

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Contamination detection

The use of electrical imaging to characterize contaminated sites

Bradley J. CARR*, Markus LAGMANSON*, Hasan AKTARAKCI**

Contaminated sites can be identified and charceized by Direct Current resistivity and induced polarization measurements. Four case histories are presented for characterizing groundwater pathways and mapping the contaminations.

Keywords: electrical surveys, contamination, resistivity profiling, induced polarization, non-aqueous phase liquids

1. Introduction

Published research illustrate that Direct Current (DC) resistivity and induced polarization (IP) (which includes time-domain IP, frequency-domain IP, and spectral IP) can be used in environmental studies to identify and characterize contaminates [e.g. OLHOEFT 1985, VANHALA 1992, SAUCK 1998, ATEKWANA et al. 2001, DELANEY et al. 2001, RUCKER et al. 2007]. In this discussion, we look at four case histories that display the latest work using DC resistivity and time-domain IP anomalies to help characterize groundwater pathways and/or map contaminant presence. The analyzed sites encompass different lithologic settings and were acquired by various companies and research institutions in the USA. For example, time-domain IP anomalies have identified Non-Aqueous Phase Liquid (NAPL) concentrations as low as 150 ppb at one highly contaminated site. Drilling and sampling at this site established the level of contaminant concentrations after the geophysical survey.

Our experience in collecting time-domain IP at environmental sites has led to the working hypothesis that environmental scale IP anomalies

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with NAPL contaminants are caused by a modified membrane polarization effect. Membrane polarization usually results in rocks/sediments that contain some clay particles as part of the overall matrix. Under an electrical current, these clay particles have a slight net negative charge that attracts the positive ions from the electrolyte present in the pores (usually water). As a result of this polarized distribution of ions, the electrical current flow is stored. Once the current flow is turned off, the positive ions redistribute themselves to return to an equilibrium position that we measure as a decaying voltage [SUMNER 1976]. Although DC resistivity data does not definitively map NAPL, it does highlight the porosity/permeability state of the subsurface. This information is used to predict preferred pathways of groundwater and/or NAPL contaminants. Since DC resistivity data are collected concurrent with the induced polarization data, a combined analysis of the IP and DC resistivity data sets can lead to maps of current contamination that allow simultaneous predictions of possible lateral and vertical flow paths.

2. Case Study I

DC resistivity study for Light Non-Aqueous Phase Liquids (LNAPLs) at a site in Enid, Oklahoma, USA

The objective of this study was to define the geological controls on the distribution and location of free product LNAPL (hydrocarbon) at an existing gasoline station. The data were collected with borehole resistivity imaging between 12 boreholes. A typical 2-D cross section for this data set is shown in *Fig. 1.* Later these data where mapped into a 3-D cube to present a better spatial representation of the site for evaluating the remediation efforts *Figs. 2 and 3.*

Data show that there is a structural dome in the subsurface at the top of Layer A along the western side of the site. This structural high corresponds with the LNAPL. Typically, LNAPL is thought to be a single, massive plume. However, it was found in 1 to 2 meter amorphous higher resistivity 'blobs' shown on the 2-D DC resistivity cross-sections (Fig. 1) and the 3-D cube view (Fig. 2). Drilling correlation established that these anomalies above 46 ohmm underlying the clay layer 10 m below surface corresponded to free product LNAPL. Prior to this study, the contaminant plume at the site was thought to be a classic cone shaped feature. With this study,

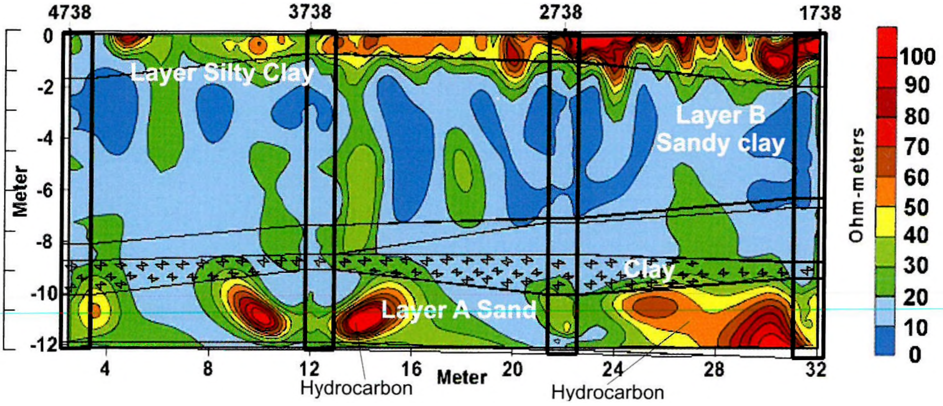

Fig. 1. Two dimensional electrical resistivity data from the Oklahoma site with an overlay of the subsurface lithologies. Beneath the clay level, isolated high resistivity anomalies indicate the presence of LNAPL

1. ábra. Kétdimenziós elektromos ellenállás adatok Oklahoma területről, a felszín alatti litológia feltüntetésével. Az agyag szint alatt, elkülönülő nagyellenállású anomáliák utalnak az LNAPL jelenlétére

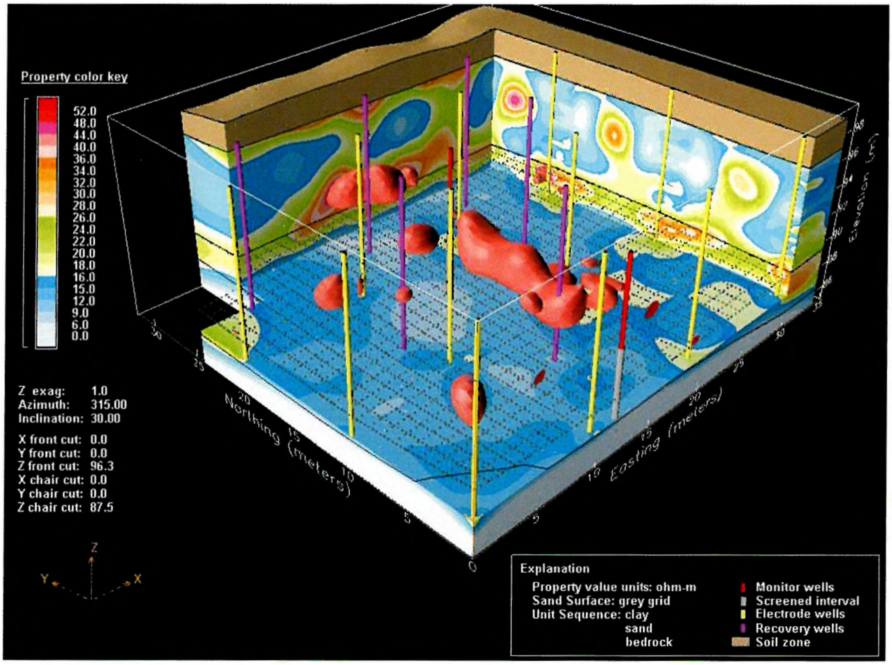

Fig. 2. 3-D Electrical resistivity model for the initial site characterization of the Oklahoma, LNAPL site

2. ábra. 3-D elektromos ellenállás modell az Oklahama terület kezdeti jellemzésére, LNAPL előfordulás

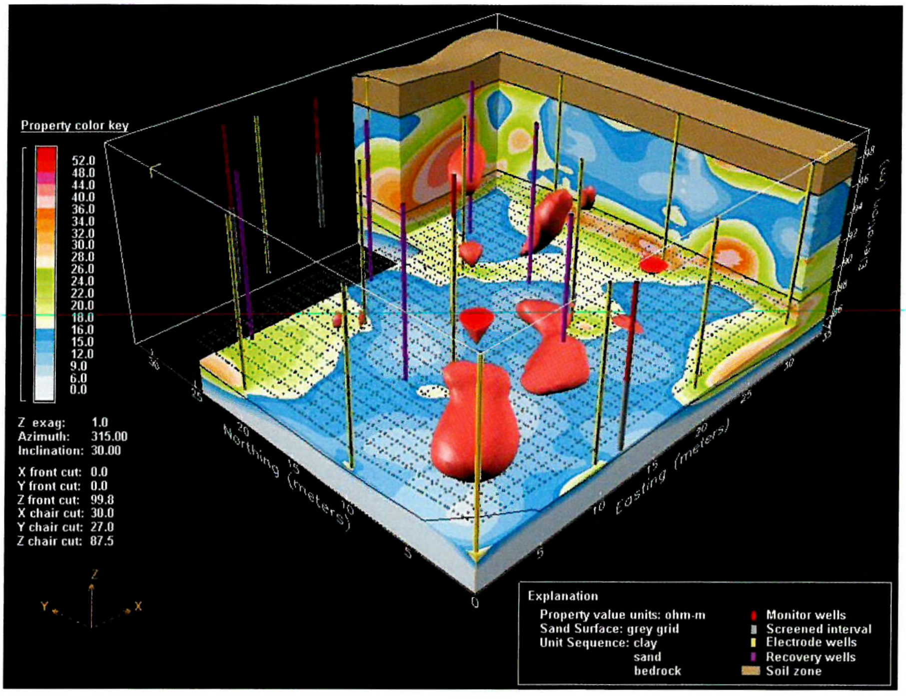

Fig. 3. 3-D Time-lapse display of the Oklahoma site after 7 months of remediation

3. ábra. Az Oklahoma telep 3-D-s időfüggő megjelenítése 7 hónappal a kármentesítés után that view of the plume shape and movement proved to be wrong. These data show that impermeable clay lenses trap LNAPL and allow it to be reintroduced to the lower aquifer as the water table lowers seasonally. After seven months of remediation, the Electrical Resistivity Tomography (ERT) was repeated to evaluate remediation progress (Fig. 3). At that time, the majority of all product plumes were near recovery wells and actively being removed from the ground.

3. Case Study II

DC resistivity & Induced Polarization study for Non-Aqueous Phase Liquids (NAPLs) at a former Chemical factory in Michigan, USA

The purpose of the study was to determine if Resistivity and Induced Polarization imaging could be used to detect DNAPL (Dense Non-Aqueous Phase Liquid) in the upper 100 m (300 feet) at a former Chemical plant. These methods were run along two perpendicular profile lines (18 m (~710') in length) within the former Fine Chemical Production Area centered about a monitoring well.

Resistivity data are displayed in *Fig. 4.* Both lines show a general pattern of high resistivity overlying lower resistivity with the transition occurring at approximately 18–24 m (60–80 ft) below the surface (i.e. the yellow–green transition). Resistivity data does not directly identify DNAPL, but provides useful information about the *in situ* permeability distribution.

The highest resistivities (red/pink colors or > 3000 ohmm) near the surface are interpreted to be well-sorted, sand in the vadose zone. These dry sands are seen at the surface on the southern edge of Line 1 and both edges of Line 2. These resistivity values compare to vadose zone sands reported in this area. Other vadose zone resistivities range between 700–2000 ohmm. According to sampling logs in nearby monitoring wells, this zone contains medium-fine sand with no significant observed difference. It is interpreted that the resistivity differences in the vadose zone reflect recent excavation deposits and amount of soil that is present. High resistivity values (> 3000 ohmm) are sands that were highly disturbed or deposited most recently and had little time for a soil to reform.

The deep blue (low resistivity) is interpreted to be areas of high permeability/porosity and higher relative silt/clay content within these glacially derived sands. These would combine to significantly lower the electrical resistivity compared to the overlying dry sands. The majority of this zone lies principally south and east of the site at depths of 30–33 m (100–110 ft) below surface and may represent a channel-like deposit where permeability is higher.

Induced Polarization data show a number of chargeability anomalies at various depths along both Lines 1 and 2 (*Fig. 5*). These anomalies are interpreted as illustrating saturated zones of DNAPL. Geometrically, these anomalies appear to be both laterally distributed in the upper 3–6 m (10–20 ft.) or bell-shaped beginning at 6–8 m (20–25 ft) and broadening with depth. Deviations in this basic geometry are interpreted to be the result of silt/clay lenses restricting movement. These IP anomalies contain DNAPL according to nearby well sampling information and were initially interpreted to highlight zones saturated with DNAPL. Later sampling of these anomalies confirmed this interpretation. It is our hypothesis that the DNAPL resulted in IP anomalies by a mechanism of:

—membrane polarization (i.e. DNAPL presence decreases the amount of pore space available to water, resulting in the remaining water behaving like a net dipole across the constricted pore spaces when an electric field is applied),

—aerobic degradation resulting in a halo of cations and anions surrounding the plume which are polarized when subjected to an electric field, or

—anaerobic degradation of the plume resulting in a halo of cations and anions surrounding the plume which are polarized when subjected to an electric field.

Certainly, the amount of DNAPL needed to create this anomaly is partially dependent on the bulk pore space volume and geometry of the affected lithologies (i.e. poorly sorted units would require less DNAPL to cause this effect than well sorted units).

4. Case Study III

DC resistivity & Induced Polarization study for Non-Aqueous Phase Liquids (NAPLs) at a former Aluminum Casting facility in Alabama, USA

The resistivity data highlight structural and physical property features at the site: *a)* low resistivity (< 500 ohmm) zones that extend to depth within the bedrock, and *b)* lineaments present across the site and off site.

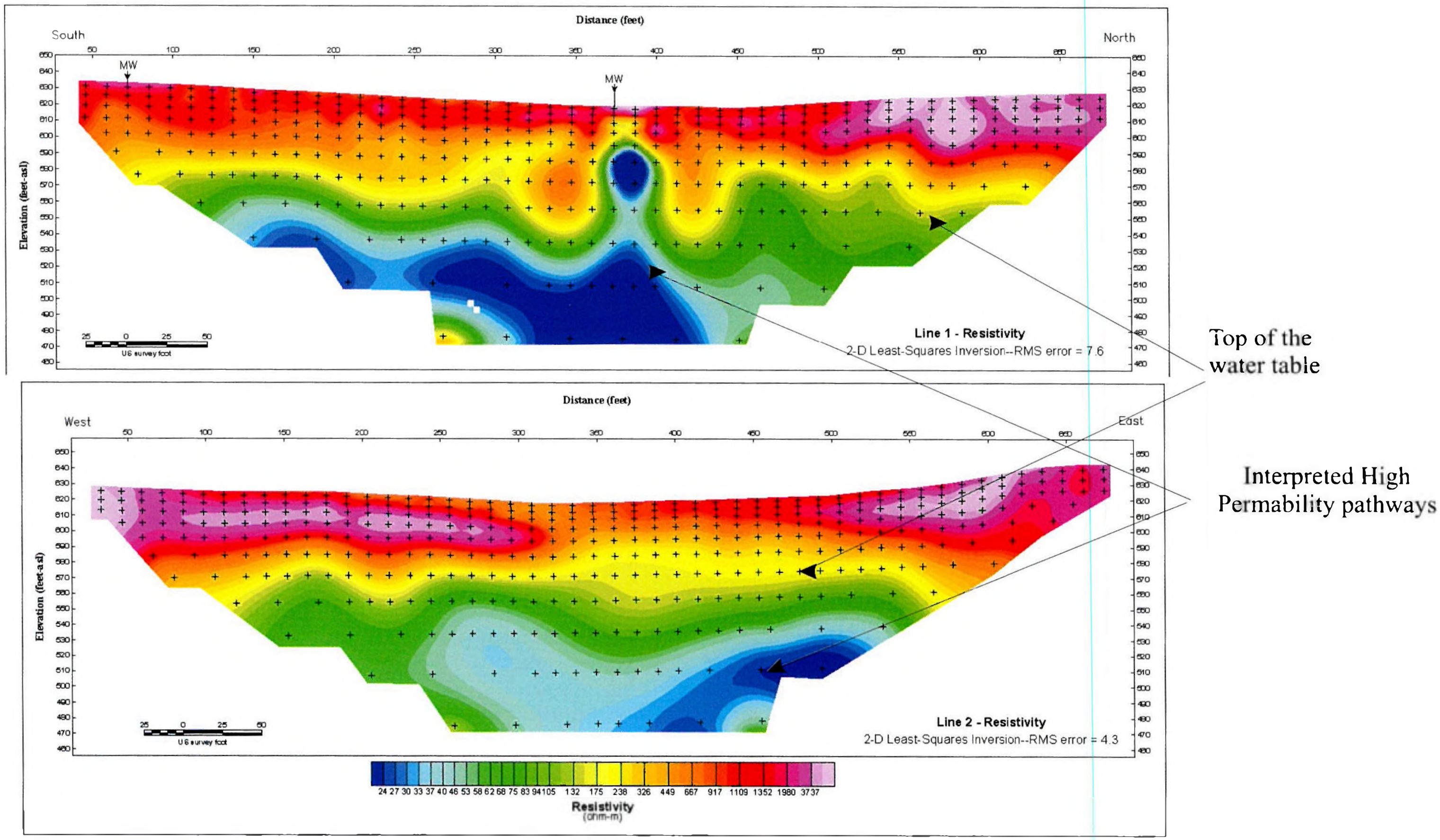

Fig. 4. Line 1 and Line 2 resistivity profiles at a former Chemical company in Michigan, USA. Low resistivities map to high porosity/permeability zones. High resistivities represent the dry vadose zone

4. ábra. Egy korábbi vegyi üzem területén készült ellenállás szelvények, Michigan államban, USA-ban. Kis ellenállások a nagy porozitás/permeabilitás zónákhoz tartoznak. A nagy ellenállások a száraz vadózus zónákat jelzik.

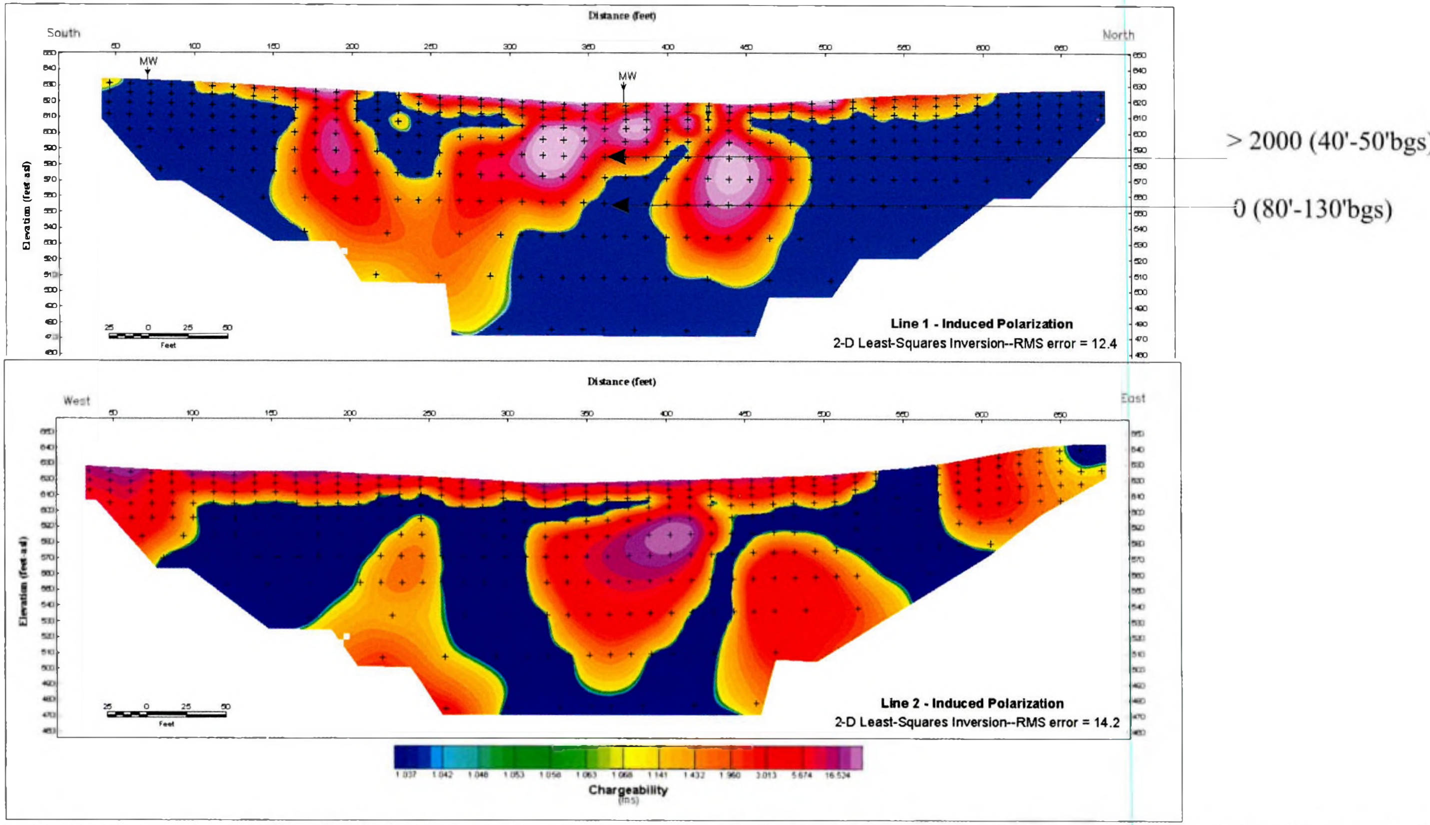

Fig. 5. Line 1 and Line 2 induced polarization profiles at a former Chemical company in Michigan, USA. IP Anomalies below the water table were sampled as Carbon Tetrachloride and appear to be moving to greater depths. Contaminated soils near the surface are still present and appear in the data. PID OVM 580B results are listed from the monitoring well with sampled depths

5. ábra. A korábbi Michigani Vegyi üzem területén mért 1. és 2. sz. gerjesztett polarizációs szelvények. A talajvízszint alatti GP anomáliákat szén-tetraklorid okozta, és úgy tűnik, hogy a nagyobb mélységek felé mozog. A felszín közelében még mindig jelen vannak a szennyezett talajrétegek és meg is jelennek az adatokban. A PID OVM 580B eredmények a mintavételi mélységekkel a figyelőkútból származnak

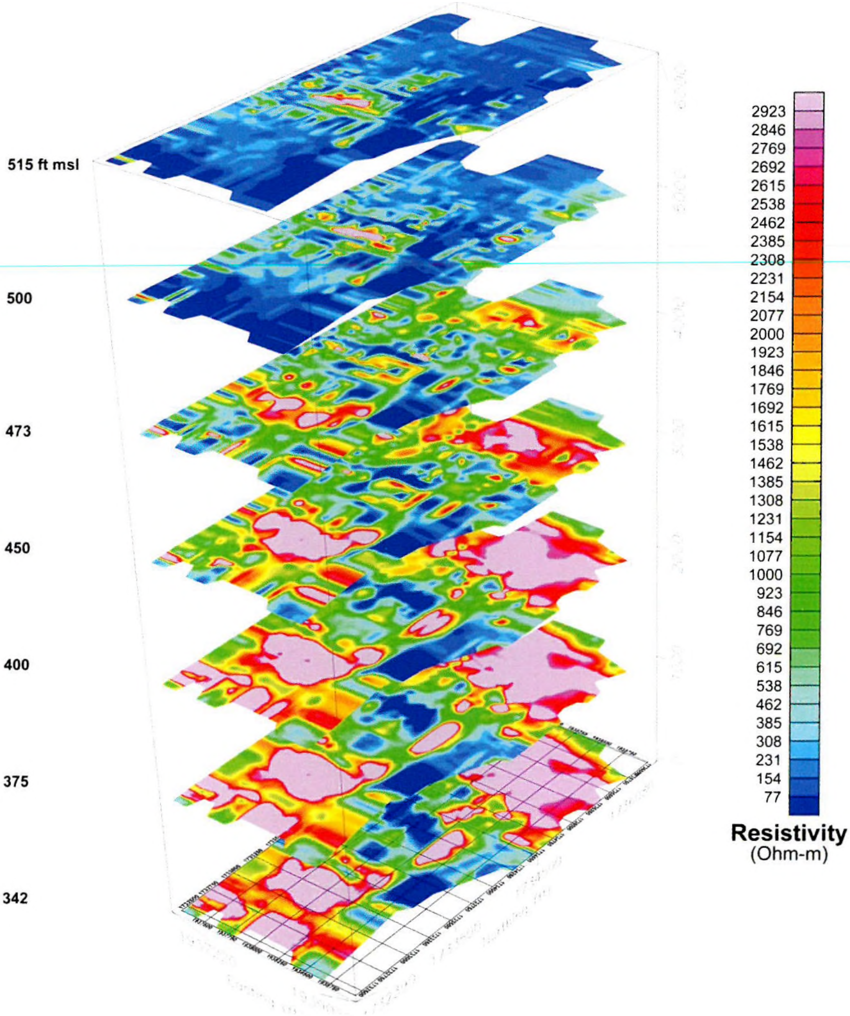

Fig. 6. Depth slices of a 3-D resistivity cube from a NAPL study at an aluminum plating facility in Alabama, USA. Low resistivities highlight high permeability vertical fractures within the limestone bedrock

6. ábra. Mélységmetszetek egy alabamai aluminium üzem területén végzett NAPL kutatás 3D ellenállásoszlopából. A kis ellenállások nagy permeabilitású függőleges töréseket mutatnak a mészkő alapkőzetben

The resistivity data highlight a distinct lack of resistivities above 500 ohmm that are laterally continuous at various locations and can extend to depth. This indicates that the physical state of the bedrock, not just the top of bedrock, changes along the profile.

Based on the comparisons of resistivity data and drilling, low resistivity zones represent changes in bulk porosity and permeability state of the bedrock. Specifically, the bedrock in these areas is interpreted to contain more groundwater and increased fracturing that enhances permeability to greater depths. To assist with the spatial representation of resistivity anomalies at the site, plots of depth slices of a 3-D cube generated from numerous 2-D profiles of these data are displayed in *Fig. 6*. Two of these elevation slices are displayed again in *Figs. 7* and *8*. Figure 7 highlights the resistivity of the shallow soils. Figure 8 shows the resistivity from 20 m below the top of the bedrock surface. The locations of the identified deep resistivity lows correlated with permeability pathways across the site. Drilling confirmation has shown that these pathways are principally due to vertically oriented fracture systems resulting from a pre-existing regional strain network expressed as SW–NW oriented lineaments.

Induced Polarization data highlight many areas and depths where NAPL's were suspected to be at elevated concentration levels. The IP anomalies within the bedrock were primarily found within the vicinity of the resistivity lows (i.e. primary permeability pathways) discussed earlier. The largest IP anomalies were initially interpreted as DNAPL that had the ability to reach greater depths due to some vertical connectivity mechanism (e.g. vertical fracture zone connectivity). Drilling confirmation showed this to be the case.

To assist with the spatial representation of IP anomalies at the site, plots of discrete depth levels from a 3-D cube (generated from the 2-D profile data) are displayed in *Fig. 9*. Two of these elevations are displayed again as depth slices in *Figs. 10* and *11*. Figure 10 highlights the resistivity of the shallow soils. Figure 11 shows the resistivity from 20 m below the top of the bedrock surface. The contaminant still present at the site is associated with (and moving within) the fracture controlled permeability pathways of the bedrock.

5. Case Study IV

DC resistivity & Induced Polarization study for Non-Aqueous Phase Liquids (NAPLs) at a copper plating factory in Michigan, USA

Resistivity and induced polarization profiling conducted at a copper plating facility site in Michigan, USA reveal preferred permeability zones and areas containing elevated concentrations of NAPL contaminant. For this investigation, dipole-dipole DC resistivity and induced polarization data were acquired along 23, 2-D profile lines totaling a linear distance of ~6.5 km (4.9 miles).

The observed changes in resistivity were interpreted to correspond with changes in bulk sediment porosities and therefore highlight zones of high and low permeability (e.g. *Fig. 12*). In the shallow subsurface, electricity is conducted almost entirely by the presence of fluid. At this site, essentially all the subsurface units are saturated. Therefore, resistivity will be controlled by the permeability of the unit more so than the specific lithology (e.g. low permeability/high resistivity silty sands are interpreted to juxtapose higher permeability/low resistivity clean sands). The exception to this hypothesis is thick clay lenses (e.g. > 0,6 m (two ft)) that appear as low resistivity. Electrically, saturated clean sands and clay layers will both appear as low resistivities and distinguishing the two is difficult. In summary, resistivity boundaries can be correlated to changes in soil and rock types (e.g. silty sand to sand, fractured to non-fractured bedrock, etc.), and sediment porosities.

These data fall into three basic categories:

a) high resistivity (> 500 ohmm) within the dry, unconsolidated above the water table,

b) low resistivity (< 500 ohmm) below the water table, and

c) high resistivity anomalies below the water table.

The first category simply represents the basic porosity changes above of the water table (i.e. low porosity–high resistivity). This 'normal' resistivity response is noted on all profiles collected outside and across parking lots (except where crossing streams or marshes). It should be noted that resistivity data within the plant (e.g. Fig. 12) generally do not show the typical data profile (i.e. high resistivity above the water table/low resistivity at/below the water table) completely. Within these data, low resistivities extend to the surface. We interpret this observation to be due to

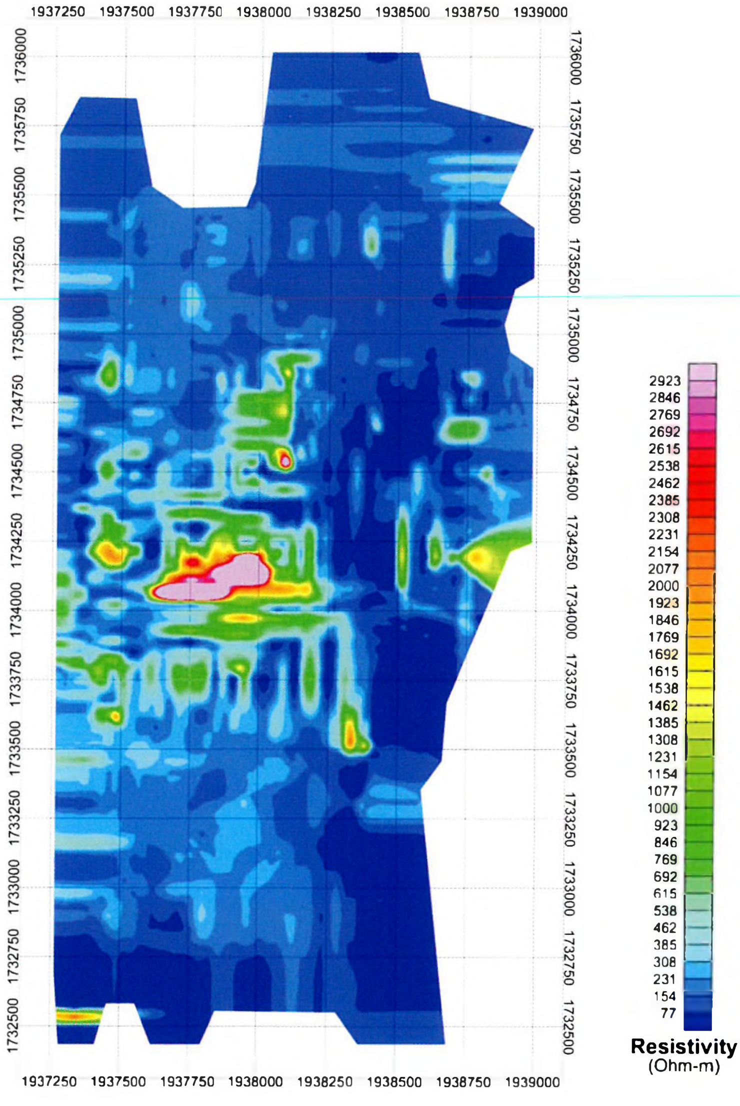

Fig. 7. Depth slice from ~10 m below surface of a 3-D resistivity cube from a NAPL study at an aluminum plating facility in Alabama, USA. The majority of the site has very low resistivity indicative of saturated clay-rich soil. The few areas of high resistivity represent filled areas associated with former buildings

7. ábra. Mélységi metszet kb. 10 méterrel a felszín alatt egy alabamai (USA) aluminium lemezgyártó telepen készült NAPL tanulmány keretében felvett 3D ellenállás hasábból. A telep túlnyomó részén nagyon kicsi az ellenállás, ami vízzel telített agyagban gazdag talajra utal. A néhány nagyellenállású terület a korábbi épületekhez kapcsolódó feltöltött területeket jelenti

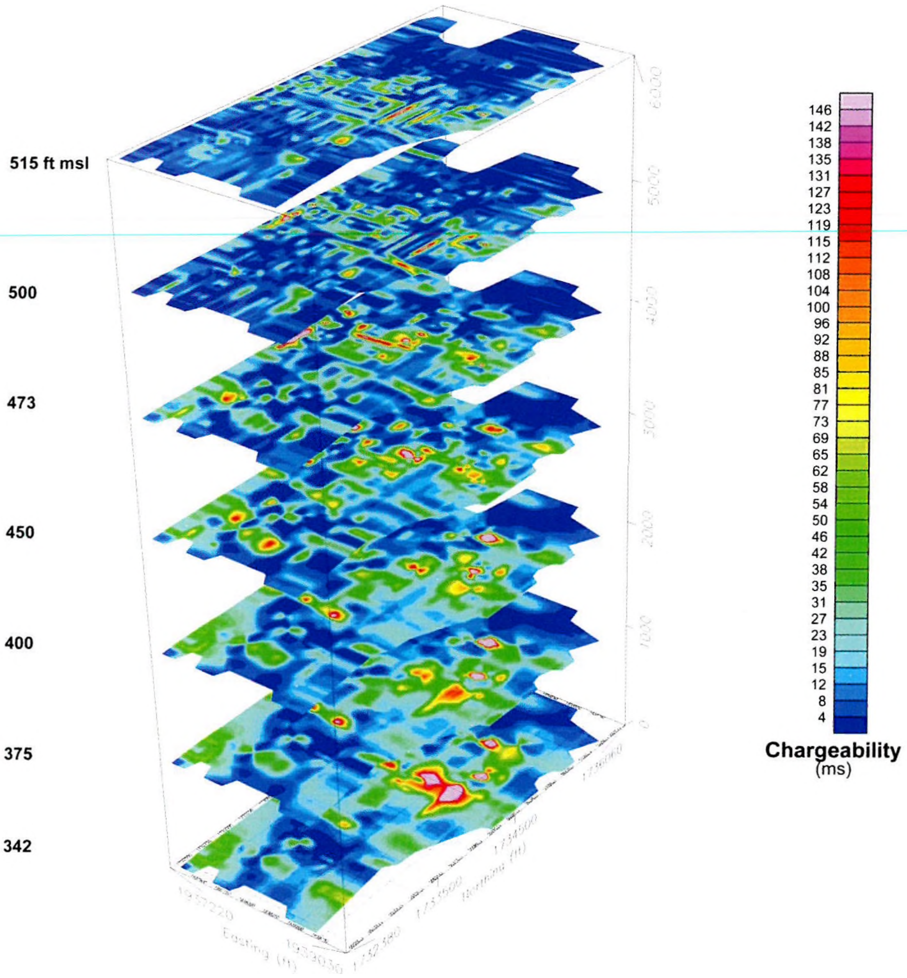

Fig. 9. Depth slices of a 3-D induced polarization cube from a NAPL study at an aluminum plating facility in Alabama, USA. High chargeability anomalies represent elevated NAPL concentrations

9. ábra. Egy alabamai (USA) aluminiumgyártó üzem területéről származó, indukált 3D gerjesztett polarizációs oszlop mélységszeletei. Nagy tölthetőségi anomáliák jelzik a megnövekedett NAPL koncentrációkat the disturbed soil conditions under the foundation that change the 'normal' shallow resistivity profile.

The majority of the resistivity data at this site fall under the second category. In the majority of these profiles, there are few areas that do not appear very permeable. However, the resistivity data are not completely uniform. The majority of the permeable groundwater zones are interpreted to exist within data profile areas less than 200 ohmm. Based on previous experience in glacial terrains, these areas are generally interpreted to be high porosity materials with occasional clay lenses. Higher resistivity zones below the water table range from 200–450 ohmm. Spatially, these zones appear to be isolated and may represent the zones of silty-sand (i.e. relatively lower porosity/permeability). In summary, we interpret these features to act as 'high resistivity islands' diverting the majority of groundwater flow but do not appear to form any large barriers.

High resistivity anomalies below the water table make up the final interpretational category. These zones have typically been silty-sand materials in other similar surveys. These zones are interpreted to be low permeability areas that will influence groundwater movement. Generally, these anomalies are isolated and again we anticipate that they will act as isolated diversions.

Induced Polarization (IP) data are interpreted to provide direct indications of NAPL and elevated levels of heavy metals at the site. Anomalies in the IP data are reported to correlate with sampling wells that showed contaminants and heavy metals in previous and current sampling datasets. After resistivity and IP data collection, correlation of IP anomalies to lithology and/or concentration levels was conducted by drilling and sampling.

In this IP data, anomalies were noted with chargeabilities ranging from 35 ms to 140 ms based on correlations to borehole data as reported to us during field acquisition (*Fig. 13*). This was initially interpreted (and later confirmed) as representing varying concentration levels on NAPL. Additionally after confirmation drilling, it was reported to us that ~10% of identified IP anomalies were associated with elevated concentrations of heavy metals in the groundwater versus NAPL levels greater than 150 ppb. Therefore, the anomaly range in IP anomalies may also represent the presence of heavy metals in addition to NAPL. Unfortunately with time domain IP alone, there is no definitive way to distinguish the two causes.

Figure 13 displays the line that was closest to one of the primary contaminant sources (TCE — trichloroethylene). The source area was identified as the data between 150 m (500 ft) and 180 m (600 ft) and displays the classic 'bell shaped' DNAPL dispersion image with depth.

6. Conclusions

In this discussion, four case histories have been presented illustrating the use of electrical imaging to characterize areas contaminated by non-aqueous phase liquids (NAPLs). Resistivity and Induced Polarization data can both be useful for this goal. Electrical images provide a means for efficiently identifying anomalous areas that are input for designing remediation or drilling plans. Additionally, site remediation progress can be tracked quantitatively if these data are recorded over time.

Acknowledgements

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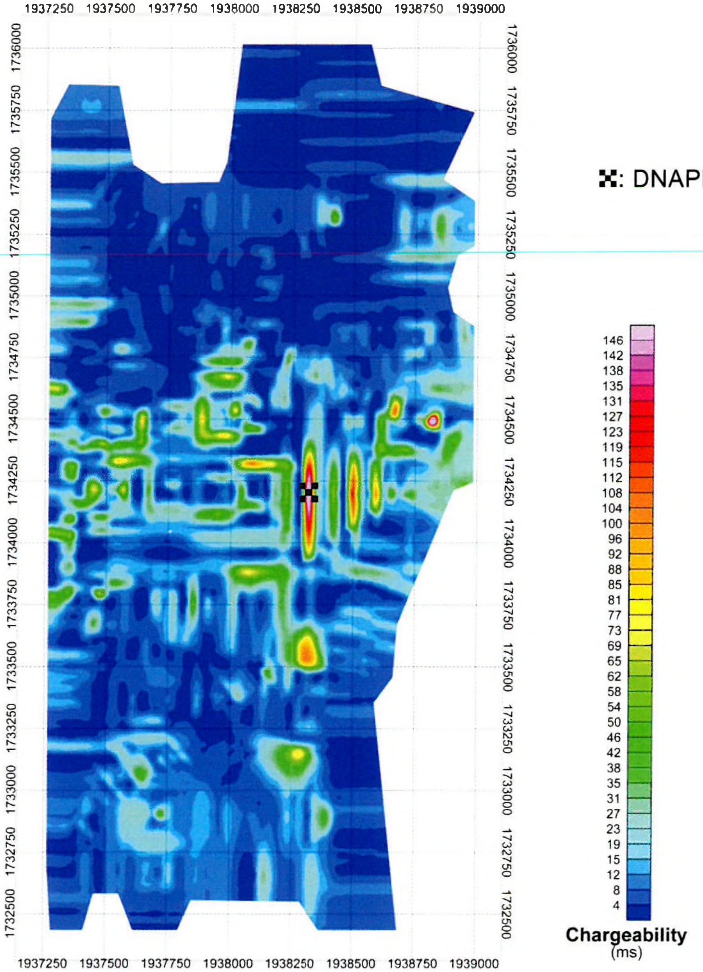

Fig. 10. Depth slice from ~10 m below surface of a 3-D induced polarization cube from a NAPL study at an aluminum plating facility in Alabama, USA. The majority of the site has very low chargeability highlighting that the source area of the contaminants was near the center and the primary movement from the source areas was vertical

10. ábra. Egy alabamai (USA) aluminiumgyártó üzem területén végzett NAPL vizsgálatból származó 3D gerjesztett polarizációs kocka mélységszelet kb. 10 m-rel a felszín alatt. A terület túlnyomó részén igen alacsony a tölthetőség, ami arra utal, hogy a szennyezés forrásterülete a központ közelében volt, és a forrástól a mozgás elsődleges iránya függőleges volt

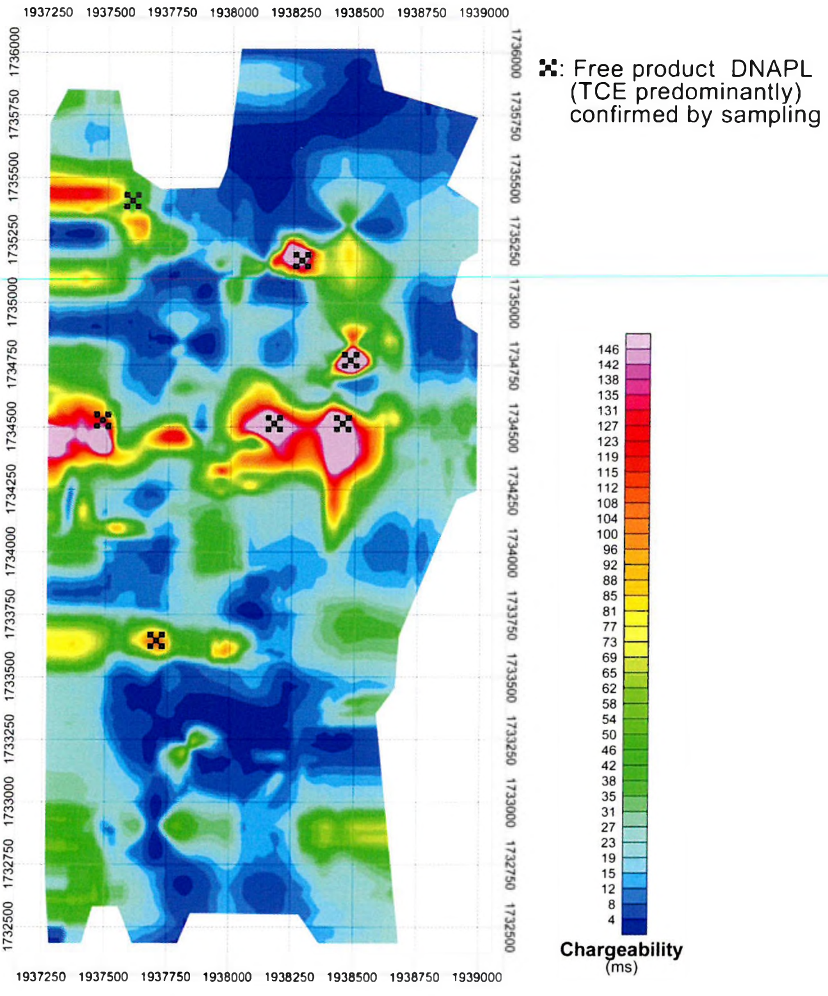

Fig. 11. Depth slice from ~25 m below surface of a 3-D induced polarization cube from a NAPL study at an aluminum plating facility in Alabama, USA. High chargeability reflects the presence of elevated DNAPL concentrations that are moving along the permeability pathways shown from the resistivity data. The wider distribution of IP anomalies also lead to the discovery of contaminants migrating to this site from neighboring chemical facilities

11. ábra. Egy alabamai (USA) aluminium gyártó üzem területén végzett NAPL vizsgálatból származó 3D gerjesztett polarizációs kocka mélységszelet kb. 25 m-rel a felszín alatt. Nagy tölthetőségi érték utal a megnövkedett DNAPL koncentráció jelenlétére, mely az ellenállás adatokból látható peremabilitási járatok mentén mozog. A GP anomáliák szélesebb eloszlása vezetett arra, hogy a szomszédos vegyi üzemekből eredő, erre a telepre migrálódó szennyeződést felfedezzék

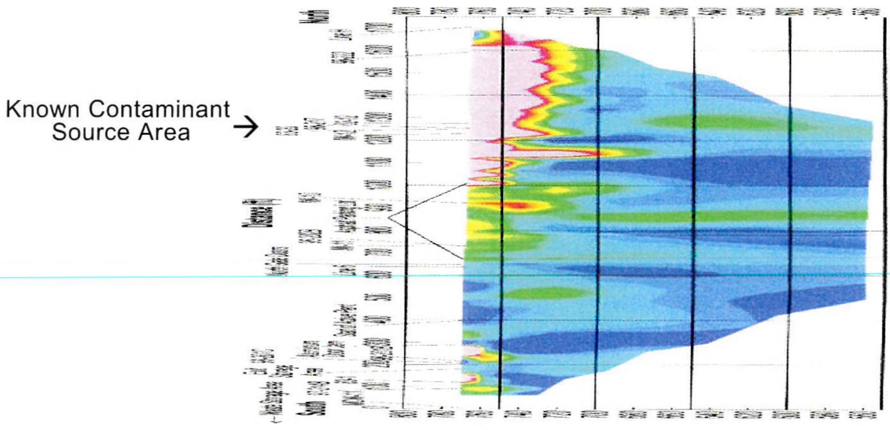

Fig. 12. Resistivity profile at a copper plating facility in Michigan, USA. Low resistivities map to high porosity/permeability zones below the water table and under the manufacturing facility. High resistivities represent the dry vadose zone outside the building. This profile is within 10 m of the known source area. No indication of the Trichloroethylene is detected uniquely in these data

12. ábra. Réz bevonatokat előállító üzem területének ellenállásszelvénye Michiganben, USA-ban. A kisellenállások tartoznak a nagy porozitás/permeabilitás zónákhoz a taljvízszint és a gyártósor alatt. A nagy ellenállások az épületen kívüli száraz vadózus zónát képviselik. Ez a szelvény az ismert forrás terület alatt 10 méteren belül van. Egyedül ezekben az adatokban nem észleltek triklóretilén nyomokat

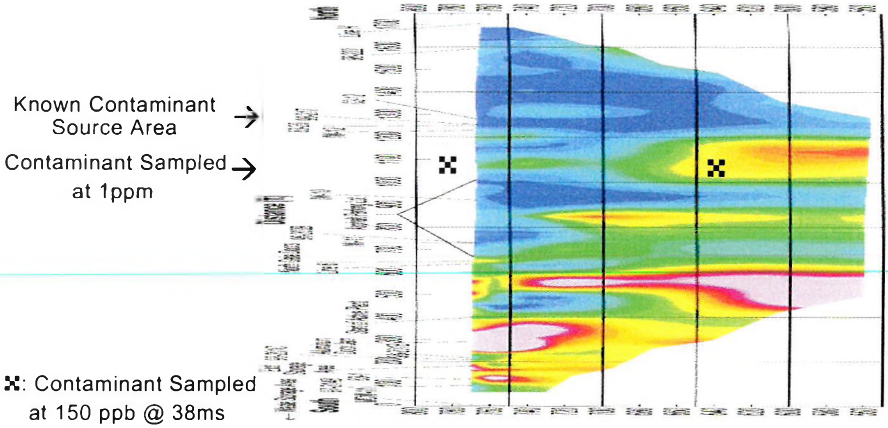

Fig. 13. Induced polarization profile at a copper plating facility in Michigan, USA. High chargeability anomalies represent elevated concentrations (~150 ppb or greater) of Trichloroethylene. The source area (between 500–600) displays a 'bell shaped' dispersion indicative of DNAPL moving to depth in saturated conditions

13. ábra. Gerjesztett polarizációs szelvény egy réz felületbevonó üzemnél Michigenben, USA-ban. Nagy tölthetőségi anomáliák jelentik a megnövekedett triklóretilén koncentrációt (~150 ppb vagy nagyobb). A forrásterület (500 és 600 között) egy "harang alakú" diszperziót mutat, ami vízzel telített térrészben a mélybe mozgó DNAPL-re utal

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Szennyezett területek leképezése elektromos módszerekkel

Bradley J. CARR, Markus LAGMANSON, Hasan AKTARAKCI

A szennyezett területeket egyenáramú ellenállás és indukált polarizációs mérésekkel lehet azonosítani és jellemezni. Négy esettanulmányon mutatjuk be a talajvíz áramlási útvonalának leírását és a szennyeződés térképezét.

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Contamination detection

Detection of hydrocarbon contamination with 3-D resistivity and IP method

Boriszláv NEDUCZA*

A consortium with three partners from different fields of environmental sciences (geophysics, hydrogeology, geotechnics) was formed for a three year long project to improve hydrogeophysical methods in order to detect and characterize special subsurface contaminants. Four different contaminated sites were chosen in Hungary as study areas to improve and calibrate special geophysical methods to provide remediation experts and hydrogeologists with necessary information for reliable transport modelling. A strong collaboration between the geophysicists and hydrogeologists evolved protocols and techniques to carry out successful site assessment and remediation schemes of contaminated lands.

This study presents the geophysical results on one of these test sites containing creosote contamination. High resolution 3-D geoelectrical measurements were applied in order to give reliable information for site diagnostics.

Keywords: remediation, geoelectrics, transport modelling

1. Introduction

Since all geological structures are 3-D in nature, a full 3-D resistivity survey using a 3-D interpretation model should give the most accurate results. At the present time 3-D data acquisition and inversion techniques for DC resistivity and IP surveys have experienced a rapid development over the past years. However it has not reached the level where, like 2-D surveys, it is routinely used. The main reason is that the survey cost is comparatively higher for a 3-D survey. There are two current developments that should make 3-D surveys a more cost-effective option in the near future. One is the development of multi-channel resistivity meters that enables more than one reading to be taken at a single time. This is important to reduce the survey time. The second development is faster microcompu-

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ters to enable the inversion of very large data sets to be completed within a reasonable time.

2. Background and site description

The field experiment was carried out at a former site of the Hungarian Railway Company. Watertight of poles and ties was carried out by creosote on this site until 1985. Coal tar creosote is a thick, oily liquid typically amber to black in colour. Virtually all wooden railroad ties and telephone poles in use are treated with creosote to retard rotting. Long-term exposure to low levels of creosote, especially direct contact with the skin during wood treatment or manufacture of coal tar creosote-treated products has resulted in skin cancer and cancer of the scrotum.

The location is illustrated in *Fig. 1.* There are many buildings and pavements, which complicates the survey planning and spreading. An eight-channel AGI SuperSting R8 resistivity and IP instrument was used for data collection. This equipment produced a relatively fast data acquisition. Command files were generated for 24 hours periods, and were uploaded to the control unit every morning. 252 electrodes were set to the surface and electrode strings were located into two boreholes (*Fig. 2*). More than 45 000 measurements were carried out during four days in a wide spread of electrode configuration (bipole–bipole, radial dipole–dipole, gradient) and location (surface–surface, borehole–surface and borehole–borehole).

3. Data processing and inversion

Due to the common data acquisition of resistivity and chargeability data with the same electrode configuration a special data filter was used to improve the signal/noise ratio. Generally, upper and lower limits of resistivity and chargeability data can be determined for all measurements. However, in this case a crossplot of the apparent resistivity and IP data was used to check data quality. *Figure 3* shows this crossplot of the raw measured dataset in log–log scale. The aggregations of measurement points are emphasized with a thick broken line. Reject data outside this area improved the first iteration of inversion.

Fig. 1. Location of the contaminated site
1. ábra. A mérési helyszín

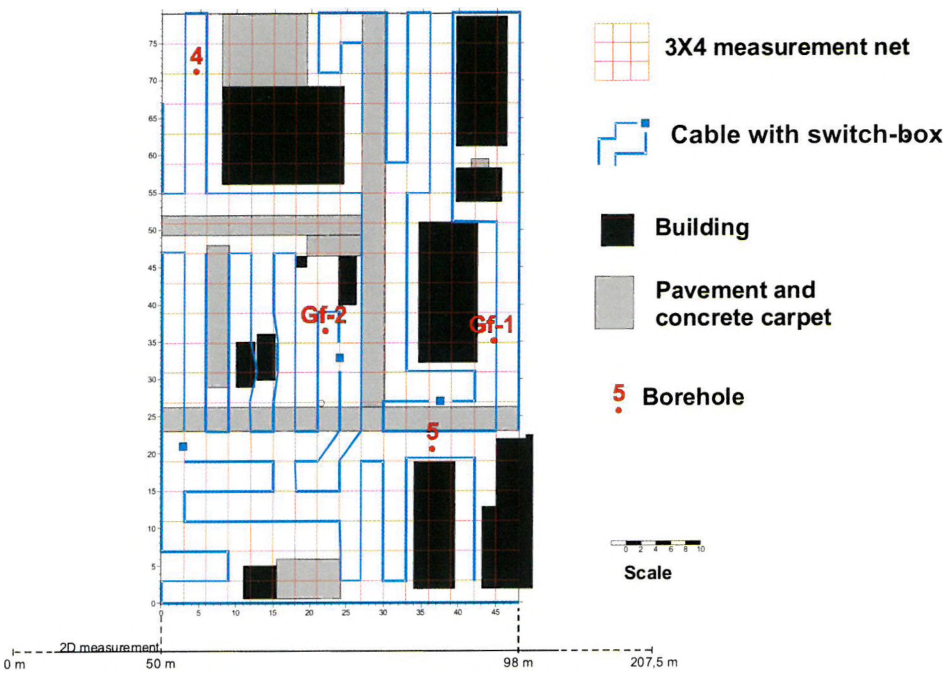

Fig. 2. 3-D spread of the electrodes on the site

2. ábra. A 3D mérés terítési vázlata

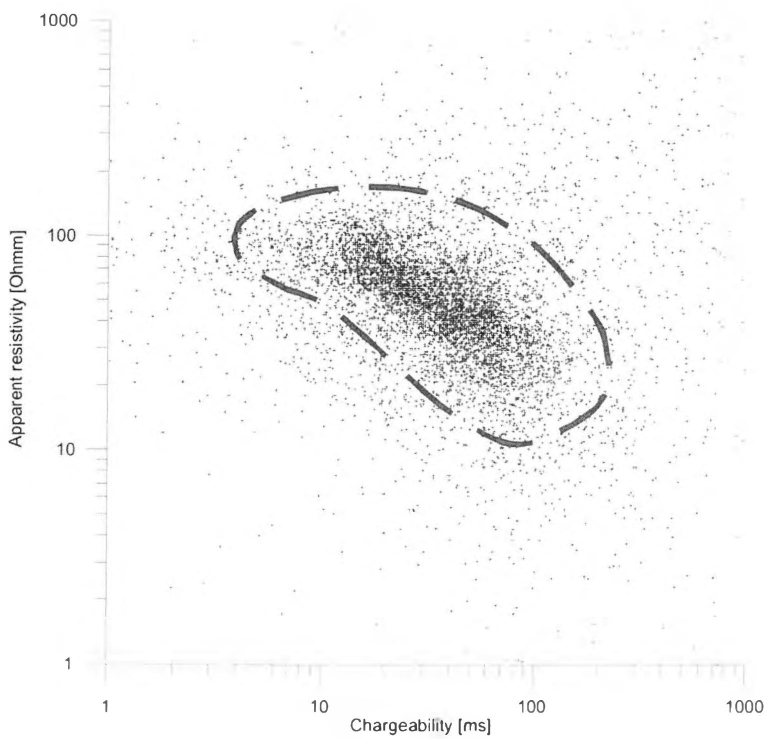

Fig. 3. Crossplot of the corresponding apparent resistivity and chargeability data in log–log scale

3. ábra. Az összetartozó ellenállás és tölthetőség adatok keresztdiagramja log–log léptékben

Common inversion of resistivity and IP data were carried out with the Res3-DInv software [LOKE 1996–2004].

4. Discussion and conclusions

The measurement mapped two separated contamination plums. The contamination has lower resistivity and higher chargeability compared to the surrounding mainly sandy aquifer. *Figure 4* illustrates the smaller plum with vertical slices in the approximate direction of groundwater flow. The direction of groundwater flow is south–north and the level is signed on the sections with a white continuous line.

The corresponding slices show similar events, but the chargeability result has a more realistic result. Characteristic layer boundary can be seen at the depth of three meters. This layer mobilized the contamination to south, while the groundwater elongated it to north direction. The creosote used for watertight of wooden utilities is stored above this plum. This fact explains this structure. Results are checked by analysis of borehole samples.

Acknowledgement

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Szénhidrogén szennyeződés kimutatása 3D ellenállás és gerjesztett polarizációs (GP) módszerrel

NEDUCZA Boriszláv

Uniós pályázat keretében fejlesztéseket végeztünk különböző típusú szennyeződések kimutatására. Ennek keretében 3D geoelektromos méréseket végeztünk kőszénkátránnyal szennyezett területen. A kőszénkátránynak igen magas (> 50%) poliaromás szénhidrogén tartalma van, mely erősen karcinogén hatású. A területen 252 darab elektródát helyeztünk el. A mérések több napon keresztül történtek és az adatok feldolgozása is több hetet vett igénybe.

A cikk tartalmaz egy ellenállás/tölthetőség diagramot, mely az összetartozó nyers mérési adatokat mutatja log–log léptékben. Az inverzió után kapott ellenállás képen is látható a szennyeződés térbeli helyzete, azonban a GP módszer sokkal karakteresebb, és a háttéradatokkal is egybevágó adatokat szolgáltatott. A kapott eredményábrákon látszik az a réteghatár, mely horizontálisan mobilizálta a szennyeződést, látszik annak útvonala a talajvízszintig, és kimutatható, hogy a talajvíz mekkora mértékben mobilizálta azt.

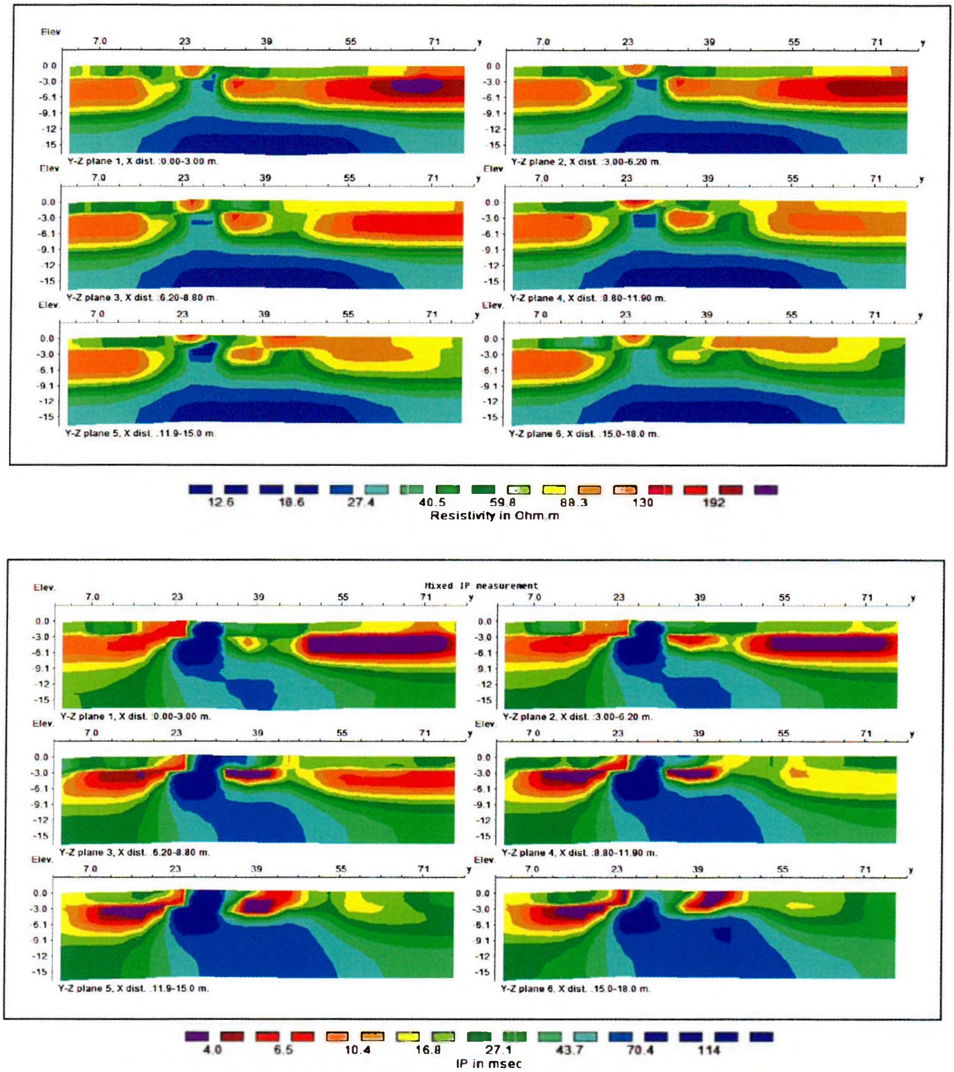

Fig. 4. Inverted resistivity and chargeability slices of the plum

4. ábra. Az inverzióval kapott fajlagos ellenállás és tölthetőség szelvények a csóva vonalában

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Palaeomagnetic studies

Tertiary rotations in the Carpatho–Pannonian region related to Western Carpathian subduction and to the rotation of the Adriatic microplate

Emő MÁRTON*

As Cenozoic palaeomagnetic results indicate, the Palaeogene was quiet from the viewpoint of tectonic rotations affecting the tectonic units which presently occupy the Carpatho–Pannonian region. Rotations started soon after the rate of rapprochement of the African and European lithospheric plates suddenly decreased, at about 20 Ma. In the ALCAPA megatectonic unit four phases of Neogene rotations are recognised. None of these rotations affected the whole ALCAPA and only the older ones can be connected to escape tectonics and subduction. These occurred in the time intervals of 18.5–17.5 Ma, 16–14.5 Ma and around 12 Ma, respectively. The first two signifies the escape from the Alpine domain and subductions in the Western Carpathians, while the third one, the subduction in the NE segment of the Carpathians. The youngest rotation is less tightly constrained than the previous three. However, it was most likely induced by the latest Miocene counter-clockwise rotation of the Adriatic microplate and the thus the time estimated is around 5 Ma.

Concerning the Tisza–Dacia megatectonic unit the palaeomagnetic results from the SW part of the Pannonian Basin contradict the existence of a microplate during the Neogene. It seems that the earlier postulated clockwise rotation is applicable to the eastern part only [see abstract by C. PANAIOTU, this volume], while in the western part both clockwise and counter-clockwise rotation occurred. The latter can be also explained as having been induced by the movement of the Adriatic microplate.

Keywords: palaeomagnetism, tectonics

Összefüggések a Kárpát-Pannon régió tercier rotációja és a Nyugati Kárpátok szubdukciója valamint az Adriai mikorlemez rotációja között

MÁRTON Emő

Amint azt a kainozoós paleomágneses eredmények jelzik, a paleogén a Kárpát–Pannon régiót jelenleg elfoglaló tektonikai egységeket befolyásoló tektonikus rotációk szempontjából nyugodt

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volt. A rotációk nem sokkal azután kezdődtek, amikor az afrikai és európai litoszféra lemezek közeledésének sebessége hirtelen lecsökkent, kb. 20 Ma évvel ezelőtt. Az ALCAPA megatektonikai egységben a neogén rotációk négy fázisát lehet felismerni. Ezen rotációk egyike sem érintette a teljes ALCAPA-t és csak az idősebbek lehettek kapcsolatban a kiszökéssel és a szubdukcióval. Ezek a 18,5 – 17,5, 16,5-14,5 és kb 12 millió éves időintervallumokban jelentkeztek. Az első kettő az Alpi doménből való kiszakadást és a Nyugati Kárpátokban való szubdukciót jelzi, míg a harmadik a Kárpátok ÉK-i szegmensének szubdukcióját. A negyedik, legfiatalabb rotáció kevésbé pontosan határozható meg, mint az első három. Azonban, nagyon valószínű, hogy az Adriai mikrolemez óramutató járásával ellentétes irányú késő miocén korú rotációja váltotta ki, és így a becsült időpont kb. 5 milllió év.

A Tisza–Dácia megatektonikai egység tekintetében a Pannon medence DNy-i részéből származó paleomágneses eredmények ellentmondanak a neogénbeli mikrolemez létezésének. Úgy tűnik, hogy a korábban feltételezett óramutató járásával egyező rotáció csak a keleti részre alkalmazható [lásd PANAIOTU, ebben a kötetben], míg a nyugati részen mindkét forgásirányú rotáció megjelent. Utóbbit az adriai mikrolemez mozgása következményeként is magyarázhatjuk.

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Palaeomagnetic studies

Palaeomagnetic constrains for the Tertiary evolution of the Romanian Carpathians

Cristian PANAIOTU*

Palaeomagnetic results from the Romanian Carpathians and Transylvanian basin obtained mainly in the last 20 years has imposed significant constrains for geodynamical models of the Carpatho–Pannonian area. These tectonic implications of palaeomagnetic data are a consequence of the basic hypothesis of palaeomagnetism that the geomagnetic field was, on average, that of an axial and geocentric dipole. If this hypothesis is fulfilled, the palaeomagnetist can interpret his results in terms of palaeolatitude of the sampling site and its location with respect to the palaeomeridians. When palaeomagnetic directions from a possibly displaced or rotated block are compared with those from a neighbouring block, the declination difference between an expected or reference direction and an observed direction indicate the amount of vertical axis rotations, whereas the palaeolatitude difference indicates north-south displacement.

Main palaeomagnetic studies [PANAIOTU 1998 and references therein; ROȘU et al. 2004; PANAIOTU et al. 2004; DUPONT-NIVET et al. 2005] are coming from the following areas:

1) Miocene volcanism from the Apuseni Mountains;
2) Miocene to Quaternary volcanism from the Eastern Carpathians;
3) Miocene sediments from the Carpathian foredeep;
4) Paleogene sediments from the Transylvanian basin;
5) Upper Cretaceous magmatic rocks from the Apuseni Mountains and the Southern Carpathians.

All these studies point to the following conclusions:

— During the Tertiary northward drift of the area, only 20° of clockwise rotation took place between Eocene and Middle Miocene and there is no

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rotation between Maastrichtian and Eocene. The northward drift was ended before the next phase of rotations.

—The main phase of rotations started after 15 Ma. The results from the Miocene volcanic rocks from the Apuseni Mountains show a continuous clockwise rotation of about 70° between 15 Ma and 11 Ma. Simultaneous differential rotations took place in the northern part of the East Carpathians (~20° contraclockwise rotation) and the external part of the Southern Carpathians (~ 30° clockwise rotation).

—After 11 Ma, the area affected by rotations was reduced to the external part of the bending area of the Eastern Carpathians (post 4 Ma rotations) and the Apuseni Mountains. The amplitude of this final counterclockwise rotation of the Apuseni Mountains is around 15° with respect to 10–11 Ma volcanism from the Eastern Carpathians which show no rotation with respect to stable Europe.

Keywords: geodynamics, tectonics, models, Carpathians, Pannonia, rotation

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A romániai Kárpátok tercierkori fejlődéstörténetének paleomágneses eredményei

Cristian PANAIOTU

Az utóbbi 20 évben végzett paleomágneses kutatások jelentősen megváltoztatták a Kárpát–Pannon terület geodinamikai modelljét. A cikk a legfontosabb eredményeket foglalja össze.

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Geophysical database services

A general overview of geophysical database* managed in ELGI

László VÉRTESY**

The article presents the results of longtime geophysical data management in ELGI. It describes the requirements, responsibilities, and outlines the related activities. ELGI is making serious efforts by establishing national repositories to improve the publicity of state owned geophysical data systems. One of the main cornerstones of a net based data service is the metadata system that is being developed in cooperation with international institutions within the framework of the GEOMIND and KINGA projects. In the title and later the term of database is used in a broader sense, meaning relational databases and digital data repositories.

Keywords: data management GEOMIND, KINGA, data service

1. Tasks of ELGI

As a state financed institute the Eötvös Loránd Geophysical Institute of Hungary (ELGI) takes part in solutions of geophysical, geology-related tasks of the state. According to the foundation letter of the institute, ELGI has a list of tasks which concern the whole country and hardly can be fulfilled without well managed databases. The institute not only uses the data but also takes part in the managing of geophysical–geological information service. The responsibility of this task belongs to the Hungarian Office for Mining and Geology (MBFH). ELGI by its experiences, technical and knowledge background can be responsible for geophysical databases.

Although the range of activities of the Institute is wide, managing data systems is one of the most important among them.

The databases are used for:

* The terms of databases in the title and later should mean systems of digital format geophysical data

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—mapping the geology of the country,
—providing information through data processing,
—basic research,
—to ensure the availability of data for the society.

2. Works in ELGI

Main activities:

—Collecting geophysical data (existing archive, and new measurements)
—Quality control
—Data conversion; digitisation, transformation, unification of formats
—Providing metadata
—Harmonising the data systems (content, structure). Fulfil the requirement of standardisation (see below ISO compliant development)
—Publishing metadata, header data, detailed (measured) data, derived information
—Physical and legal safety.

To fulfil these requirements experienced staff is needed. In ELGI about 20–25 people work on these tasks.

These traditional databases (*Table I*) are most wanted by geophysicists and geologists. Although the table doesn't contain all existing geophysical data, it demonstrates the wide variety of datasets and the order of magnitude of data quantity.

Beyond the above listed databases other datasets are under development from the network measurements like gravity, magnetic and radiometry, observatory data.

The international practice tells us, that the most frequent request is for seismics, geoelectrics and gravity data (*Fig. 1*). A most recent international survey made by the GEOMIND Consortium for user needs, based on 63 interviewees from private and public companies and organizations of 9 countries, has confirmed that [BUCCELLATO, LOCATELLI 2007]. The practice of ELGI shows that the growing demand for seismics can be related to increasing energy prices, and Hungarian geological background. The reason of negligible demand for geoelectric and electromagnetic data compared to international practice is due to the low publicity of these data sets.

Data	Quantity	Content
Gravity	387 617	Gravity field data (points)
Magnetics	128 085	Ground magnetic *DZ* (76812), *DT* (51970) data (points)
Tellurics (TE)	16 509	Survey points
Magnetotellurics (MT)	2 059	Sounding data
Airborne Radiometrics	16	K, eU, eTh, U grid
	18	K, eU, eTh, U shape
Airborne Geophysics	3 975 435	Interpolated DT data
	41 231	EM, DT, K, cU, cTh, TC
	9	Location (polygon)
Geoelectrics–Electromagnetics	40 356	VES soundings
	5 186	TEM soundings
Seismics	639	Location and processed profile
	231	Profile
	1 035	File
Litospheric Data	297	Seismic profile data
	164	RMS velocity data (number of profiles)
Well-logging	891	Well-logging dataset (digital) / (number of boreholes)
	8 479	Well-logging data (analogue) / (number of boreholes)
Engineering Geophysical Data	539	Cone Penetration Test complete dataset (digital form)
	1 144	Cone Penetration Test location data (digital)
Geothermics	4 666	Temperature and heat flow data from boreholes (MBFH/MGSZ)
	605	Temperature and heat flow data from boreholes (barren HC-boreholes)
Radiometrics	363	Spectrum

Table I. Official databases of ELGI [KISS et al. 2007]
I. táblázat. Az ELGI hivatalos adatbázisai [KISS et al. 2007]

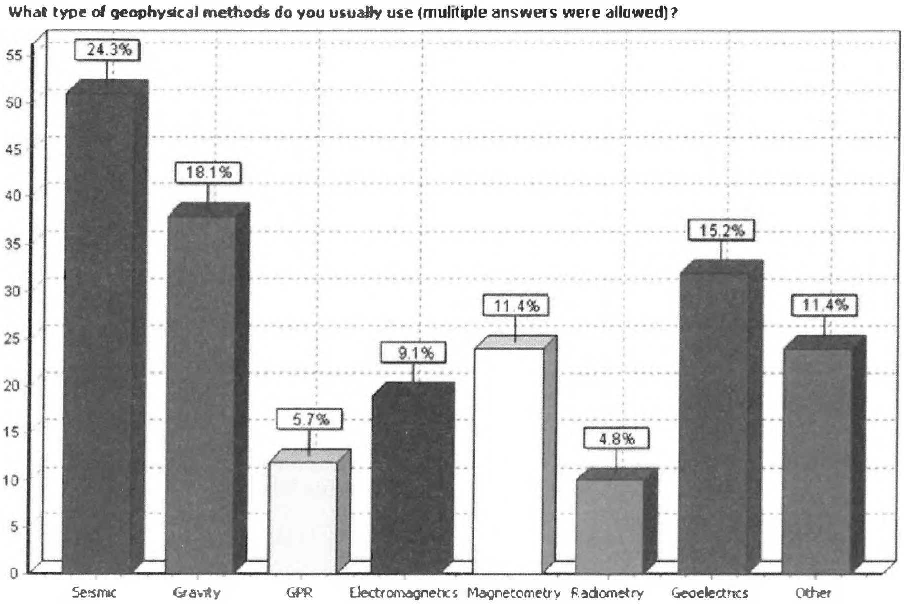

Fig. 1. The users' needs by methods [BUCCELLATO, LOCATELLI 2007]
1. ábra. A felhasználók igényei módszerek szerint [BUCCELLATO, LOCATELLI 2007]

The spatial coverage of data is highly method specific (*Fig. 2*). Seismic lines are mainly concentrated in deep basins, in the area of hydrocarbon prospecting. Most of the shallow geoelectric surveys are concentrated in western Hungary for historical reason. The gravity and magnetic basic datasets cover the country in a more or less even grid.

2.1. Data collecting

According to the mining regulations all geological data derived from geological exploration must be reported to the authority. So the regulation creates the legal basis that the once archived data won't be lost, they will be collected.

It is highly desired that the new survey data, coming from industry or contractor companies would be built in, into a uniform national data system. The growing demand for natural values, like ores, fresh water, energy sources generates the increase of geophysical data quantity as well. It means that we can expect an increasing quantity of new data.

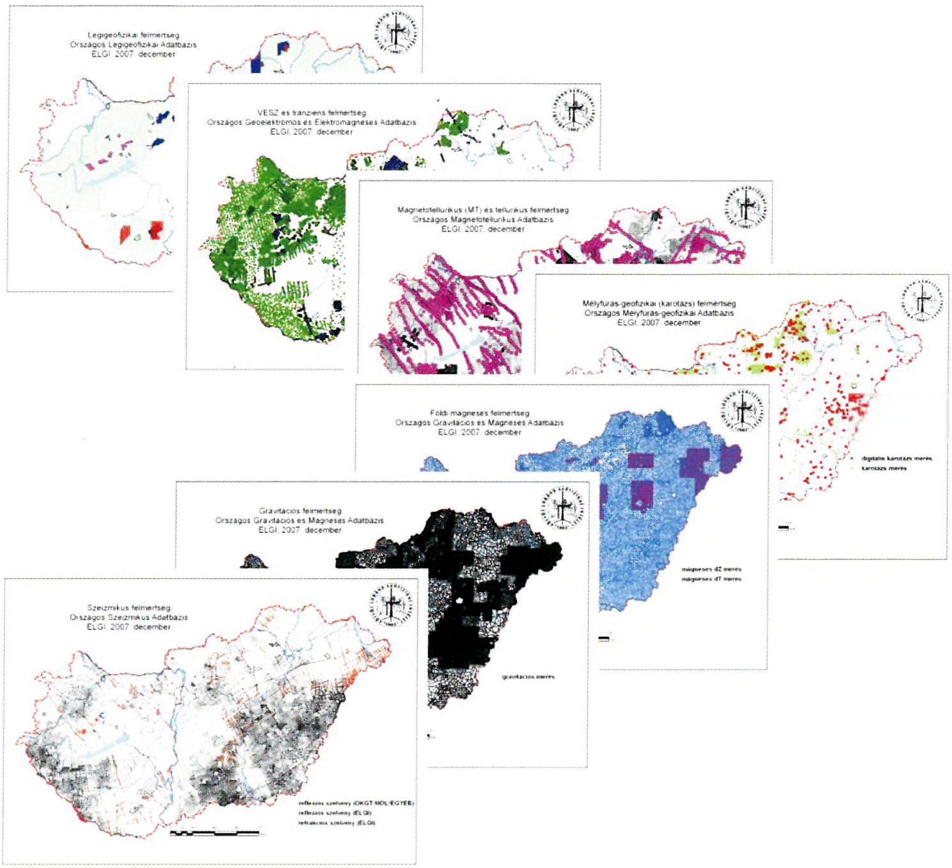

Fig. 2. Completeness of digital geophysical datasets handled in ELGI

2. ábra. Az ELGI kezelésében lévő digitális geofizikai adatbázisok készenléti fokai

2.2 Quality control

Quality control of the data systems ensure that products or services meet customer requirements. On the gravity database a general quality control process has been performed. As a result outliers, duplicated points have been filtered out and the completeness was also checked. In the case of other databases, similar and methodspecific quality controll has to be done in the future.

2.3. Data conversion

In the last 10 years a series of databases were converted into digital format. This was a basic concept. The analogue format is not acceptable in most cases. Present data availability is the result of more than 10 year's work. Source data arrive from different companies and institutions. Files are archived on different media, spreadsheets or maps. To build databases digitisation is needed. This really time and manpower consuming activity was done for magnetics, gravity, airborne geophysics, tellurics. In other cases like geoelectrics, it is soon coming to an end. In some cases the work has only been started. Even the digitally available borehole data needs conversion, to have a digital dataset ready for quality control and database manipulations.

The estimations below show the completeness of conversion of datasets owned or handled by ELGI. Different data types means different ratio of digitised data (*Table II.*).

Method	**Completeness [%]**
Vertical Electric Sounding (VES)	90
Magnetotelluric Sounding (MT)	90
Gravity	99
Airborne geophysics	90
Seismics	under processing

Table II. Completeness of digital geophysical datasets handled in ELGI
II. táblázat. Az ELGI által kezelt digitális geofizikai adatbázisok készenléti foka

2.4. Providing metadata

Getting information on data in a very short time in the epoch of internet and search engines is an obvious demand. The net technology in the 21st century (see Google) has raised the level of information distribution fairly high. The volume of available or potentially available digital content is enormous. Answers to questions, like *What? Where?* and *What for?* are essential. To give more information on data sets we had to increase dramatically the amount of descriptive information, improve the so called metadata system.

We are in the implementation phase. These are in the focus of ELGI activity on database management. ELGI spent more 150 man-month work load for that and the next task. The results can be followed on the website: http://www.kingaelgi.hu.

2.5. Harmonising the data systems (on national and international level)

The right solution of metadata improvement was to do it by following international standards. At the moment organisations from 7 countries are working on the installation of the common metadata concept that should be ISO conform. The transparency and the flexibility is an elementary interest of geology related part of the society. Beside professional point of view, to make the possibility of the free (crossborder) information stream is a political issue as well. Several EU directives deal with the topics, like Aarhaus Convention 1998 to make environmental information available to the public (Implemented into Hungarian legalization by Act LXXXI. of 2001) and INSPIRE Directive (Directive of EC establishing an Infrastructure for Spatial Information in the European Community). The GEOMIND EC supported project was launched to realize these goals. It is a part of e*Content*plus program of 6th Framework Programme of the European Union with a start date of Sept 2006 and end date of Sept 2008.

On the website of the project (*Fig. 3*) more information is available.

2.6. Publishing metadata, header data, detailed (measured) data

Perhaps this is the most visible task of ELGI's activity related to database management. Through this task ELGI takes part in solving national and EU legalisation derived tasks of the state.

Fig. 3. Front page of the working portal of GEOMIND project, www.GEOMIND.eu

3. ábra. A www.GEOMIND.eu, GEOMIND projekt munkahonlapjának nyitóoldala

Main results are:

Published geophysical maps. The Bouguer Anomaly Map, Magnetic ΔZ Anomaly map, Telluric Conductance maps in scale of 1:500 000 are available in the library of ELGI and on the we website as well:

http://www.elgi.hu/newwww/index.php?akt_menu=513.

Constructing maps in scale 1:100 000 of 10 parameters by map sheets is an ongoing project. The project named KINGA is supported by GVOP 4.2.2 programme. Up to now 126 maps have been constructed. The maps are available on the server of ELGI.

To give information on *location of geophysical* data is the most important task. At the moment location information is available on website of ELGI in similar format to Fig. 3. The location data are not complete. It contains only data sets created between 1993–2007:

http://www.elgi.hu/newwww/index.php?akt_menu=345.

Interactive sarching is possible on http://www.kingaelgi.hu.

Data providing service for the request of Hungarian Office for Mining and Geology (MBFH) is an every day task. Most of the data handled by ELGI is freely accessible to the public. The request should be addressed to MBFH (www.mbfh.hu).

2.8. Physical and legal safety

The intact condition of digital databases is warranted by a regulated archiving system. All data files are archived to CD media, twice a year. For temporal backup in most cases streamers and raid0 mirror data storage systems are used. The use of data is strictly regulated.

There are nominated responsible administrators. All data movement is registered by the administrators. These processes ensure the authenticity of data service.

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Geofizikai adatbázisok az ELGI-ben

VÉRTESY László

A cikk bemutatja az ELGI geofizikai adatrendszerek menedzselése területén végzett hosszú távú tevékenységét, az állami adatszolgáltatással kapcsolatos kötelezettségeit, a felhasználói elvárásokat. Az intézet komoly erőfeszítéseket tesz az állami adatok nyilvános elérhetőségének javítása érdekében. Az internetes adatszolgáltatás egyik fontos pillére a metaadat rendszer, melynek fejlesztése nemzetközi együttműködésben, a GEOMIND és KINGA projektek keretében történik. A címben használt adatbázis kifejezés a szó tágabb jelentésében értendő, amely a relációs adatbázisokat és egyéb digitális adatrendszereket is magába foglalja.

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Geophysical database services

Recent developments in database management and standardisation in the GEOMIND project

László SŐRÉS*, Mikael PEDERSEN**, Valdas RAPŠEVIČIUS***, Klaus KÜHNE****, Jörg KUDER****

With the financial support of the European Community *e*Content*plus* program the GEOMIND project established two pioneer international standards for geophysical information: the GEOMIND Profile, an extension of the ISO 19115 metadata standard for geographic information, and the General Geophysical Data Model (GGDM) for geophysical measurement and interpretation data. The article summarizes the role of these two models in the GEOMIND information system, and explains the benefits of using a general approach and schema based XML languages in geophysical data exchange.

Keywords: ISO-19115 metadata, XML, geophysical standards, data model

1. Introduction

In 2007 with the financial support of the European Community *e*Content*plus* program an international project was started with the intention of building a web portal providing information on the geophysical data resources of seven European countries. The GEOMIND (Geophysical Multilingual Internet-Driven Information Service) project is believed to be a new milestone in geophysical data standardization and integration.

The two cornerstones of data integration in the GEOMIND project are the ISO 19115 Metadata Standard and the General Geophysical Data Model (GGDM). Recent developments are implementing the GEOMIND

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Metadata Profile that is the geophysical extension of ISO 19115, and a new XML based geophysical markup language. The results will be extensively used for data exchange within the GEOMIND system.

2. GEOMIND Metadata Profile

The ISO 19115 is an international metadata standard developed for geographic datasets, accepted and supported by the W3C and the OGIS consortium. It is widely used in Geographic Information Systems (GIS), especially in internet data search applications. The standard is very deep and sophisticated, allowing very detailed description of spatial datasets.

In general, metadata answer questions of what, who, when, where, why, how etc. Typical questions, and metadata answers:

What	citation/title
Who	metadata contact, point of contact, citation/responsible party
When	metadata date stamp, citation/dates, time extent
Where	geographic code, geographic description, bounding box, bounding polygon
Why	abstract
How	data quality/lineage
From whom	distributor
How to get	distribution options
How much	distribution options/fees

To be able to use it for geophysical datasets the core of the original standard was extended by a new geophysical section. It is used to describe instrumentation and measuring conditions. New codelists and ISO codelist elements were added to the standard. The extended set of metadata elements is called the GEOMIND Metadata Profile. The Profile defines three main element types that are sub-classed from the ISO MD_Metadata element. Using these three element types and their relationships most complicated data and documentation systems can be described on metadata level.

3. GE Geophysical Object

Geophysical object is a collective term for a set of geophysical data that is used as a natural unit. It is a matter of convention what is considered to be a geophysical object. In the GEOMIND profile one gravity station, one DC sounding, a set of geophysical logs in the same borehole, or a seismic line is a geophysical object. Geophysical models (results of modelling or inversion) also belong to this category.

4. GE Geophysical Object Set

A Geophysical Object Set is a collection of geophysical objects, grouped by some common properties, or constraints. There are several types of object sets. Projects, campaigns, or data repositories are typical examples of Geophysical Object Sets. Object sets may be aggregated to form higher level object sets.

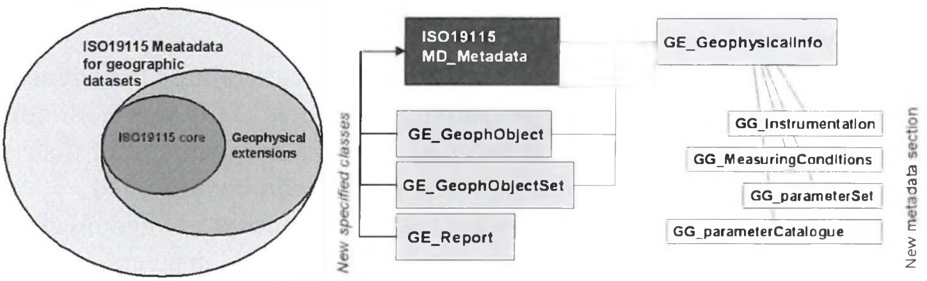

Fig. 1. Left: The ISO 19115, and the GEOMIND Metadata Profile with the core, and the geophysical extensions. *Right*: The three main GEOMIND metadata classes.
1. ábra. Baloldal: Az ISO 19115 és a GEOMIND metaadat profil magja a geofizikai kiterjesztésekkel. *Jobboldal*: a három fő metaadat osztály

5. GE Report

Report is a collective term for any kind of documentation. It can be text, map, profile, image, printed or digital document. Reports may be aggregated to form complex documentation.

Reports, geophysical objects and object sets are related to each other. Defining and storing those relationships in the metadata records makes it possible to handle a large geophysical data system as one well structured.

The technical specification of the ISO 19115 is defined by the ISO 19139 XSD schema package. The GEOMIND standard follows the standard by including the original schema definitions and by defining the extensions in ISO style schema definitions. Extended and added codelists are documented in ISO compliant XML resources.

6. General Geophysical Data Model (GGDM)

Detailed data exchange within the GEOMIND system will be possible in two ways: in well known international data formats and in GEOMIND format. Major industry standards, like SEG and LAS will be accepted by GEOMIND. At the same time GEOMIND will provide standard format for selected geophysical methods. Initially the number of supported methods will be five (gravity, magnetometry, VES, TDEM, airborne measurements) and it will be increased later. The GEOMIND format is based on the General Geophysical Data Model.

The aim of a uniform geophysical data model is to eliminate unnecessary structural diversity in the geophysical data sets. This way common data management tools can be developed, and the transparency of distributed national systems and local data repositories can be improved.

The main idea of GGDM is to get rid of the concept of 'geophysical methods'. The model handles geophysical measurements in a very general way: a measurement is a set of data collected in different measuring layouts using different layout components (sensors and sources). The geometry (size, position, orientation) of layout components can be strictly defined and linked to items in instrument catalogues. Measured data is stored as parameter sets (groups of key-value pairs) and one, or multi-dimensional data arrays. Description of (one and) multi-dimensional data is similar to GML point coverages. It is defined by domain sets and range sets. Domain sets define the reference points in the multidimensional parameter space (abscissa) and range sets define the measured data values (ordinate). Domain sets may be regular, or irregular sequences, and may represent any physical property (space, time, frequency etc). Measurement geometry is defined in a local coordinate reference system that is described by the local CRS entity. The measuring point reference location (origin) can be either in Cartesian or spheric coordinate system. Any number of CARS can be used. Elevation may also be defined in more than one vertical datum.

Figure 2 gives an overview of the measurement data structure. Multiple boxes mean unlimited number of nested structures.

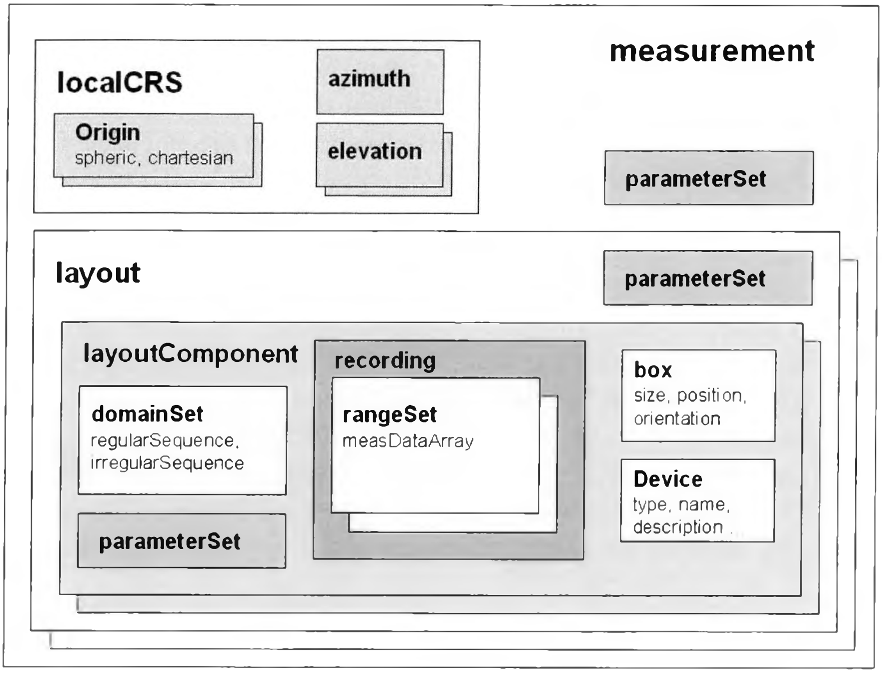

Fig. 2. Measurement in the GGDM data model

2. ábra. Mérés a GGDM adatmodellben

The use of parameters is strictly controlled in GEOMIND. Parameters are referenced by a code that identifies a type definition record in the parameter catalogue. Name, unit of measure, data type, description of the parameter can be found there. Parameter catalogues must be cited in the corresponding metadata records.

7. GEOMIND Portal and the Metadata Editor

The GEOMIND portal was launched on the 1st of September 2008. It is a server application, and a flexible, multilingual user interface with several search facilities. Searches are carried out against the central database. The server application automatically collects metadata from the distributed metadata repositories by CS-W harvesting. Metadata are edited and validated locally using the Metadata Editor application, or created by 3rd party metadata tools, and uploaded to the central portal manually.

Data transfer is taking place in the form of XML files. Data integrity is ensured by XSD schema validation. During data upload XML-s are parsed and disassembled to nodes. Nodes are identified by checking against the schema and together with their parent–child relations stored in the database. The schema—the meta-model—is also stored in the database. During downloading nodes are collected and assembled to XML text for http transfer.

The GEOMIND Metadata Editor (MDEditor) is a powerful java application to edit schema-based XML documents (*Fig. 3*). The user interface is generated from the meta-model that ensures great functional generality. Apart from manual editing the MDEditor has multi format import/export functionality, and a built in mechanism to generate metadata from external JDBC data resources. To use this upload-profile must be set up by defining a sequence of SQL queries. By executing the upload-profile metadata records are assembled from the external resources, validated and stored automatically in the local database. MDEditor also has publishing functionality.

8. Summary

With the common effort of 12 European organizations the GEOMIND project will set up a multilingual web portal to integrate metadata resources about geophysical datasets in the participating countries. To overcome the problem of data source in homogeneity XML based metadata and detailed data standards were developed. The GEOMIND Metadata Profile extends the existing ISO 19115 standard for geographic datasets. The GGDM data model establishes a new geophysical markup language that will be used within the GEOMIND system. The portal application will provide a convenient interface and efficient search facilities to find geophysical datasets. The metadata editor makes it easier for data providers to share their valuable data with the public.

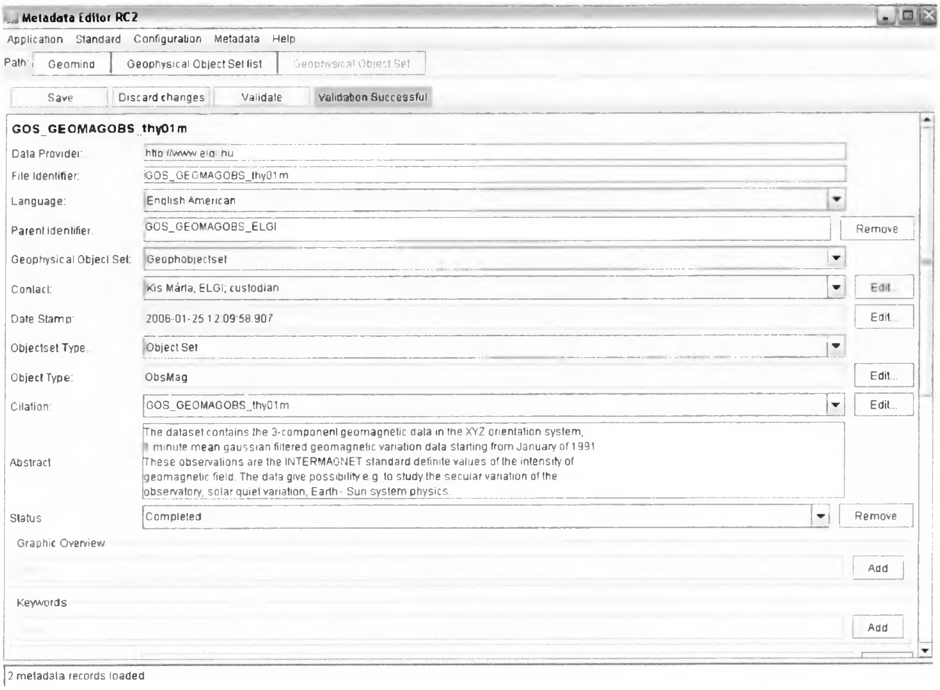

Fig. 3. The MDEditor application

3. ábra. Az MDEditor metaadat szerkesztő program

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Az adatbázis kezelés és szabványosítás legújabb eredményei a GEOMIND projekt tükrében

SŐRÉS László, Mikael PEDERSEN, Valdas RAPŠEVIČIUS, Klaus KÜHNE, Jörg KUDER

Az Európai Közösség *e*Content*plus* programjának támogatásával a GEOMIND projekt két úttörő jellegű nemzetközi geofizikai szabvány alapjait rakta le. Egyik a GEOMIND profil, a földrajzi adatokra vonatkozó ISO 19115 metaadatszabvány geofizikai kiterjesztése, másik a geofizikai mérések, és értelmezési adatok leírására szolgáló Általános Geofizikai Adatmodell (GGDM). A cikk összegzi a két adatmodellnek a GEOMIND információs rendszerben játszott szerepét és bemutatja, hogy az általános megközelítés, valamint az XML alapú adatleírás a geofizikai adatok cseréjének terén milyen előnyökkel jár.

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Geophysical database services

Multilingual functionality of the GEOMIND system

Greg DETZKY* and Valdas RAPŠEVIČIUS**

Overall objective of the GEOMIND project is providing users of geophysical data through the internet in a real multilingual environment, making the search and download of international geophysical information using interfaces with native languages of nine participant countries beside English. For this purpose a sophisticated IT solution had been developed to seamlessly maintain the multilingual interface elements and content of geophysical thesaurus of the GEOMIND system. The recent paper presents some aspects of the topic.

Keywords: database, geophysics, thesaurus

1. Introduction

Originating from the successful practice of last decade, the general support of the R&D activity in the European Uninon is realised through the framework programmes managed by the European Comission. Framework Programmes (FP) form a tightly connected sequence by means of content and chronology. They serve such kind of general objectives, preferences ordered in activities as 'Quality of life', as 'Sustainable development', or 'Information society'.

Recently the FP7 is under preparation and FP6 is active. One of the FP6's programmes is the eContentPlus which has an objective to improve quality and accessibility to the internet content of European origin with special attention to the geographical, scientific and educational categories. Enhancing of the European internet content in multilingual environment is an explicit preference of the eContentPlus programme. A consortium established by 12 institutions and companies from 9 European countries had earned a contribution by the eContentPlus programme for a project to create the Geophysical Multilingual Internet-Driven Information Service.

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This is the GEOMIND project, in the realisation of which ELGI is greatly involved.

2. The GEOMIND system in general

The GEOMIND project aims to enhance the public utilisation activity of geophysical information by integration of national databases and making those available via Internet on a certain level, offering cross-border, European-wide, unified electronic service. The project was launched in September 2006 and is planned for 24 months.

What is GEOMIND about?

— GEOMIND system is developed to meet the needs of persons who will potentially use geophysical data,

— GEOMIND is a web-based multilingual information service (portal) to search and display geophysical metadata information across Europe. This system gives a convenient way for online ordering and downloading (in selected cases) of geophysical data from providers as well, taking into consideration all nationally specific legal issues,

— GEOMIND Portal is a multilingual pulic access platform to utilise geophysical data without a limitation of national boundaries.

GEOMIND is built for Governmental- and local authorities; exploration, mining, civil engeneering, insurance and other companies; scientists, researchers and students; individual citizens taking into consideration the results of the completed user needs assessment phase of the project.

The GEOMIND project consortium consists of 12 considerable member organisations (10 of which are data provider) involving more than 100 professional specialists from 9 EU countries (see *Fig. 1*):

Polish Geological Institute—PGI;
Czech Geological Survey—CGS;
Eötvös Loránd Geophysical Institute—ELGI (Hungary);
Geocomplex a.s. (Geophysical Exploration Company, Slovakia);
Geological Survey of Denmark and Greenland—GEUS;
Leibniz Institute for Applied Geosciences—GGA (Germany);
Golder Associates Srl. (Italy);
Institute of Geology and Mineral Exploration – IGME (Greece);
Information Technology co. (Lithuania);

Institute of Engineering Seismology and Earthquake Engineering—ITSAK (Greece);
Miligal, s.r.o. (Geophysical Exploration Company, Czech Republic).

Fig. 1. Member countries of the GEOMIND consortium
1. ábra. A GEOMIND konzorcium tagállamai

3. GEOMIND system concept

Function and architecture

System architecture has been built for reliable managing along the aimed functionality of the involved geophysical information in the form defined by GEOMIND metadata Profile and General Geophysical Model through the GEOMIND portal (*Fig. 2*). An individual interested in geophysical data will be able to search (textually or geographically) GEOMIND system for types of data available from data providers.

Once the user has found data he/she will be able to place his/her order to the data provider using the GEOMIND portal online tools.

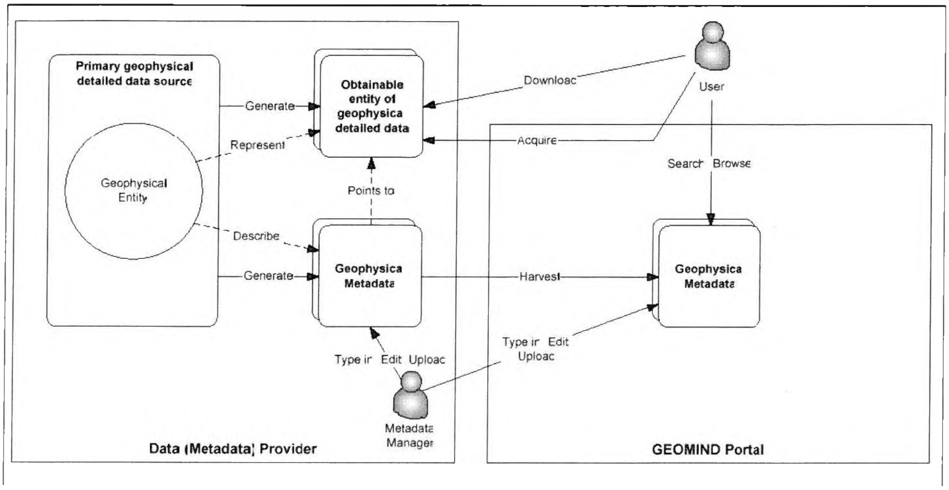

Fig. 2. Functional components of the GEOMIND system
2. ábra. A GEOMIND rendszer funkcionális elemei

Components of the multilingual representation of information in the GEOMIND system

The multilingual (cross-border) approach of the GEOMIND project and its outcomes is emphasized (*Fig. 3*). The launched GEOMIND portal prototype (www.GEOMIND.eu) recently can be reached in 10 different languages of current participants and in English. Multilingual support covers elements of the system interface, GEOMIND metadata profile, and the hierarchical geophysical thesaurus with independent usability.

Multilingual textual system elements

This allows easy future extension by adding any other languages (as well as other data providers) from new countries (*Fig. 4*). These components make national data provider administrators to be able interactively translate any textual content of the system and assist any average user to translate geophysical text out of the system too, by using searchable multilingual geophysical thesaurus.

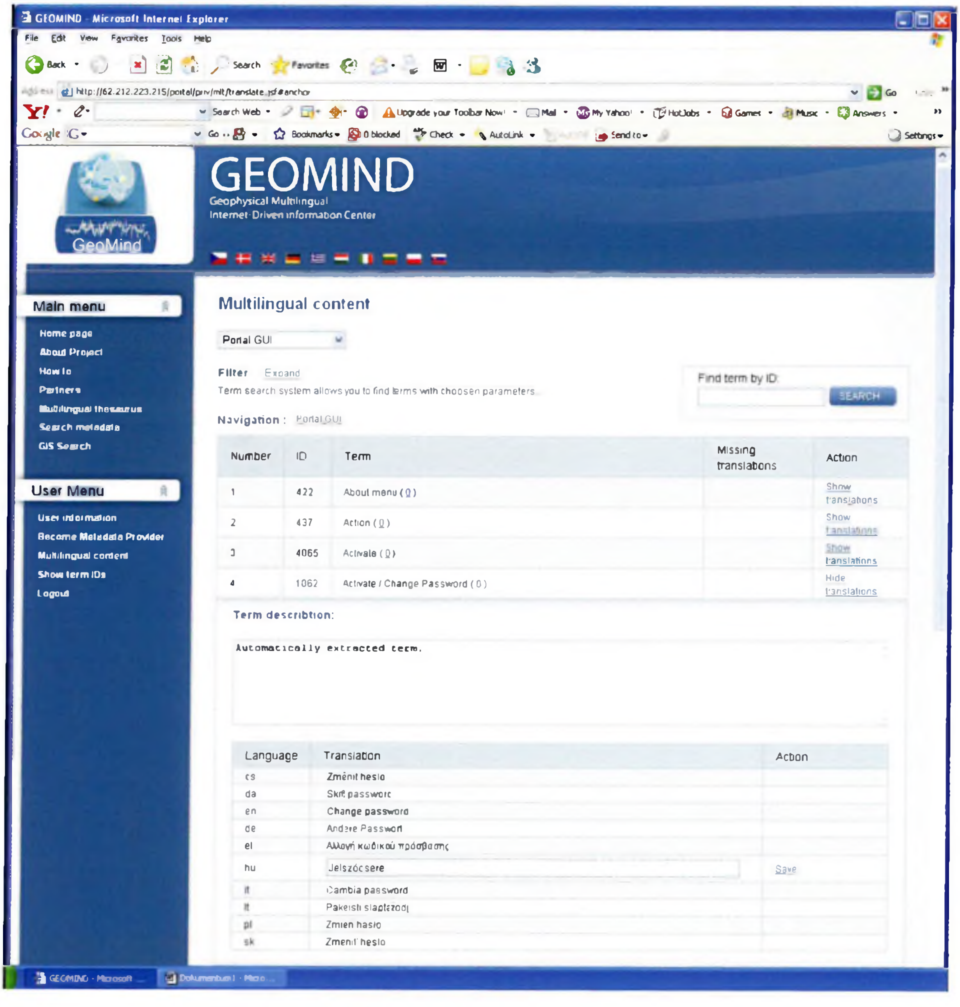

Fig. 3. Interactive web-application for the System interface translation

3. ábra. Interaktív web alkalmazás a rendszer interfész fordításhoz

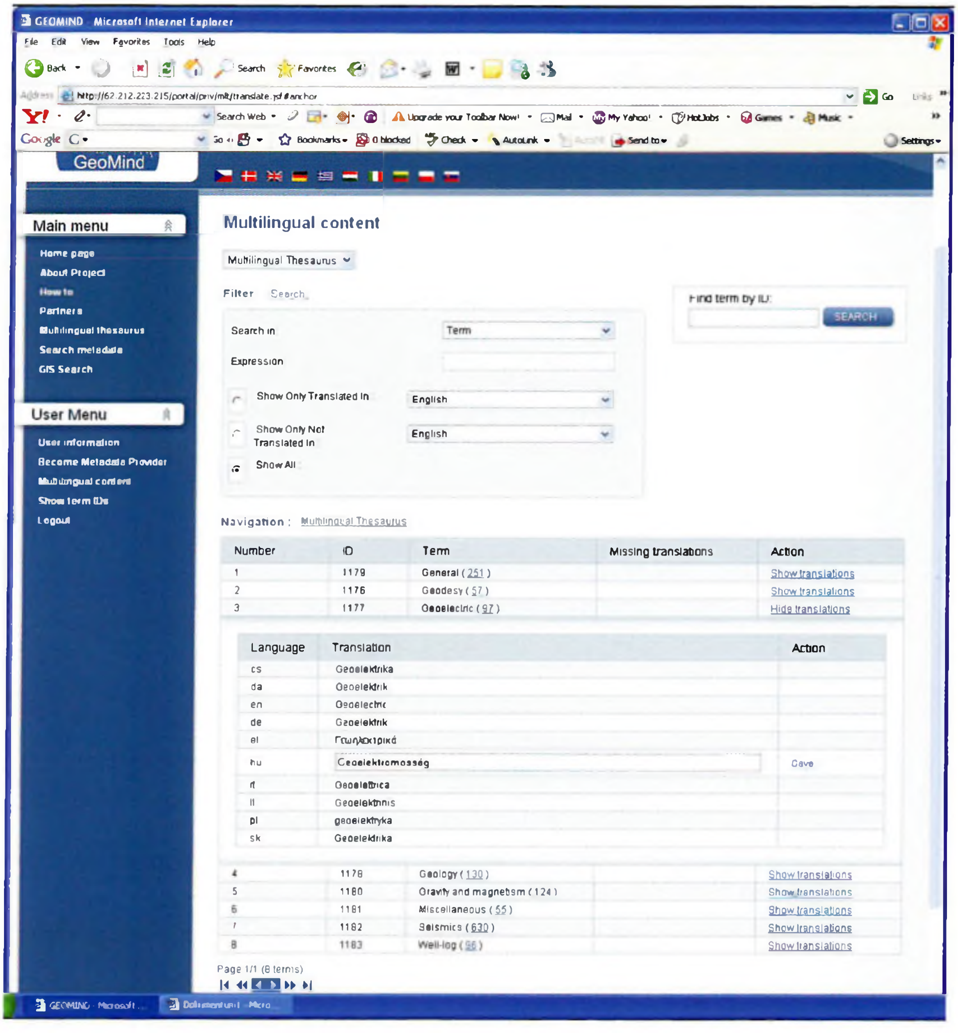

Fig. 4. User interface of the Multilingual Geophysical Thesaurus

4. ábra. A többnyelvű geofizikai tezaurusz felhasználói felülete

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Többnyelvűség megvalósítása a GEOMIND rendszerben

DETZKY Gergely és Valdas RAPŠEVIČIUS

A GEOMIND projekt átfogó célkitűzése geofizikai adatok internetes szolgáltatása a felhasználók számára olyan többnyelvű környezetben, mely anyanyelvi felhasználói felületen biztosítja a nemzetközi geofizikai információk keresését és letöltését az angolon kívül a résztvevő 9 ország nyelvén. A GEOMIND rendszer többnyelvű felhasználói interfész-elemeinek és a beépített geofizikai éretelmező szótár tartalmának hatékony karbantartására egy korszerű informatikai rendszer lett kifejlesztve. A cikkben ennek rövid bemutatása olvasható.

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ASAP

Advanced Seismic Acquisition and Processing (ASAP) — introduction of the EU research project

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The Eötvös Loránd Geophysical Institute (ELGI) as the leading (host) institution, Schlumberger Cambridge Research (SCR) and WesternGeco as the industrial partners started a common project within the 6th Framework Programme (FP6) Human Resources and Mobility (HRM) Activity, Marie Curie Actions, Marie Curie Host Fellowships for the Transfer of Knowledge (ToK) Development Host Scheme at the end of 2006. The EU financial support is given to carry out research on the field of seismic acquisition and processing, and provides opportunities for researchers from all over the world to enhance their knowledge by the help of the host (ELGI) and its partners. Furthermore it also enriches the host by the results of the research project. The project lasts for 3 years and we have almost one million euro to cover the cost of employing foreign researchers (maximum 2 years), the visiting scientist of partners (at ELGI) and the outgoing researchers of ELGI (visiting the partners). The budget provides the background for the project costs as well.

In this introduction we summarise the premises, introduce the partners, the research topic and the transfer of knowledge activities based on the proposal submitted successfully to the EU.

Keywords: seismics, vibrator, Transfer of Knowledge, Framework Programme

1. Introduction

Investing in oil and gas technologies, including environmental technologies, is critical to meet the world's growing energy demand (+ 3% yearly). Although renewable resources are growing, it is predicted that they will meet as little as 10% of the world energy demand in 2020. The world will thus still heavily rely on fossil fuels for several decades, during the transition to the hydrogen economy. With the world-wide reduction of oil and gas reserves and reduced number of newly discovered oil fields, the main focus of oil companies is aging oil fields with need of production enhancements. Therefore advanced technologies for more detailed and precise imaging of the geological structures are required.

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To reduce the greenhouse effect, the issue of capture and geological storage of carbon dioxide (CCS) is getting more emphasized. The economic application of this process also needs advanced seismic data acquisition and processing techniques. Successful CCS requires well-defined reservoir models both in terms of vertical (temporal) resolution and lateral (spatial) resolution. The subsequent reservoir monitoring requires highly accurate, and repeatable, sub-surface definition.

2. Research topic

In view of the world's rising energy demand and in the absence of breakthrough carbon-free technology, a portfolio of options is needed to manage the risk of global climate change. All sustainable options must be developed and used. Capture and geological storage of carbon dioxide arising from chemical and combustion processes is a relatively new option that is rapidly gaining support. In a study released in December 2004, the International Energy Agency says that 'CCS is a promising emission reduction option with potentially important environmental, economic and energy supply security benefits'. CCS requires well-defined reservoir models both in terms of vertical (temporal) and lateral (spatial) resolution. The subsequent reservoir monitoring requires highly accurate, and repeatable, sub-surface definition.

The application of Advanced Seismic Acquisition and Processing techniques is an effective tool in support of CCS. The knowledge transferred by the project will be of great benefit to all disciplines where it is required to investigate the Earth's sub-surface structure using vibratory sources. Definition of the sub-surface detail for storage of CO_2 will be greatly enhanced.

Hungary as a less favoured region of the EU is targeted with the knowledge transfer and it is here that these technologies will be developed. In Hungary, the theoretical knowledge and understanding required to develop such technologies is at a high international level. However, the lack of resources results in a low level of technological skills. With this ToK project, there will be the opportunity for transferring high level technological knowledge to this region. This is emphasized by working together with the particular industrial partners where world class geophysical and business experts will participate in the knowledge transfer.

In Hungary current applications are for the definition of the sub-surface for nuclear waste repositories, and for the mapping of the sub-surface for geothermal potential. Exploration of hydrocarbons will also benefit from these advances, and it is noted that this industry has a current major interest in CO_2 storage.

3. Project objectives

The aim of the project is to acquire knowledge in order to develop advanced seismic data acquisition and processing technologies, using the Transfer of Knowledge (ToK) instrument of EU FP6 (Sixth Framework Programme). The project will create an interface between the developed and less favoured regions of the EU and provide the transfer of technological and theoretical knowledge.

More specifically the project will aim at:

—developing signal analyses tools,

—determine source signal,

—develop simultaneous vibratory techniques and source signal separation methods.

4. Host organization

The host organization (Eötvös Loránd Geophysical Institute of Hungary — ELGI) provides the basic idea meaning a great step forward in seismic signal processing. It was internationally published and accepted by the scientific community [SCHOLTZ 2002, SCHOLTZ 2003, SCHOLTZ 2004, SCHOLTZ, NYÁRI 2004]. However, ELGI needs further human resources to develop the basic theory into a usable product and to fully understand the method's potential in the enhancement of sub-surface definition. The scientists in ELGI have strong theoretical skills but for further development and understanding, technological skill is needed from partner institutions. ELGI participates in local and EU financed projects on current scientific topics like CCS, disposal of radioactive wastes and sustainable use of geothermal energy. With successful transfer of knowledge the effectiveness of projects will be strongly improved.

5. Transfer of knowledge

The ASAP project aims to achieve a two-way transfer of knowledge: from the developed region of Europe to Hungary and from Hungary to the partners.

ELGI will transfer its theoretical knowledge base on seismic signal analysis to the participants of the more developed regions. Meanwhile Hungary will gain knowledge from both the hosted international research team and the partner institutions. The participant scientists will become experts in the fields of seismic signal analysis and special vibratory acquisition, processing techniques (*Fig. 1*). Through interaction with participating world class geophysical and business experts at the industrial partners, they will also develop technological skills and training in areas such as current best practice techniques, field methodologies, industry hardware and software, as well as additional other skills in project management, intellectual property rights and patents. The industrial partners market lead in the geophysical industry is maintained through an acute understanding of international IP. These skills will make the leaders of the international group manage research at a high scientific level in order to produce new theoretical results for correct technical applications.

6. International state of the art

The current common technique in seismic exploration on land is based on multiple vibratory sources and grouped geophone receivers. The acquired geophone data are correlated with the theoretical sweep signal controlling the vibrator signal in order to compress and enhance the received signals [ANSTEY 1964]. The grouping is required to attenuate unwanted coherent noise, to reduce ambient noise and to increase the input signal level. This kind of acquisition and pre-processing technique is both robust and uncomplicated, but it suffers from limitations. The major drawbacks are the degradation in spatial and temporal resolution due to the simple summing in the group formation of the sources and receivers (intra-group differences, inappropriate filter response), and the usage of a theoretical, rather than true, signal in the pre-processing [BLACQUIÉRE, ONGKIEHONG 2000, BAETEN et al. 2001a, BAETEN et al. 2001b, SERIFF KIM 1970, BAETEN, ZIOLKOWSKI 1990].

Fig. 1. Seismic vibrator group
1. ábra. Szeizmikus vibrátor csoport

There are several methods already developed to overcome the described limitations, but they either do not give satisfactory results, or are too complicated to utilize successfully. Examples of such methods are correlation noise filtering, encoded sweeps, weighted group members, etc. [SORKIN 1974, BERNHARDT, PEACOCK 1978, WERNER, KREY 1979, CUNNINGHAM 1979, RIETSCH 1981, EDELMANN, WERNER 1982, OKAYA et al. 1992, ALLEN et al. 1998].

A major breakthrough on the receiver side came when technical advances made it possible to build equipment with enough channel count to avoid the simple summing of geophone signals in the field. The WesternGeco Q-Land system records all the single sensor data so that intelligent processing can be carried out on the raw data before decimation (previously simple group forming) is performed [BAETEN et al. 2000]. Such systems result in a significant improvement in data quality. The major challenge was to find and develop the appropriate processing algorithms to deal with the huge amount of data.

The success of Q-Land is due to the more than incremental improvement in data quality. To make a further breakthrough and push the boundaries of sub-surface definition even further, we believe it is necessary to apply similar innovative concepts to the source side. These innovative concepts are now discussed.

7. Innovative concepts

Complimentary source side techniques now need to be developed, and this is where the proposed research will concentrate. Based on theoretical considerations, the approximation of the theoretical sweep signal is currently based on ground force signal calculations of accelerometer data (mounted on the vibratory source) [BAETEN, ZIOLKOWSKI 1990]. This ground force signal can be used in a deterministic deconvolution process, which could take into account the real output of the vibratory source (distorted nature) [ALLEN et al., 1998; WILKINSON et al., 1998]. The problem with this approach is the mismatch between the higher harmonics of the calculated ground force signal and the higher harmonic components of the measured geophone signals [BAETEN et al. 2001a, SCHOLTZ 2002, SCHOLTZ, NYÁRI 2004].

The main reason for grouping on the source side is productivity — a certain amount of energy is required, and greater numbers of vibratory sources working together allow the vibrating time (the sweep time) to be shorter, thus reducing the time to acquire surveys. Even more, there is a further need to increase productivity with simultaneous usage of several grouped sources. The current solutions (to separate out the energy from the simultaneous groups of sources) [PRITCHETT 1991] are based on signal separation techniques, which are mostly dependent on the quality of the source signal estimation [MARTIN 1993].

The proposed research will concentrate on development of complementary source side technique. In the frame of the ASAP project the following innovations will be executed:

—analyzing the vibratory source to understand its behaviour (especially distortion),
—finding reliable source signal analysis tools,
—developing source signal estimation techniques,
—developing signal separation methods.

The expected results will provide more accurate tools for the scientists to study the Earth and for the researchers in the quest for raw materials.

8. Research objectives and methodology

The research group will develop advanced vibratory seismic techniques, both acquisition and processing, to increase data quality (fidelity, resolution, etc.) and/or to increase productivity. It should be noted that productivity increase must not be undervalued. Productivity is a key driver for land geophysical surveys due to the enormous expense of the massive exploration operations. During the research, it is expected to learn new information on the seismic signals emitted by the vibrator, especially on the harmonic distortion. We will also obtain data on the quality of the accelerometer signals (mounted on the vibrators), thought to be representing the source signal. A major result of the research will be a source signal estimation method where distortion is taken into account. It can be used in pre-processing to replace the common correlation technique, utilized in filtering where the upper harmonics are removed, and can be used in source signal separation methods to enhance resolution or productivity.

The group will use seismic data from 2-D surface seismic reflection measurements and downhole data both acquired over the same subsurface space at the same time using common vibratory source. The downhole data (i.e. using geophones clamped to a borehole wall at depth) allow a true estimate of the source signature to be measured (this is not possible with surface measurements only) and makes it possible to compare with data derived from the surface measurements. The surface data must be single receiver data (which can only be provided by WesternGeco) in contrast to the current measurements in order to avoid the distortions associated with the otherwise group formed data. In combination the research group will investigate the source signals and their separation possibilities, for which the acceleration data of the vibrators are recorded, as well.

9. Host: Eötvös Loránd Geophysical Institute

Eötvös Loránd Geophysical Institute (ELGI), is one of Hungary's most significant research centres in the field of geosciences. Its activity includes research both in the pure and applied parts of geophysics as well as geophysical exploration and prospecting. It embraces the application of seismic methods in investigations spreading from the shallowest engineering problems to the deepest Earth's crust and upper mantle studies. ELGI applies not only seismic methods, but also gravity, magnetic, electrical and electromagnetic including tellurics, magnetotellurics and radar are utilized in structural studies, geological mapping, engineering and environmental investigations. In addition, ELGI handles the geophysical databases of Hungary, too. Laboratory- and Observatory Services are operated to fulfill ELGI's public service functions. The palaeomagnetic-, radiometric-, metrology and the instrument development laboratories are functioning without interruptions, according to international standards. Data are continuously transferred to other Hungarian organisations and international data centres. The research scientists at ELGI give university lectures and organising field practices on several subjects.

The proposed ToK project will be fitted into the running programme of methodological development of geophysical techniques and instruments. ELGI's activities cover most of the geophysical methods, e.g. seismic, gravity, geomagnetic, image-processing, well-logging, geoelectric, EM and geothermic. Our results in methodology and instrument development are well recognized.

Privately or government funded projects and contracts in which ELGI is participating are not the only beneficiaries of the methodological research results to be developed during the Transfer of Knowledge project. With spreading the knowledge base the international geophysical community could build on the results. At ELGI amongst the varied contracts the most important is the long-term geophysical study of the planned radioactive waste disposal sites. The geophysical data acquired, processed and interpreted are establishing the basis on which future decisions will be taken. Our planned ToK activities are vital to these investigations, too.

10. Industrial partner: Schlumberger Cambridge Research

Schlumberger Cambridge Research (SCR) is the scientific center of Schlumberger Limited, the leading oilfield services company (*Fig. 2*). Schlumberger supplies technology, project management and information solutions that optimize performance for customers working in the international oil and gas industry. SCR provides research support to Oilfield Services in the domains of real-time interpretation, geo-mechanics, physical chemistry, fluid mechanics and geophysics. SCR approach is based on developing understanding of the underlying processes through a synergistic combination of experimentation, mathematical modeling and computational simulation. Research teams are multidisciplinary, embracing physics, chemistry, materials science, mathematics, statistics, earth sciences, solid and fluid mechanics, computer science, signal processing and instrumentation.

At SCR, one area of research within the Geophysics discipline (approximately 20 scientists and 3 managers) is Acquisition and Processing (5 scientists + 1 manager). This includes the fields of land seismic sources and reservoir monitoring, within which the proposed Transfer of Knowledge project will reside.

Over the past 10 years, the geophysical department patented 80 new inventions, 10 alone in 2004. SCR publishes 40 to 50 publications a year and approximately 250 internal Schlumberger reports. The department of Geophysics currently participates in another ToK, IMAGES (Induced Microseismics Applications from Global Earthquake Studies) and has

Fig. 2. Research facility of Schlumberger Cambridge Research
2. ábra. A Schlumberger Cambridge Research kutatási bázisa

hosted three Marie Curie Fellows under a recently completed FP5 project (DEMARES). In total, SCR currently participates in 8 EU projects (of which 5 Marie Curie).

SCR scientists who develop a prototype of answer products test the newly developed techniques. These prototypes are transferred to Schlumberger development centers, which develop the final version of the answer products (effective recoding). These centres, in this project particularly Houston, Oslo, Fuchinobe (Japan) and London development centres, commercialize products and pass them to marketing which will sell these to customers of Schlumberger.

11. Industrial partner: WesternGeco

WesternGeco (WG) is the largest seismic contractor in the world. It operates the most extensive range of seismic crews and data processing centres in the industry, as well as holding the largest multiclient seismic library. WesternGeco has large development and processing centres both in the UK and in Norway. The WesternGeco Oslo Technology Center develops data acquisition systems for seismic surveys on land, at sea, and on the seabed. The WesternGeco Oslo Technology Center employs more than 270 software, electrical, mechanical, and geophysical engineers representing 36 nationalities. WG is leading the industry's transition to large-channel count single-sensor and single-vibrator acquisition, as opposed to the conventional use of vibrator groups and sensor groups. The new type of data offers both opportunities and challenges when it comes to increasing the data quality and maintaining productivity. It is felt that on the vibrator (source) side significant improvements remain to be made.

12. Summary of the first year's activities

To help the recruitment we have placed several advertisements at relevant web sites (EU, EAGE, ELGI) and also we have distributed leaflets at the appropriate conferences and meetings (EAGE London, Istanbul, GNGTS Rome). It was difficult to attract as many researchers as anticipated and fulfil all the planned positions at the required level of experience. This is clearly due to the current oil market situation: the geophysical exploration industry is booming, hence most of the geophysicists are having competitive permanent jobs.

To enable us to host new recruits and welcome the visiting scientist for shorter periods of time from the partner organizations, we have set up the infrastructure. Dedicated rooms were refurbished. We have provided new and/or refurbished up-to-date personal computers to all of the new recruits with the necessary software and from the EU budget we were able to get maintenance cover for the seismic processing and interpretation software packages, too.

The scientific research was started by gathering relevant scientific references and by studying the available analysis and processing methods of the source signal estimation based techniques. Some of them were tested on synthetic and real field data. The amplitude and phase relation of harmonic components were calculated and analysed on experimental borehole and surface data. New approaches were implemented for harmonic noise attenuation in slip-sweep data based on a Genetic Algorithm.

The teaching and training activity was carried out with the help of the industrial partners. Induction presentations and lectures were given on general signal processing methods, specific research topic related acquisition and processing techniques. Trainings were held on the Matlab software environment. The Omega processing package was also introduced and the Simulink package was covered, too. Workshops were organised to discuss the project topics and the achieved results.

Though it was only the first year of the project we were able to present our new results at two international conferences [SCHOLTZ 2007, DAL MORO et al. 2007]. Both of them has written abstract published in the conference books and at the meetings one of them was an oral and the other one was a poster presentation. We have also published an introductory paper of the project with highlighted scientific results in the Hungarian Geophysics journal [SCHOLTZ, NYÁRI 2007].

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Fejlett szeizmikus mérés és feldolgozás — az EU kutatási program ismertetése

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Az Eötvös Loránd Geofizikai Intézet (ELGI), mint a vezető (fogadó) intézmény, a Schlumberger Cambridge Research (SCR) és a WesternGeco, mint ipari partnerek, 2006 végén egy közös projektet kezdtek a Hatodik Keret Program (FP6) Emberi Erőforrás és Mobilitás (HRM) Aktivitás, Marie Curie Akciók, Marie Curie Fogadó Ösztöndíjak a Tudás Átadásért (ToK) Fejlesztési Fogadó Séma alatt. Az EU pénzügyi támogatását a szeizmikus mérés és feldolgozás területén végzendő kutatásra adta és esélyt nyújt a világ bármely részéről érkező kutatóknak, hogy a fogadó intézmény (ELGI) és partnerei segítségével tudásukat fejlesszék. Továbbá a kutatási projekt eredményei által a fogadó intézményt is gazdagítja. A projekt 3 évig tart és mintegy 1 millió euró szolgál a külföldi kutatók (maximum 2 éves) alkalmazására, a partnerek látogatásaira (az ELGI-nél) és az ELGI kiutazó kutatói (a partnereket látogatandó) számára. A projekt dologi kiadásaira is ez a költségvetés nyújtja a fedezetet. Az EU számára benyújtott sikeres pályázat alapján ismertetőnkben összefoglaljuk az előzményeket, bemutatjuk a partnereket, a kutatási témát és a tudás átadási tevékenységeket.

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Overview of efficient Vibroseis acquisition methods

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Many methods have been developed in the past 25 years to speed up Vibroseis acquisition. I give an overview of the most promising ones and propose a classification of them in three categories: simultaneous shooting, cascaded sweeps and slip sweeps. The main features of these methods are summarized and some criteria for the selection of the most suitable are introduced.

Keywords: separation, productivity, sweep, attenuation

1. Introduction

The progress made in the last two decades in Vibroseis productivity has been mainly due to the recording system channel count, which, for a typical heavy-effort 3-D seismic crew, increased almost two orders of magnitude. On the source side, even though more powerful seismic vibrators have allowed reduction of the sweep lengths, this reduction can be quantified in percentages rather than orders of magnitude. A substantial increase of Vibroseis productivity from the source side can only be obtained with more than one vibrator or group of vibrators shooting at the same time as proposed by SILVERMAN [1979] in his pioneer work. Because data quality should not be significantly affected by the technique used to speed up acquisition, signal processing methods have been developed to separate simultaneously acquired shot gathers. In this extended abstract, I describe the principles and the features of the most promising of these methods.

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2. Harmonic noise attenuation

The strict connection between the harmonics generated by hydraulic seismic vibrators and the effectiveness of the techniques developed to efficiently acquire Vibroseis data requires mention of the techniques developed to attenuate the harmonics. The techniques considered in this section aim at attenuating the harmonics, i.e., improving the data quality, rather than enhancing acquisition efficiency.

The method proposed by SORKIN [1972] to suppress harmonics and its generalization developed by RIETSCH [1981] require several consecutive sweeps. Each of the M sweeps that compose the sequence has an initial phase differing from that of the previous one by the phase angle $2\pi/M$. The value of M depends on the maximum harmonic order that it is desired to suppress. Prior to stacking, the shot gathers must be correlated with the corresponding sweep. It can be demonstrated that harmonics up to and including the Mth are suppressed. The case M=4 is of particular interest because all the even harmonics in addition to the critical 3rd harmonic are suppressed.

3. Cascaded sweeps

The price to be paid to attenuate the harmonics using SORKIN [1972] and RIETSCH [1981] methods (often called variphase methods) is the additional acquisition time due to the required series of consecutive sweeps. However, only in some circumstances, the target depth, the maximum offset, the expected absorption and the signal-to-noise ratio require transmitting a large amount of energy to the earth's interior, and therefore several sweeps are required.

To speed up acquisition while preserving the harmonic attenuation properties, ANDERSEN [1994] proposed the so-called cascaded sweep. Andersen's method eliminates the listen time by linking or cascading a number of sweep segments. The sub-sweeps, which span the entire frequency range, are identical except for different initial phases. The initial phase angles of consecutive sweeps increment by $2\pi/M$, where M is the number of sweep segments. The listen time is added only after the last sweep segment. In Andersen's method, the correlation sweep has an additional segment whose phase and position in the cascaded sweep are chosen to eliminate harmonics up to a certain order that depends on M.

4. Simultaneous shooting

Separation by phase encoding.

SILVERMAN [1979] is credited with the original idea and the first method developed to separate shot gathers obtained after simultaneous shooting. If the sweep length required at each source location is T and the listen time is L, the sequential acquisition from two locations would require (ignoring the reset time) a total time of $2(T+L)$. In Silverman's method (2×2 scheme), two consecutive sweeps of length $T/2$ are shot from two locations simultaneously, giving a total acquisition time of $2(T/2+L)$. If L is much smaller than T, the method yields an efficiency improvement of almost 50%. The 2×2 method requires the combination of a shot gather obtained with two vibrators sweeping in phase at two locations and a shot gather obtained with two vibrators sweeping with opposite polarities from the same locations.

With the 2×2 scheme, the separated shot gather at the first location suffers from the contamination of all the even harmonics generated by the other vibrator. All the self-harmonics of the first shot-gather are preserved. WARD et al. [1990] proposed a 4×2 (4 sweeps at 2 vibrator locations) phase encoding scheme that eliminates the contamination of all the harmonics generated by the other vibrator. Because the 4×2 scheme does not suppress the odd self-harmonics and in particular the third harmonic, which is often energetic, WARD et al. [1990] also proposed an 8×2 scheme.

Table I summarizes the most common simultaneous phase encoding schemes, the corresponding source matrixes and the main properties. The source matrixes, whose elements correspond to amplitudes and initial phases of the reference sweeps for a single frequency, assume that each individual vibrator can repeat its sweep except for the desired different initial phase. The summarized properties of these methods are also valid if the vibrators emit different sweeps at the different locations (e.g., s_1 different than s_2 in the 2×2 scheme). The separation of the shot gathers can be obtained by multiplying the recorded gathers by the inverse (or pseudo-inverse for rectangular matrixes) of the source matrix. The properties of the schemes in Table I can be derived by elevating each element of the source matrix to the order of the harmonic under consideration and performing the shot-gather separation. It should be noted that the higher-order schemes in

Scheme	Attenuated self harmonics	Harmonic leakage	Scheme	Attenuated self harmonics	Harmonic leakage
$2\times 2: S=\begin{bmatrix} s_1 & s_2 \\ s_1 & s_2 \end{bmatrix}$	None for the first shot gather*	Even harmonics	$8\times 2: S^T=\begin{bmatrix} s_1 & s_1e^{i\varphi} & s_1e^{i2\varphi} & s_1e^{i3\varphi} & s_1e^{i4\varphi} & s_1e^{i5\varphi} & s_1e^{i6\varphi} & s_1e^{i7\varphi} \\ s_2e^{i7\varphi} & s_2e^{i6\varphi} & s_2e^{i5\varphi} & s_2e^{i4\varphi} & s_2e^{i3\varphi} & s_2e^{i2\varphi} & s_2e^{i1\varphi} & s_2 \end{bmatrix},\ \varphi=\frac{\pi}{4}$	Up to the 8th	The 7th is the first harmonic that leaks
$4\times 2: S^T=\begin{bmatrix} s_1 & s_1 & -s_1 & s_1 \\ s_2 & -s_2 & s_2 & s_2 \end{bmatrix}$	All even harmonics	None	$5\times 2: S^T=\begin{bmatrix} s_1 & s_1e^{i2\varphi} & s_1e^{i4\varphi} & s_1e^{i\varphi} & s_1e^{i3\varphi} \\ s_2 & s_2e^{i3\varphi} & s_2e^{i\varphi} & s_2e^{i4\varphi} & s_2e^{i2\varphi} \end{bmatrix},\ \varphi=\frac{2\pi}{5}$	Up to the 5th.	The 4th is the first harmonic that leaks
$4\times 3: S=\begin{bmatrix} s_1 & s_2 & s_3 \\ -s_1 & s_2 & -s_3 \\ s_1 & -s_2 & s_3 \\ -s_1 & -s_2 & s_3 \end{bmatrix}$	All even harmonics	None	$4\times 4: S=\begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ s_1 & -s_2 & s_3 & -s_4 \\ s_1 & s_2 & -s_3 & -s_4 \\ s_1 & -s_2 & -s_3 & s_4 \end{bmatrix}$	None for the first shot gather*.	All the even harmonics leak to the first shot gather

Table 1. Source matrixes and main properties of the most common simultaneous acquisition schemes
*Even harmonics of the other shot gathers are attenuated

1. táblázat. Forrás mátrixok és a legáltalánosabb rengéskeltési sémák fő tulajdonságai. *A másik adatgyűjtő páros harmonikusai csillapodnak

Table I were developed for sweep lengths larger than those typically required with modern powerful vibrators and for finer receiver sampling.

MARTIN [1993] conducted a comprehensive set of experiments to assess the capability of simultaneous shooting methods to separate shot gathers and to suppress harmonics in practical conditions and concluded that the Vibroseis systems (electronics and mechanics) available in the early 90 s would permit approximately 30 dB of separation for the 2×2, 4×2 and 8×2 schemes. Because the dynamic range of the processing algorithms used to enhance the signal-to-noise ratio is often more than 30 dB, these schemes were not considered adequate.

HFVS separation

The High-fidelity-vibratory-seismic (HFVS) [ALLEN et al. 1998] method for acquiring seismic data is based on the principle that, in a Vibroseis survey, the far-field signature can be estimated from measurements made at the vibrator. These measurements, which include harmonics, are used to perform a multi-channel deterministic deconvolution of the simultaneously acquired gathers. The elements of the source matrix in this method are the estimated far-field signatures. The different initial phases of the sweeps are designed to obtain an invertible source matrix. If the assumptions made in this method are satisfied, this method achieves two objectives: shot gather separation and source signature deconvolution.

5. Slip sweep

Slip sweep is a Vibroseis acquisition method that was introduced by ROZEMOND [1996]. This method essentially consists of a vibrator group sweeping without waiting for the previous group's sweep to terminate. In the absence of harmonic noise, and if the time interval between consecutive sweeps (slip time) is larger than the listen time, the responses of the earth to consecutive sweeps do not overlap in the time–frequency domain as shown by the dotted area in *Fig. 1*. In the presence of harmonic noise, the responses may overlap as shown by the dashed area in Fig. 1, where only the earth's response to harmonics up to the second order is shown. JEFFRYES [2002] and MEUNIER and BIANCHI [2002] developed two techniques to attenuate harmonic noise in slip sweep surveys.

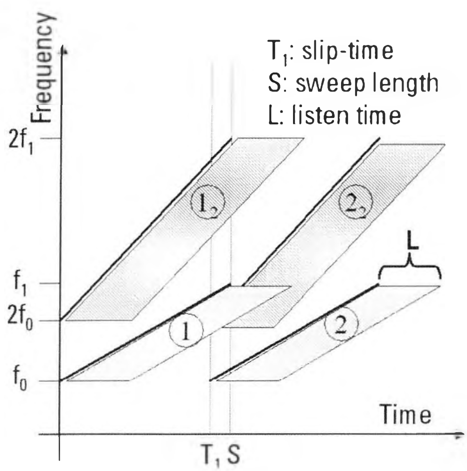

Fig. 1. Schematic representation in time–frequency domain of one trace of slip-sweep uncorrelated data obtained with two consecutive linear up-sweeps

1. ábra. Két egymást követő lineáris up-sweep-pel nyert slip-sweep korrelálatlan adatai egy csatornájának sematikus képe idő–frekvencia tartományban

6. Combination of methods

MOERIG et al. [2002] developed the simultaneous cascaded sweep method to increase the efficiency of Vibroseis acquisitions and to obtain deterministic attenuation of harmonic noise. This elegant method permits the use of cascaded sweeps during a simultaneous acquisition. The initial phases of the sweep segments that compose the cascaded sweeps are selected according to the EDINGTON and KHAN [1989] scheme and do not have to be progressively rotated by $2\pi/M$ as required in ANDERSEN [(1994].

The simultaneous slip-sweep method proposed by JEFFRYES [2002] consists of grouping the available vibrators in two or more sets and performs slip-sweep shooting between the sets of vibrators. Separation of the shot gathers within a group is obtained by simultaneous shooting with different initial phases. If, for example, two sets (A and B) of vibrators are used, at least three simultaneous sweeps per set are needed. The acquisition sequence could be A_1-B_1-A_2-B_2-A_3-B_3, in which the elapsed time between A_i, B_i and A_{i+1} is the slip time.

HUFFORD et al. [2003] also proposed to group the available vibrators in sets. The difference between this proposal and that of JEFFRYES [2002] is that the separation of the shot gathers within a set is done using HFVS deconvolution rather than simultaneous phase encoding.

7. Practical considerations

What is the best-performing efficient Vibroseis acquisition method that preserves data quality? Two key parameters dictate the effectiveness and the capability to preserve data quality of the methods described in this extended abstract: source signature repeatability and magnitude of the generated harmonics. For a given source effort, the relative importance of these two parameters along with the effectiveness of the processing methods used to compensate for the lack of source repeatability and/or energetic harmonics determine the most suitable method. The described features and assumptions of these methods lead to the qualitative classification in *Fig. 2*, where the most promising method for a given combination of parameters is indicated.

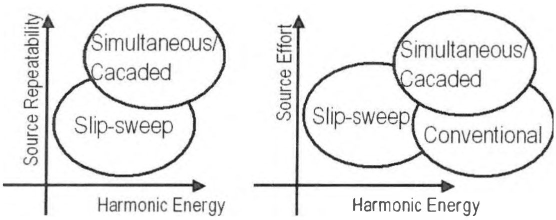

Fig. 2. Qualitative selection of the best performing efficient Vibroseis acquisition method

2. ábra. A leghatékonyabb viborszeiz módszer minőségi kiválasztása

In the case of high source signature repeatability, the deterministic cancellation of the harmonics given by the simultaneous shooting techniques is appealing and, particularly if a substantial source effort is required, simultaneous shooting techniques should be considered. If source repeatability is not satisfactory, the effectiveness of the data processing techniques to compensate for it should be assessed before considering these methods. If the harmonic noise contamination is weak compared to the response of the target reflectors to the fundamental energy, or the method to attenuate it is effective, slip sweep techniques should be considered. For short sweeps, non-repeatable source signatures and strong harmonic noise, conventional shooting may be the only viable approach.

8. Conclusions

Many methods have been developed in the past 25 years to speed up Vibroseis acquisition. I have given an overview of the most promising ones and proposed a classification of them in three categories: simultaneous shooting, cascaded sweep and slip sweeps. The main features of these methods and some combinations of them have been summarized and some criteria for the selection of most suitable one have been listed. Examples of datasets acquired with the described methods are presented.

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A hatékony viborszeiz módszerek áttekintése

Claudio BAGAINI

A vibroszeiz mérési módszer felgyorsítására sok módszert fejlesztettek ki az utóbbi 25 évben. A leginkább perspektivikus módszerekről egy áttekintést adok és javaslatot teszek felosztásukra, mely három kategóriából áll: szimultán rezgéskeltés, összefűzött vibrojelek és elcsúsztatott vibrojelek. Ezen módszerek legfontosabb jellemzői kerülnek összefoglalásra és bevezetésre kerül néhány kritérium a legalkalmasabb módszer kiválasztására.

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ASAP

Optimized harmonic noise reduction in vibratory seismic data

Giancarlo DAL MORO*, Péter SCHOLTZ*, Kambir IRANPOUR**, Christos SARAGIOTIS*

Due to non-linear phenomena and coupling problems, Vibroseis acquisitions often suffer from source signal distortion that can cause a remarkable decrease of the signal-to-noise ratio. Such phenomenon can become particularly problematic when slip-sweep techniques are adopted in order to improve acquisition productivity. In such conditions harmonic distortion due to a shot can in fact mask fundamental energy belonging to the previous shot. In order to reduce the unwanted noise contamination an evolutionary-algorithm based optimization scheme is introduced into the harmonic noise estimation scheme. The effectiveness of the implemented noise attenuation procedure is shown on synthetic and field datasets.

Keywords: noise, filtering, optimization, slip sweep

1. Optimization scheme for harmonic noise estimation

The slip-sweep vibratory acquisition method can help to increase productivity and/or quality of seismic data if the harmonic distortion caused noise is sufficiently removed from the seismic records [BAGAINI, 2006; LEBEDEV, BERESNEV 2004; MEUNIER, BIANCHI 2002, 2005]. In the published techniques first the harmonic noise components are estimated relative to the fundamental source signal, then the harmonic noise content is calculated enabling the subtraction operation to be carried out.

The estimation problem can be tackled in terms of amplitude of the upper harmonics with respect to the fundamental one. Analyses show that upper-harmonic amplitudes are frequency-dependant values [SCHOLTZ 2002; 2003; 2004]. A *ratio trace*, defined as the ratio between a given

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upper harmonic and the fundamental one can be adopted [SCHOLTZ 2002, 2003, 2004],

$$R_n^m(f) = \frac{V_m(f)}{V_n(f)} \tag{1}$$

where V is the contribution of the m and n harmonics (in our case n is the fundamental one).

The fundamental harmonic (that some authors define as *first* harmonic) is basically represented by the theoretical sweep used as input (commonly named 'pilot sweep'). When we correlate the observed trace with the harmonic component n and mute the data outside a window centered on the main peak we somehow isolate the contribution due to that harmonic. If we then divide the resulting quantity by the conjugate of the considered harmonic we get back to the previous uncorrelated status but having removed the contribution of all the other harmonic components. Estimation of the contribution of the upper harmonics can be performed by minimizing the following expression:

$$\frac{[T \otimes P_n]}{P_n^*} - \frac{[T \otimes P_0] * R_0^n}{P_0^*} \Rightarrow 0 \tag{2}$$

where P_0 represents the pilot sweep (fundamental harmonic), P_n the distortion due to the nth harmonic, the square brackets denote the muting of the data outside the window centered on the main peak and $\otimes$ represents correlation. In order to obtain an expression easier to handle, Eq. [1] can be also rearranged as

$$[T \otimes P_n] \otimes P_0 - [T \otimes P_0] * R_0^n \otimes P \Rightarrow 0 \tag{3}$$

The first part pertains to the observed data, the second part to the *ratio trace* to be evaluated.

Phase differences between upper and fundamental harmonics are often reasonably constant (at least for most of the considered frequency range) and a constant value for each harmonic can thus be often sufficient to describe their behaviour. By considering the upper-to-fundamental harmonic ratio and an optimization procedure based on Evolutionary Algorithms (EAs) we attempt to attenuate upper-harmonic components. Evolutionary algorithms belong to the family of heuristic optimization tools and have been successfully adopted for a number of geophysical problems [e.g. NIKRAVESH et al. 2003; DAL MORO, PIPAN 2007]. Their main (but not unique) advantage consists of being little prone to local-minimum failure thus resulting particularly suitable for complex problems hard to be solved with gradient-based methods. By means of an upper-harmonic forward modeling based on the analyses presented in SCHOLTZ [2002; 2003; 2004], we designed an EA-based tool to minimize the energy in the portion of the seismic trace where upper harmonics occur.

The cost function is then defined as the mean amplitude of the difference between the actual trace (containing the upper harmonics and possibly primary signal(s)) and the estimated one (that contains only upper harmonics as predicted from the pilot sweep via the EA-based procedure). Amplitude ratio (see Eq. [1]) curves are discretized into a limited, but sufficient, number of frequency–amplitude points and linearly interpolated along the entire considered frequency range (*Fig. 1*).

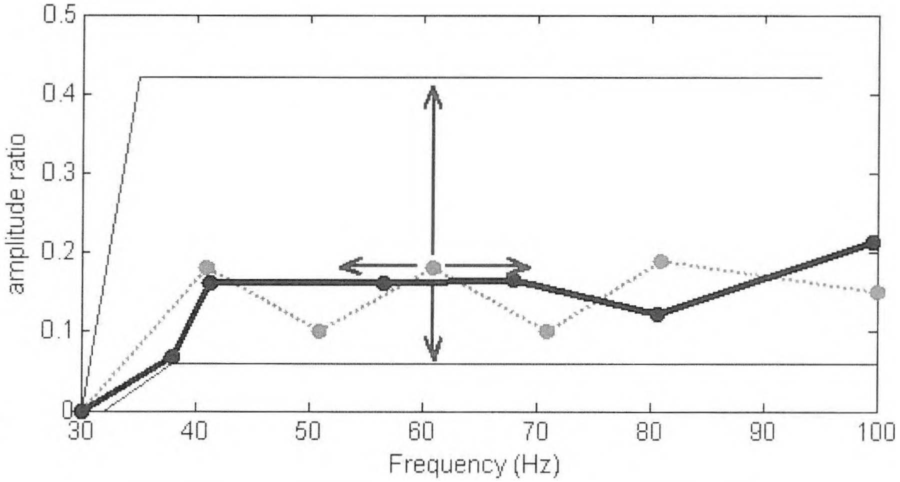

Fig. 1. Discretization of the amplitude ratio curve. Light-gray dotted line: the model used as starting point for the genetic search. Each point is free to move both vertically (amplitude) and horizontally (frequency). Thick black line: final model. Also reported the search space where the solutions are sought

1. ábra. Az amplitudó hányados görbéjének megadott pontjai. Szürke pontvonal: a genetikai algoritmus kiindulási pontjául használt modell. Minden pont szabadon mozoghat függőleges (amplitúdó) és vízszintes (frekvencia) irányban. Vastag fekete vonal: végső model. Adott a tartomány is, ahol a modell megoldást kerestük

Main input data are the number of harmonics to consider, the search space within which seeking the optimal solution, the size of the population, the generation number and the time of occurrence of the first arrivals (required to separate the so-called *positive* and *negative* times). The implemented toolbox was tested both on synthetic and field datasets.

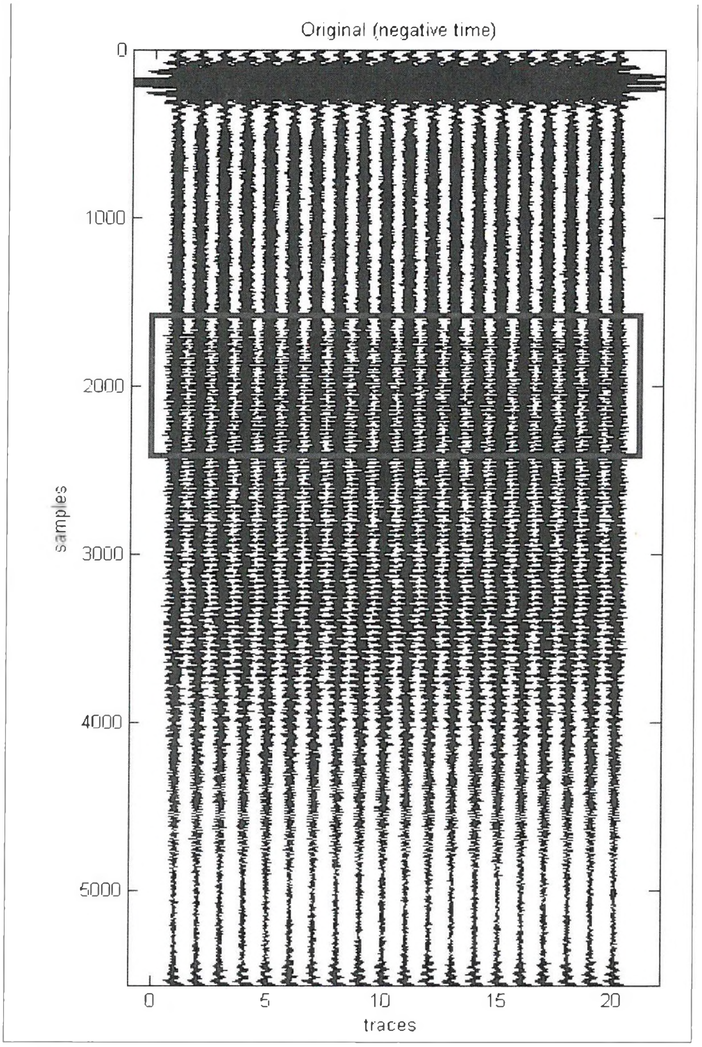

Fig. 2. Synthetic dataset (correlated with pilot sweep): in the rectangle the area of the data where a primary signal is severely obscured by upper harmonics and random noise

2. ábra. Szintetikus adatrendszer (elméleti vibrojellel korrelálva): A négyszögben azt az adatrészt jelöltük, ahol az elsődleges jelet a felső harmonikusok és a véletlen zaj lényegesen elfedi

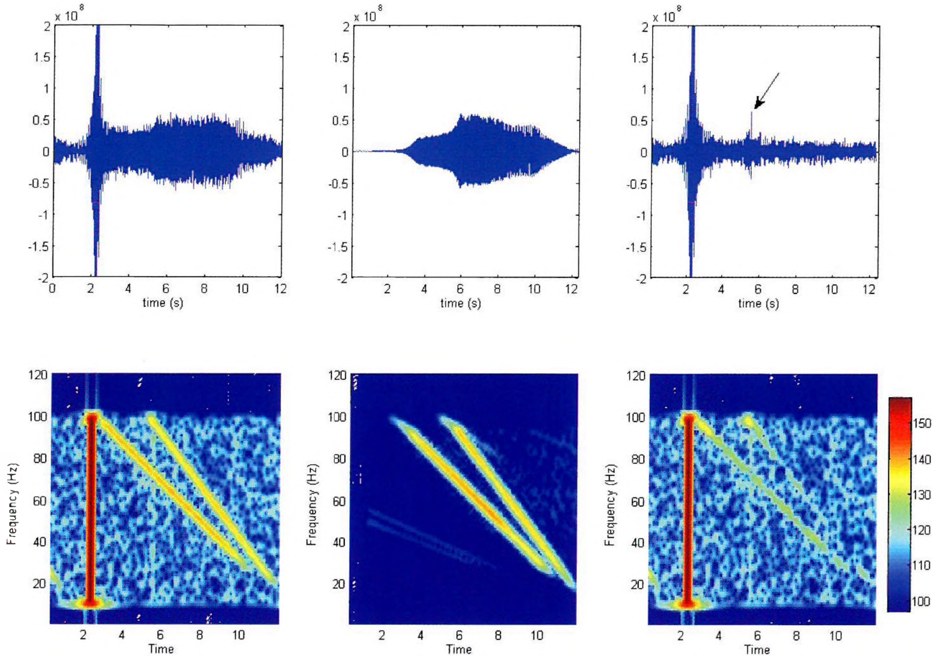

Fig. 3. Synthetic dataset. From left to right: original trace (above) and its spectrogram (below), estimated upper harmonic components, trace obtained by subtraction of this latter from the actual trace

3. ábra. Szintetikus adatrendszer. Balról jobbra: eredeti csatorna (fent) és spektrogramja (lent), becsült felharmonikus komponensek, ez utóbbinak az aktuális csatornából történő levonása után keletkezett csatorna

2. Synthetic dataset

A synthetic dataset (*Fig. 2*) was created by considering first two upper harmonics with frequency-dependant amplitude up to 15 and 25% respectively of the fundamental one and constant phase difference (–0.5 and 0.5 rad). Two events were included: a first arrival with no move out and a weaker later event with amplitude equal to 1% of the first one and with a linear move out. Random noise with maximum amplitude equal to the second event was also added.

Results of the EA-based processing are reported in *Figs. 3* and *4* where the comparison between spectrograms and traces before and after data processing show the effectiveness of the designed optimization scheme (notice the small signal previously obscured by the harmonic and random noise and put in evidence by the processing). Depending on the amount of added random noise upper harmonics are attenuated by 15 to 25 dB.

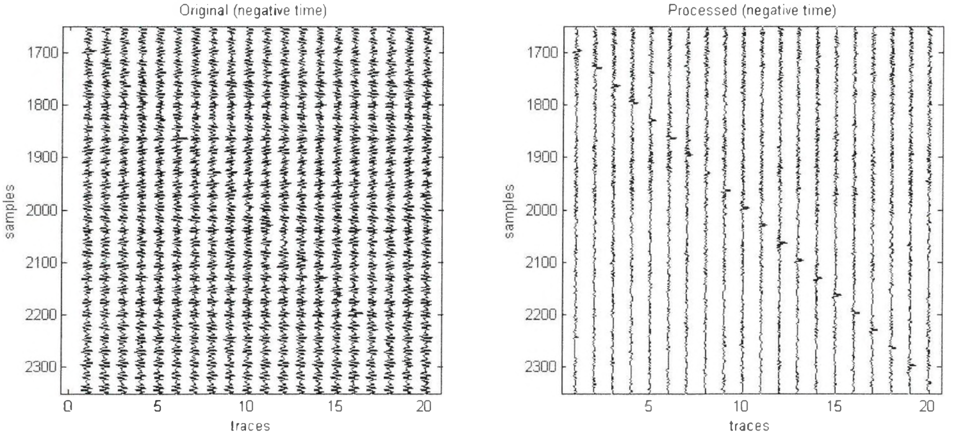

Fig. 4. Data region where a weak signal is obscured by harmonic and random noise (rectangle in Fig. 2), before (left) and after (right) the designed optimization procedure is applied

4. ábra. Adattartomány, melyben a harmonikus és a véletlen zaj elfedi a jelet (a 2. ábrán négyszöggel jelölt terület), mielőtt (bal oldal) és miután (jobb oldal) a kijelölt optimalizációs eljárást alkalmazták

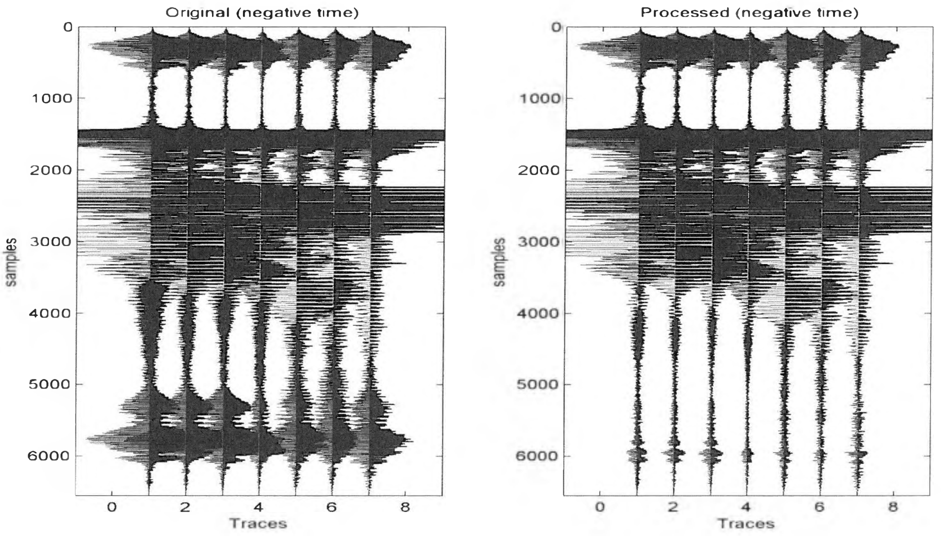

Fig. 5. Field dataset: original (left) and processed (right) traces
5. ábra. Terepi adatok: eredeti (balra) és feldolgozott (jobbra) csatornák

3. Field dataset

A field dataset acquired by ELGI in the framework of the ASAP project was considered. Results of the processing are reported in *Figs. 5* and *6* and show the attenuation of the energy due to upper harmonics (spectrograms show upper harmonic attenuation of about 15 dB).

4. Conclusions

It can be appreciated that the *ratio trace* approach (on which the present optimization schemes are based) can be proficiently adopted to handle the problem of harmonic distortion attenuation. Even if harmonic distortion can vary from trace to trace, in order to avoid problems related to instabilities due to other sources of noise, the basic entity to consider when reducing its energy is probably the common shot gather (characteristics of upper harmonics should be evaluated as average values for several traces). In this perspective stochastic optimization can provide a suitable family of

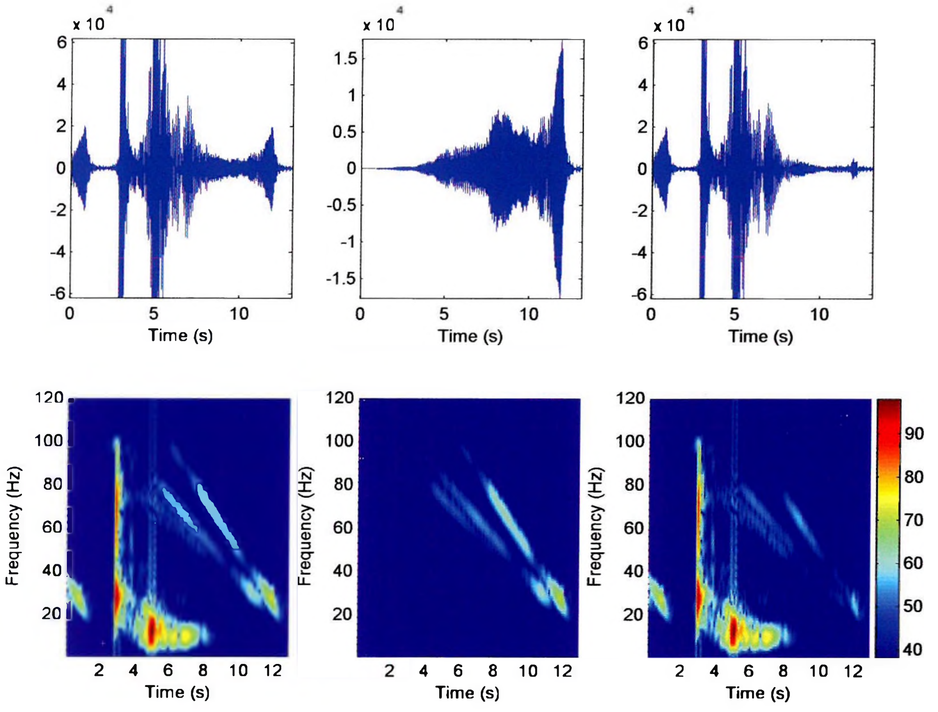

Fig. 6. Field dataset. From left to right: actual trace (and its spectrogram), estimated upper harmonic components, subtraction of this latter from the actual trace

6. ábra. Terepi adatok. Balról jobbra: aktuális csatorna (és spektrogramja), becsült felharmonikus komponensek, ez utóbbiak és az aktuális csatorna különbsége tools to handle the problem of several-trace datasets and the results presented in this study show that such approach can be successfully applied.

It can be underlined that in spite of some theoretical considerations, performance comparison between an approach based on the minimization of all the harmonics at once (energy minimization in the negative times) and a strategy to handle the different harmonics one by one (energy minimization of the correlation peak) so far shows no clear superiority of the second strategy (theoretically neater).

Further improvements currently under study regard a formulation able to limit as much as possible the use of the convolution in the forward modeling adopted in the optimization scheme (so to decrease the computational load) and a more complex way to handle the phase to allow frequency-dependent phase variations.

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Optimalizált harmonikus zajcsökkentés vibroszeiz adatokon

Giancarlo DAL MORO, SCHOLTZ Péter, Kambir IRANPOUR, Christos SARAGIOTIS

A vibroszeiz mérések gyakran szenvednek a forrásjel torzulásától, a nemlineáris jelenségek és csatolási problémák miatt, ami jelentős jel-zaj viszony csökkenést képes okozni. Ez a viselkedés különösen problémássá válik, amikor a slip-sweep mérési módszer kerül alkalmazásra a mérés produktivitásának fokozására. Ebben a helyzetben a jelgerjesztés által létrejött harmonikus torzítás valóban képes elfedni az előző rezgéskeltéshez tartozó alapharmonikus energiát. A nemkívánatos zaj csökkentésére, a harmonikus zaj meghatározási folyamatába, egy evolúciós algoritmusú optimalizációs séma kerül bevezetésre. A megvalósított zaj elnyomási eljárás hatásossága szintetikus és terepi adatrendszereken kerül bemutatásra.

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Lithospheric studies

Seismic probing of the Pannonian lithosphere: a review

Endre HEGEDŰS*

Keywords: crust, mantle, Békés Basin, refraction, reflection, astenosphere

1. Early results of lithospheric research by refraction and wide-angle reflection methods

During the first experiments in 1955 seismic arrivals were obtained from the crust–mantle boundary. Those first attempts have revealed that the crust is thinner in the Pannonian Basin than the European average (see *Fig. 1*) [GÁLFI, STEGENA 1955, 1957].

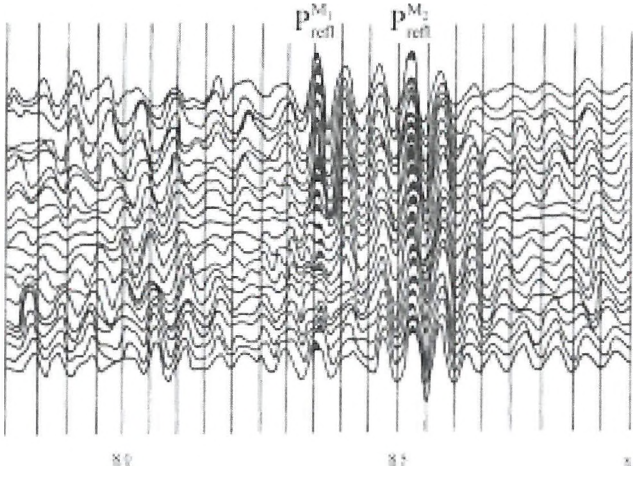

Fig. 1. Double reflection echoed from the crust-mantle boundary
1. ábra. A köpeny-kéreg határról visszaverődött kettős reflexió

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In the 60's and early 70's it became possible to map the crustal thickness in Central Europe by a grid of deep seismic profiles. An example of the international cooperation is the Adriatic Sea–Pannonian Basin–Ukrainian Shield profile (see *Fig. 2*) [POSGAY 1977].

2. Results of deep seismic reflection investigation of the Earth's crust and upper mantle: the Pannonian Geotraverse Program

In eastern Hungary seismic velocity measurements have revealed that the upper zone of the asthenosphere is in elevated position, at 53 km depth (see *Fig. 3*).

Deep seismic profiles in southern Hungary gave first evidence of a domal uplift structure of the lithosphere–asthenosphere boundary [POSGAY et al. 1995]. Beneath the Békés Basin, geomagnetic, gravity, seismic, magnetotelluric and geothermal measurements contributed towards recognizing the uplifted position of the lower crust, the crust–mantle boundary at 20–25 km depth and of the lithosphere–asthenosphere boundary at 40–45 km depth. In some places displacement (shear) zones affecting the whole lithosphere and magmatic intrusions in the upper crust have been revealed. As an example, at the SW end of the PGT–4 profile, a NE dipping major low angle shear zone is shown (*Fig. 4*). This characteristic feature can be traced downward to several tens of kilometres. The strike direction of this shear zone agrees with the known strike line of the normal fault in the western flank of the Hódmezővásárhely–Makó Graben. Besides the subsidence of the Békés Basin it may have caused a lithospheric scale slipping displacement along the downward sloping shear zone from the west. This process was able to take place along the low angle shear zone. This explains the anomalously thick sedimentary deposition in the Hódmezővásárhely Makó Graben in spite of normal (Pannonian Basin) lithosphere thickness.

3. New generation of seismic wide-angle reflection and refraction experiments in Central Europe: POLONAISE'97, CELEBRATION 2000, ALP 2002 and SUDETES 2003 programs

Beginning in 1997, a series of large seismic refraction experiments covered Central Europe with an unprecedented network of seismic profiles

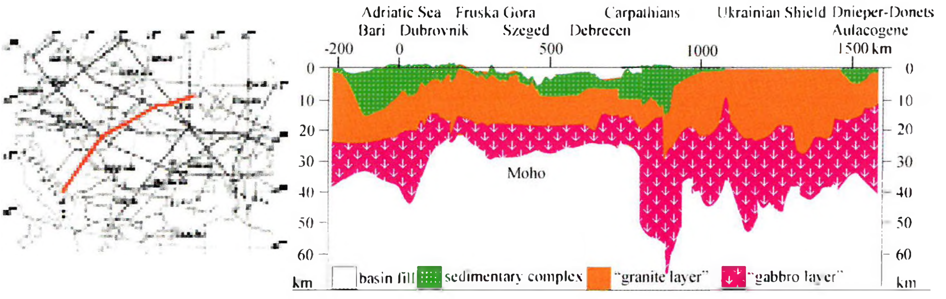

Fig. 2. Dubrovnik–Donets international refraction profile

2. ábra. A Dubrovnik–Donets nemzetközi refrakciós szelvény

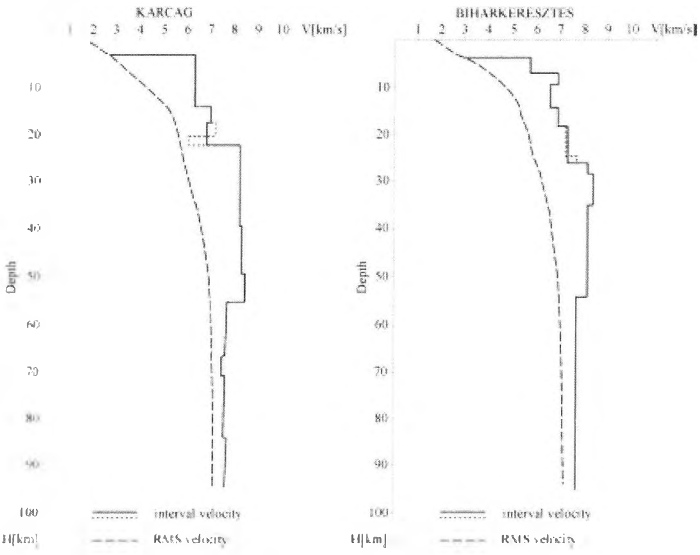

Fig. 3. Velocity determinations penetrating the asthenosphere: measured near Karcag and Biharkeresztes

3. ábra. Az asztenoszférán áthaladó sebességmeghatározások: Karcag és Biharkeresztes közeli mérések

with considerable threedimensional coverage and drew the attention of the international community to the crustal and lithospheric mantle structure and tectonics of the area. These experiments—POLONAISE'97, CELEBRATION 2000, ALP 2002, and SUDETES 2003—were only possible due to a massive international cooperative effort. Since the lithospheric structure in the region is very complex, the need for a 3-D approach was recognized early. The first of the new experiments was POLONAISE'97 [GUTERCH et al. 1999] and it showed how much could be learned from even modest 3-D coverage. A series of even larger experiments followed in rapid succession: CELEBRATION 2000, ALP 2002, and SUDETES 2003 [GRAD et al. 2006]. The coverage extends from northern Poland to the Eastern-Alps, Adriatic Sea and the Dinarides. The scientific goals of this effort included attaining a better understanding of the formation of continental Europe in the Paleozoic and the Variscan and Caledonian orogenies, as well as the subsequent formation of the Alps-Carpathian mountain chain and the Pannonian Basin. Apart from producing 2-D models along the many seismic profiles recorded, the ultimate goal was to construct a 3-D model of the lithospheric structure in the area and provide the structural background for other geophysical modeling (e.g., potential fields, heat flow).

Finally, these 3-D models could be the starting point to evaluate and develop new geodynamic models for the tectonic evolution of the whole region. The crustal structure of the Pannonian Basin is relatively simple. Below the 2–5 km thick Neogene sediments, a layer of low-velocity rocks (5.8–6.1 km/s) with a very small velocity gradient occurs down to 18 km depth. The uppermost mantle is characterized by velocities of 7.95–8.0 km/s, and the Moho lies here at a relatively shallow depth of only 22–23 km (see *Fig. 5*).

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A Pannóniai litoszféra szeimikus kutatása – áttekintés

HEGEDŰS Endre

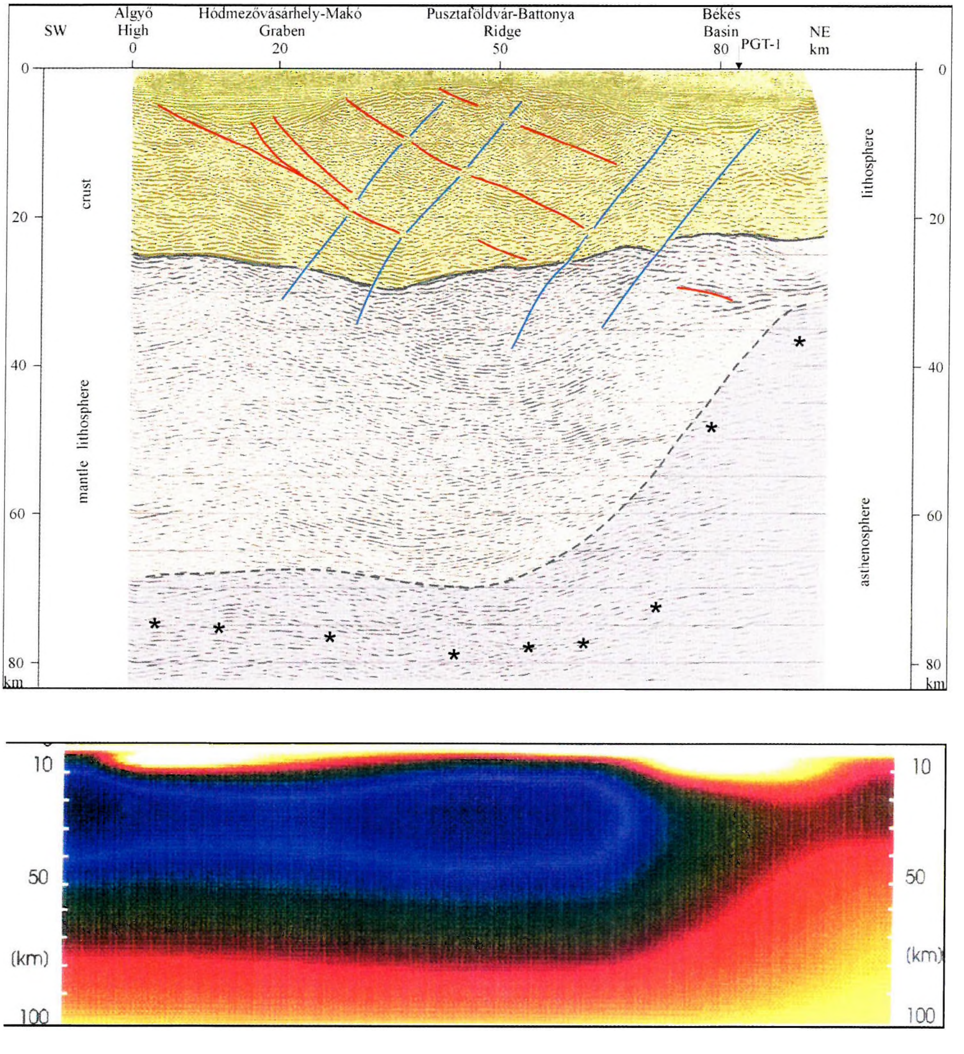

Fig. 4. PGT-4 deep reflection profile with MT profile below

4. ábra. Fent a PGT-4 mélyreflexiós szelvény, alatta az MT szelvény

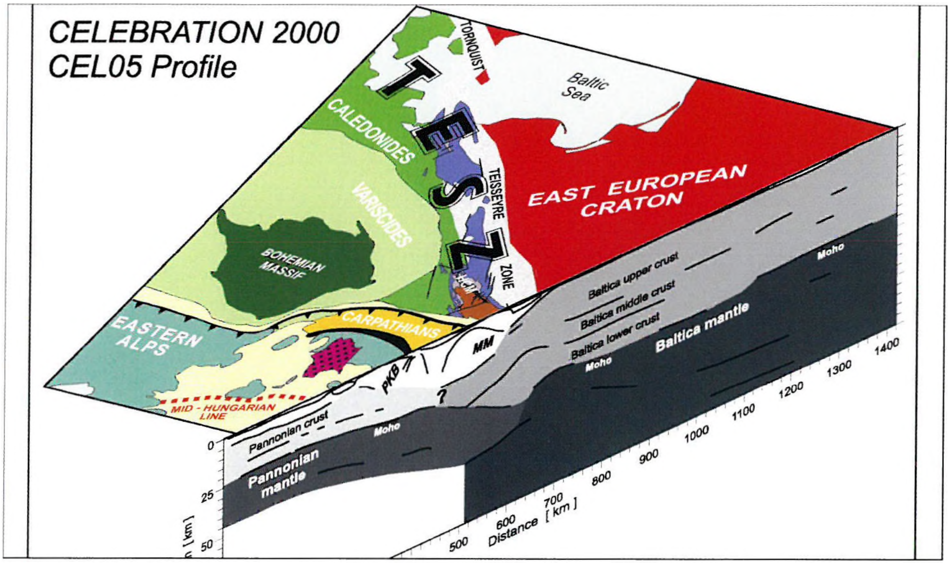

Fig. 5. Lithospheric model with tectonic map along profile CEL05 [GRAD et al. 2006]

5. *ábra.* Litoszféra modell a CEL05 szelvény mentén készített tektonikai térképpel [GRAD et al. 2006]

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Lithospheric studies

Crustal structures and tectonic processes in the Eastern Alps revealed by recent controlled source seismic experiments

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Keywords: Moho, geodynamics, lithosphere, reflection, Vienna Basin

1. Introduction

The Eastern Alps are part of the Alpine–Himalayan orogeny formed by the collision between Africa and Europe. The Eastern Alps and surrounding tectonic provinces attract geoscientific interest since the 19th century. Seismological research and findings of global relevance date back to the early 20th century [CONRAD 1925, MOHOROVIČIĆ 1910]. Investigations by controlled source seismic experiments started around 1960 [GIESE et al. 1976]. Further insight into the Alpine lithosphere brought the ALP 75 longitudinal profile [ALPINE EXPLOSION SEISMOLOGY GROUP 1976, ARIĆ, GUTDEUTSCH 1987, YAN, MECHIE 1989]. A major effort was TRANSALP, a steep angle reflection profile crossing the central part of the Eastern Alps from Munich in the north to Venice in the south [TRANSALP

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WORKING GROUP 2002, LÜSCHEN et al. 2004]. The steep angle reflection profile was supplemented by wide angle observations [BLEIBINHAUS, GEBRANDE 2006], receiver function studies [KUMMEROV et al. 2004], and gravimetric modelling [EBBING et al. 2004]. Short steep angle profiles were measured in NE Styria, near the Penninic Rechnitz window [GRASSL et al. 2004].

Despite these efforts data was not sufficient to generate a 3-D model of the crust and the Moho discontinuity at the same standard as in the Western Alps [e.g. WALDHAUSER et al. 1998]. A new chance to improve this situation has been the CELEBRATION 2000 and the ALP 2002 seismic experiments. These two experiments cover Europe from Poland to North Italy and Croatia, crossing the eastern part of the Eastern Alps. In this paper we report about results derived from this data in the Eastern Alps and their surrounding geologic provinces. We further introduce current investigations within the ALPASS – Alpine Lithosphere and Upper Mantle Passive Seismic Monitoring experiment.

2. Tectonic setting

Most imprinting tectonic development of the Alps reach back to the opening of the Atlantic and Indian Ocean in Jurassic times, anticlockwise rotation of Africa and the closure of the Tethys Ocean [e.g. LE PICHON et al. 1988]. The Adriatic–Apulian micro-plate, which belongs to the African domain, collided with Europe in Late Cretaceous to Early Tertiary forming the Eastern Alps (*Fig. 1a*). The nappe stack of the Eastern Alps overthrusted Flysch and Molasse to the north and builds the accretionary wedge. The Molasse basin represents the foreland and the Bohemian Massif, dipping to the south under Molasse, Flysch and the East Alpine nappes is part of the European platform. The Southern Alps, which continue into the Dinarides, follow south of the Peri-Adriatic Lineament (PAL). The Po plain represents the hinterland of the Alps, Istria the 'rigid' Adriatic indenter. To the east the Eastern Alps transit to the Pannonian Basin, to the north-east they continue over the Vienna basin into the Carpathians.

Tectonic structures related to convergence are the North Alpine thrust, the front of the Northern Calcareous Alp, and the South Alpine thrust. Crustal thickening took place due to the overthrusting of the accretionary

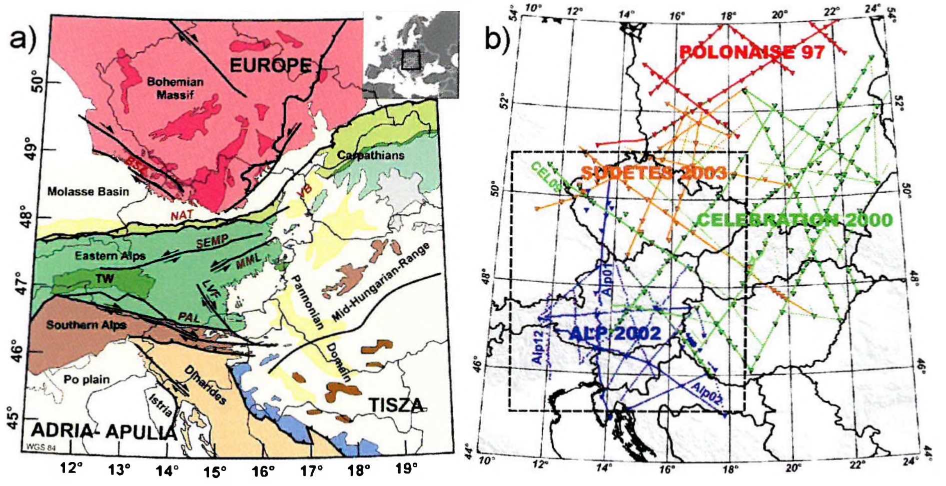

Fig. 1. a) Tectonic Setting (Eg.L.—Eger Line, NAF—North Alpine front, SEMP—Salzach–Ennstal–Mariazell–Puchberg fault; MML—Mur–Mürz Line, PAL—Periadriatic Lineament, LVF—Lavanttal fault, VB—Vienna Basin);
b) Field layout of recent large WAR/R experiments in Central Europe (POLONAISE'97, CELEBRATION 2000, ALP 2002, SUDETES 2003); CEL10, Alp01, Alp02, and Alp12 are profiles referred to in the text

1. ábra. a) Tektonikai szerkezet. (Eg.L.—Eger vonal; NAF—Észak alpi front; SEMP—Salzach–Ennstal–Mariazell–Puchberg vető; MML—Mur–Mürz vonal; PAL—periadriatikai lineamens; LVF—Lavanttal vető; VB—Bécsi medence;
b) A napjainkban folyó nagy WAR/R kísérlet terepi terítésrendszere Közép Európában. (Polonaise'97, CELEBRATION 2000, ALP 2002, SUDETS 2003); CEL 10, Alp 01, Alp02 és Alp 12 a szövegben hivatkozott szelvények

wedge and fold-thrusting. The Penninic Windows were exhumed during these processes. Lateral extrusion and post-collisional crustal thinning took place by gravitationally induced extension to the Pannonian Basin. A system of conjugate left and right lateral strike slip faults (SEMP, MML, LVF, PAL) has been activated or generated by this process [ARIĆ, GUTDEUTSCH 1987, RATSCHBACHER et al. 1991]. The Vienna Basin (VB) was deepened in this tectonic regime by the pull-apart mechanism.

3. New data

Huge amount of new seismic data was supplied by the Wide Angle Reflection / Refraction (WAR/R) experiments between 1997 and 2003 in Central Europe (*Fig. 1b*) [GUTERCH et al. 2003]. During these campaigns up to ~1000 single channel recorders were deployed along several profiles with a typical in-line spacing of 3–6 km. Shots were recorded not only along one profile, but simultaneously by all instruments. Thus a 3-D coverage of the subsurface was achieved, offering the opportunity to apply innovative processing and interpretation techniques. The data we used for our processing and interpretation comprise ~79,000 seismic traces acquired by the 3rd deployment of CELEBRATION 2000 (55 shots, 844 recorders) and the ALP 2002 experiment (39 shots, 947 recorders).

Figure 2 shows examples of records from the Bohemian Massif (CELEBRATION 2000 data) and the Eastern Alpine area (ALP 2002). All these records have good signal to noise ratio. Inline shots (Figures 2 a, c) are easy to interpret in terms of the main crustal phases. Interpretation of cross-line shots is not so easy (Figures 2 b, d). The examples shown in Fig. 2 represent high data quality, which was not achieved by all of the recordings. Interpretation difficulty of cross-line shots and low signal to noise ratio, especially in parts of the Eastern Alpine area lead to application of stacking techniques. A model of the 3-D *P*-wave velocity structure of the crust and a new Moho map have been generated by these techniques in combination with travel time tomography [BEHM 2006, BEHM et al. 2007]. Furthermore, 2-D modelling of recordings along profiles has been carried out by classical interactive ray-tracing [e.g. BRÜCKL et al. 2007].

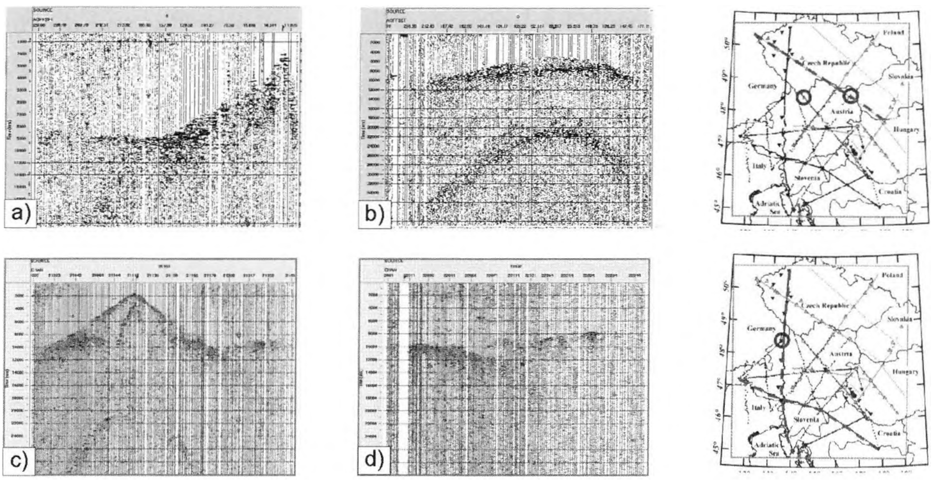

Fig. 2. Examples of records from CELEBRATION 2000, 3rd deployment and ALP 2002; (a) inline record, Bohemian Massif; (b) cross-line record, Bohemian Massif; (c) inline record, Alpine area; (d) cross-line record, Alpine area

2. ábra. Példák a CELEBRATION 2000, a 3. terítés és az ALP 2002 felvételeiből. (a) Cseh Masszivum, vonalmenti felvétel; (b) keresztező vonal felvétele, Cseh masszívum; (c) vonalmenti felvétel, Alpi terület; (d) keresztező vonalmenti felvétel, Alpi terület

4. 3-D velocity structure of the crust

Figure 3 shows *P*-wave velocity slices through the upper (5 and 7 km depth), middle (10 and 14 km depth), and lower crust (21 and 29 km depth). Penetration depth of diving *Pg*-waves differed considerably over the investigation area, as can be seen from sparse coverage at greater depth.

Velocities lower than 5 km/s correlate with Tertiary basin fillings and are found down to 7 km depth in the Pannonian and Vienna Basins. At depths of 7–14 km the Bohemian Massif is clearly differentiated into a central part (Moldanubian) with moderate velocities (5.5–6.1 km/s) and higher velocity areas (6.2–6.4 km/s) in northwest (Saxothuringian) and south-east (transition from Moldanubian to Moravian units). The peninsula Istria, a part of the unfolded Adriatic foreland, shows exceptionally high velocities in the uppermost crust (6.3–6.5 km/s). Relatively high velocities in the upper and middle crust are found in a belt north and north-east of the central Eastern Alps. The highest velocities (6.8–7.2 km/s) are found in the lower crust in an area extending from the south-eastern Bohemian Massif over the Vienna Basin to the north-western Pannonian Basin.

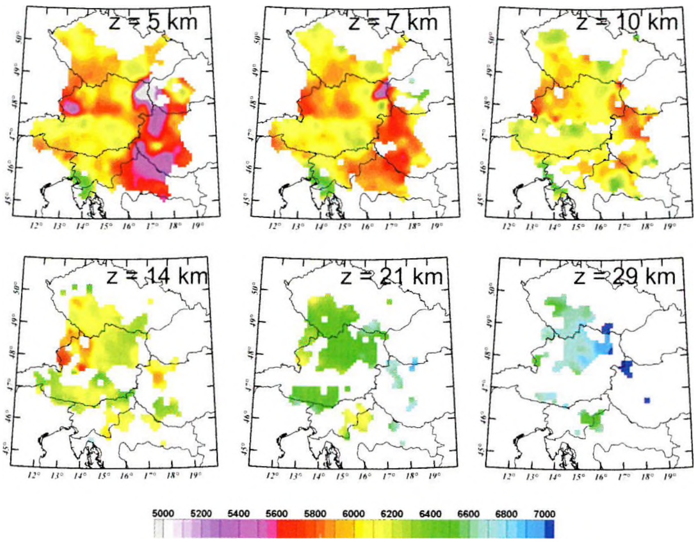

Fig. 3. *P*-wave velocity slices through the crust at 5–29 km depth; scale of colour bar is m/s; redrawn after BEHM [2006]

3. ábra. *P*-hullám sebességmetszetek a kéregben 5–29 km mélységben. A színek léptéke m/s, BEHM [2006] nyomán

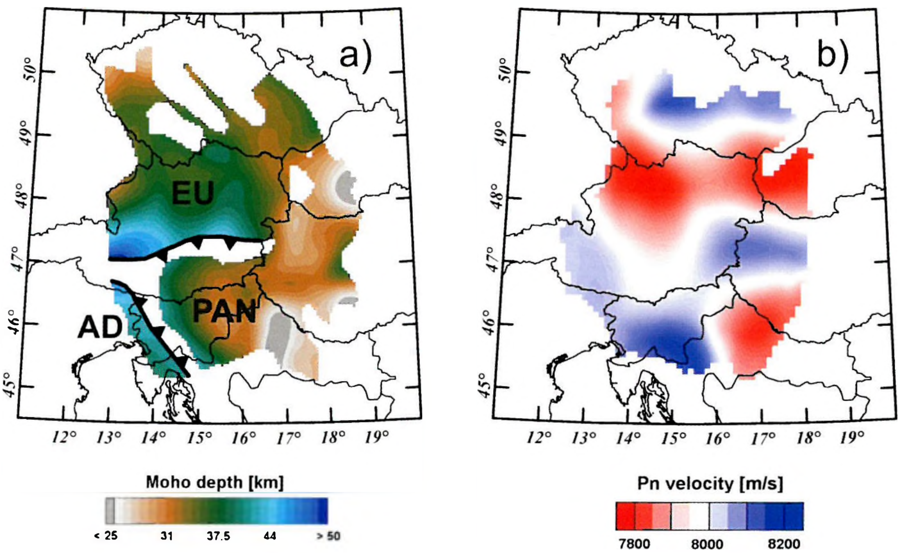

Fig. 4. *a*) Moho depth, *b*) *Pn* velocity; redrawn after BEHM [2006]

4. ábra. *a*) Moho mélység, *b*) *Pn* sebesség, BEHM [2006] nyomán

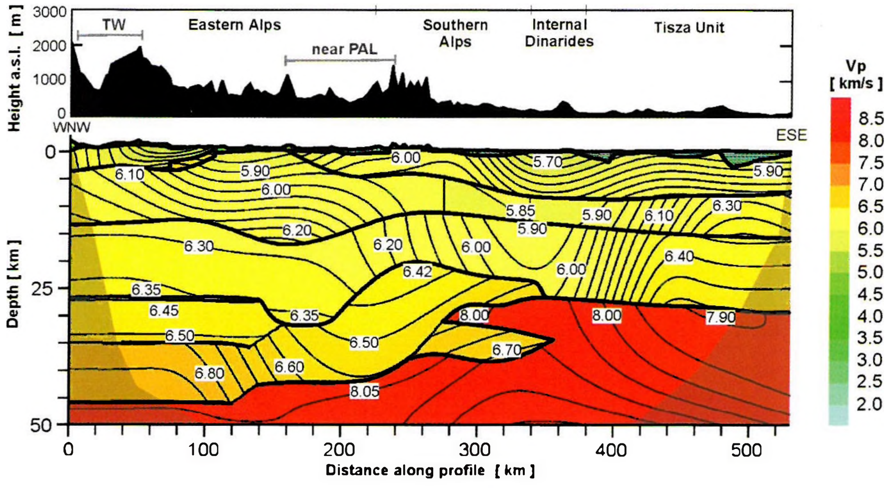

Fig. 5. Alp02 *P*-wave velocity depth section (vertical exaggeration 4:1) with velocity bar; surface topography (vertical exaggeration 25:1) and major tectonic units are shown on top; redrawn after BRÜCKL et al. [2007]

5. ábra. Alp02 *P*-hullámsebesség–mélység szelvény (függőleges nagyítás 4:1) sebesség jelmagyarázattal; a felszíni topográfia (függőleges nagyítás 25:1) és a fő tektonikai egységek az ábra felső részén láthatók; BRÜCKL et al. [2007] nyomán

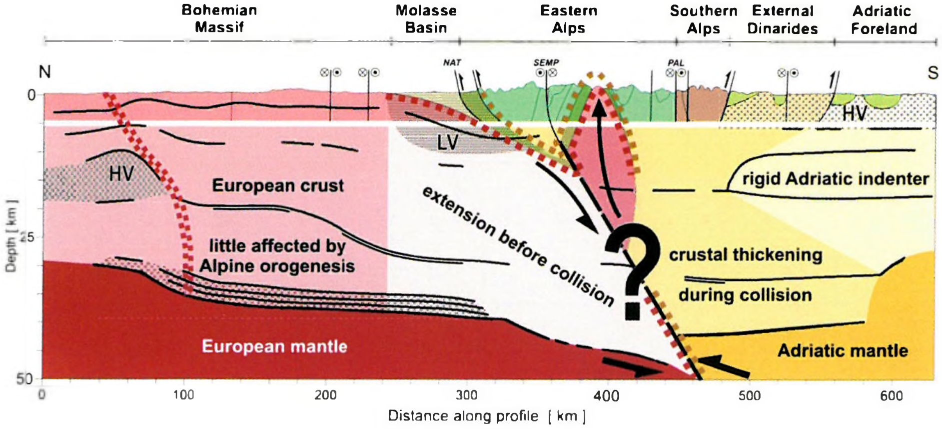

Fig. 6. Alp01 tectonic model based on *P*-wave velocity depth section derived by forward modelling using ray-tracing techniques; for description see text; redrawn after BRÜCKL et al. [2007]

6. ábra. Alp01 tektonikai modell a *P*-hullámsebesség–mélység szelvény alapján, sugárkövetéses módszerrel készített előremodellezésből levezetve; leírását lásd a szövegben; BRÜCKL et al. [2007] nyomán

5. New Moho map

The application of stacking techniques to *Pn*- and *PmP*-phases, as well as the 3-D delay time decomposition of *Pn* travel times (refraction tomography) indicate a fragmentation of the Moho in the investigated area into three parts: 'Europe' (EU), 'Adria' (AD) and the newly interpreted fragment 'Pannonia' (PAN) (*Fig. 4a*). The boundaries of these parts correlate with the strike of the Eastern Alps and the Dinarides. The Moho depths vary between 51 km in the Alpine region and 24 km in the Pannonian Basin. The European Moho dips to the south and the Adriatic Moho dips to the north-east. Both are interpreted to underthrust the Pannonian fragment. The vertical offset and fragmentation between Pannonian and the European Moho vanishes at the transition of the Eastern Alps to the Pannonian basin.

6. 2-D cross-sections

2-D forward modelling using interactive ray-tracing techniques was applied to profiles of the investigation area. The longest profiles comprising the Eastern Alpine area are the north-south directed Alp01 and the WNW–ESE directed Alp02 [BRÜCKL et al. 2007]. An important profile in the southern Bohemian Massif is CEL09 [HRUBCOVÁ et al. 2005]. BLEIBINHAUS et al. [2006] modelled in-line and cross-line data recorded at Alp12, where receivers were deployed along the former TRANSALP line. Further interpretations and publications of other profiles by interactive ray-tracing technique are in progress [e.g. GRAD et al., submitted to GJI].

The *P*-wave velocity–depth section of profile Alp02 is shown as an example in *Fig. 5*. This profile starts in the central part of the Eastern Alps and crosses the Tauern Window (TW) and takes its course sub-parallel to PAL, until it enters the Southern Alps, the Internal Dinarides, and by its last part the Tisza unit. *P*-wave velocities in the crust vary from 5.7–6.0 km/s near surface to 6.0–6.8 km/s in the lower crust. Moho-depth varies considerably from the Eastern Alpine region (~46 km) over the Southern Alps to the Internal Dinarides and the Tisza Unit (~28 km). A significant jump of ~10 km in under the Southern Alps has been interpreted as a crocodile structure.

7. Insights into tectonic processes

Collision between the European plate and the Adriatic micro-plate left its tectonic imprint on the crustal structure of the Eastern Alps in the western part of our investigation area. Tectonic interpretation of the NS directed Alp01 profile is an attempt to resolve these processes (*Fig. 6*; for location see Fig. 1b) [BRÜCKL et al. 2007].

The European Moho dips to the south below the Bohemian Massif and crystalline crust thickens. High velocity zones (HV in Fig. 6), crustal reflectors and a reflective zone above the Moho distinguish the crust. However, we assume that the Bohemian Massif was little affected by the Alpine orogenesis in this part. To the south the European plate dips below the Molasse basin. The Flysch belt and the East Alpine accretion wedge overthrust the European plate. Extension prior to collision is indicated by thinning of the crystalline crust in this area. A low velocity zone (LV) below the Molasse Basin may be a consequence of this extension or the bending of the crust. We introduced the Sub-Tauern ramp, revealed by the TRANSALP transect [TRANSALP Working Group 2002] into our interpretation. Its location is constrained at depth by the jump of the Moho from the European to the Adriatic plate, and near surface by the SEMP. Exhumation of the Tauern Window (TW) was supported by fold-thrusting along this ramp. The northern part of the Adriatic crust thickened during collision. The 'rigid' Adriatic indenter corresponds with the Istria high velocity zone (HV) and a higher Moho. The question mark over the Sub-Tauern ramp shows the zone where interpretation is most tentative.

The existence of a Pannonian fragment was derived from the Moho topography shown by the new Moho map (Fig. 4a). The pronounced jump of the Moho at Alp02 (Fig. 5) and a similar jump at the ALP'75 profile [e.g. YAN, MECHIE 1989] support this interpretation. *Figure 7a* is a schematic sketch of plate kinematics and interactions between Europe, the Adriatic micro-plate, and the Pannonian fragment. We assume that the crust of the Pannonian fragment belonged before and during collision to the Adriatic micro-plate. Lateral extrusion [RATSCHBACHER et al. 1991] accompanied by crustal thinning due to gravitationally induced extension forced isostatic Moho uplift and lead to the fragmentation. The interpretation of the *Pn*-phase stack, imaging the Moho along profile A–A' (*Fig. 7b*) supports this idea. Subsidence of surface topography corresponds to Moho uplift at depth (indicated by arrows in Fig. 7b). Ongoing NS compression is facil-

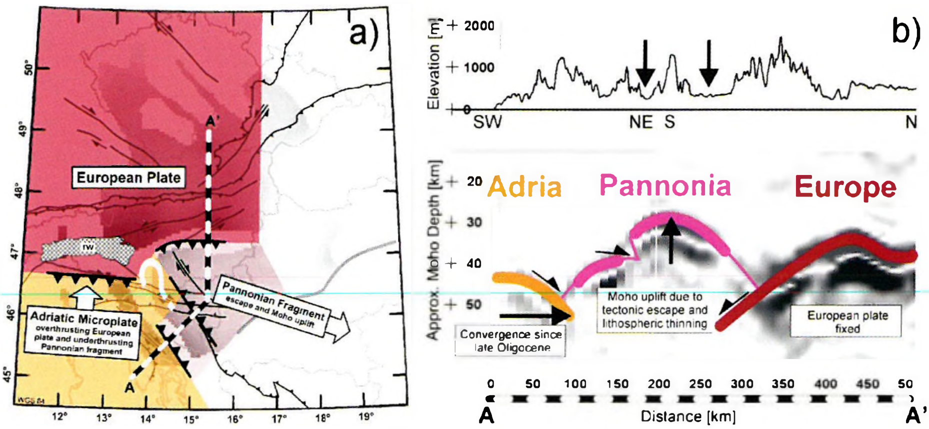

Fig. 7. Generation of the Pannonian fragment — geodynamic model; *a)* plate kinematics and interactions between Europe, the Adriatic micro-plate, and the Pannonian fragment; *b)* interpretation of *Pn*-phase stack, imaging the Moho along profile A–A'

7. ábra. A Pannon törésrendszer keletkezése — geodinamikai modell; *a)* lemez kinematika és egymásrahatások Európa, az Adriai mikrolemez és a Pannon törésrendszer között; *b)* a *Pn*-fázis stacking értelmezése, a Moho leképezése az A–A' szelvény mentén

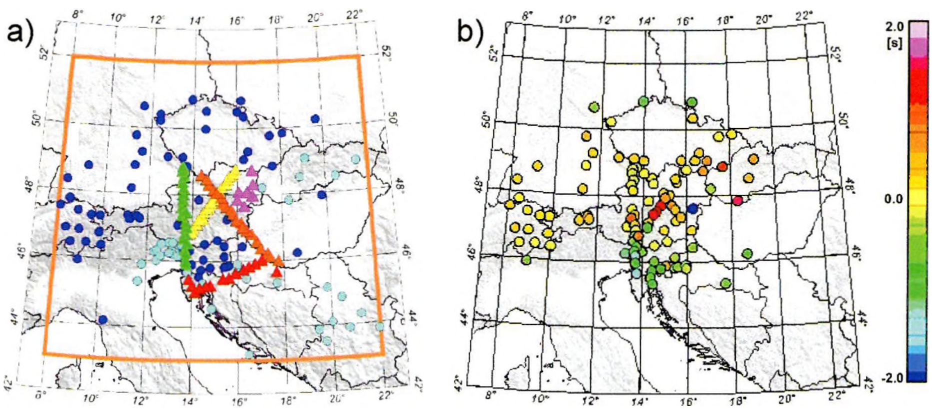

Fig. 8. ALPASS — teleseismic tomography; *a)* locations of temporary seismic stations (triangles) and permanent observatories (circles); *b)* travel time residuals of the 05 10 05 Kuril Islands earthquake.

8. ábra. ALPASS — teleszeizmikus tomográfia; *a)* az ideiglenes szeizmikus állomások helyei (háromszögek) és az állandó megfigyelési helyek (körök); *b)* menetidő reziduálok a 2005. október 5-i Kuril szigeteki földrengésről

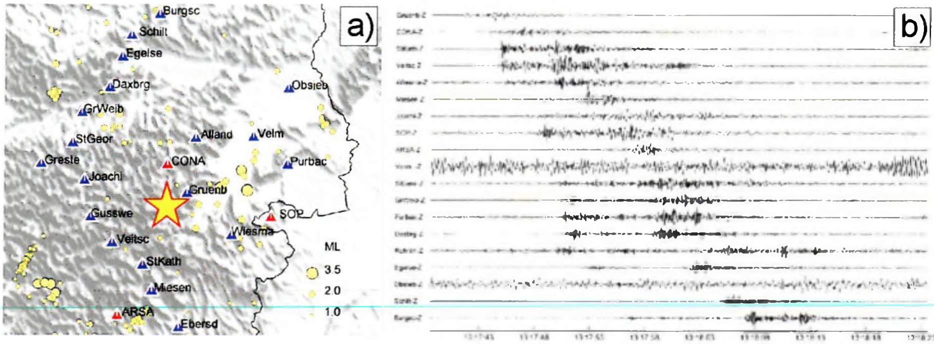

Fig. 9. ALPASS—Relocation of local earthquakes; *a)* location of temporal (blue triangles) and permanent (red triangles) seismic stations, epicentres of earthquakes during observation period (yellow circles, diameter represents local magnitude), *b)* recordings of the 2006 04 15 13:17, Ml 2.2 earthquake (location marked by yellow star in 9a) by the temporal ALPASS stations

9. ábra. ALPASS — a lokális földrengések helyei. *a)* ideiglenes (kék háromszögek) és állandó (piros háromszögek) szeizmikus állomások elhelyezkedése, a földrengések epicentrumai a megfigyelési időszakban (sárga körök, az átmérő a helyi magnitudóval arányos), *b)* a 2006. április 15-i 13óra 17 perces, Ml 2.2 földrengés felvételei az ideiglenes ALPASS állomásokon (a helyszínt a 9a ábrán sárga csillag jelöli) itated by underthrusting of the European as well as the Adriatic mantle below the Pannonian fragment.

8. ALPASS — work in progress

ALPASS is a passive seismic monitoring project aiming to reveal lower lithosphere and upper mantle beneath the wider Eastern Alpine region, and to contribute to a better understanding of the geodynamic processes at work [MITTERBAUER et al. 2007]. By cooperation of Austria, Croatia, Finland, Hungary, Poland, and the USA 57 temporary seismic recording stations were deployed from May 2005 until May 2006. The layout (*Fig. 8a*) was designed to extend the efforts of earlier experiments (e.g. TRANSALP) and to support two other passive seismic experiments (BOHEMA, CBP—Carpathian Basin Project) [PLOMEROVA et al. 2003, STUART et al. 2007], which are overlapping in the investigation area. Additionally, data from permanent networks was collected to improve coverage of the investigation area. 144 events (50% with M > 5.6) from epicentre distances between 30° and 100° were selected for teleseismic inversion. Travel time picking of *P*-wave arrivals has been done by a semi-automatic correlation technique. Crustal corrections benefit from the high resolution velocity model of the crust and the new Moho map derived from CELEBRATION 2000 and ALP 2002 data. Work on travel time picking, crustal corrections and inversion is in progress. An example of residual travel times calculated by subtracting IASPEI 91 travel times, applying the crustal corrections, and subtracting the mean is shown in Fig. 7b. This data is one of more than 100 events, which are used for inversion.

Another goal of ALPASS is relocation of local earthquakes. We first concentrate on the Vienna Basin and the upper Mürz valley. ALPASS and permanent seismic stations used for this investigation, and earthquakes occurring in this area during the observation period are shown in *Fig. 9a*. Recordings of the 2006 04 15 13:17, Ml 2.2 event (location marked by yellow star in 9a) is shown in *Fig. 9b*. Relocation will benefit from the seismic velocity model of the crust and the uppermost mantle . By accurate locations and—in case of sufficient data quality—source mechanisms derived by waveform modelling, we expect new information on seismogenic faults and their relation to known tectonic structures.

We expect both aspects of the ALPASS project will support and extend the results achieved by the recent controlled source seismic experiments. The teleseismic tomography will bring more light into the mantle structure and general plate tectonic regime, especially the existence and orientation of subducting slabs. Relocation of local earthquakes will image active faults. These structures were not resolved directly by the WAR/R type controlled source seismic experiments presented in this paper.

Acknowledgments

The CELEBRATION 2000 (3rd deployment), ALP 2002 and ALPASS projects have been realized by the efforts of scientists from 13 countries (Austria, Canada, Croatia, Czech Republic, Denmark, Finland, Germany, Hungary, Poland, Slovenia, Slovakia, Turkey, and USA) and many national grants. The Austrian contribution to these international projects has been funded by the Austrian Academy of Sciences (Geophysics of the Earth crust) and the Austrian Science Fund (FWF–P15576).

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Kéregszerkezet és tektonikai folyamatok a Keleti Alpokban

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Lithospheric studies

Lithospheric structure at the contact of the Dinarides and the Pannonian Basin in the area of Croatia

Franjo ŠUMANOVAC*, Jasna OREŠKOVIĆ*, Saša KOLAR*, and ALP2002 Working Group

Two-dimensional interpretation of the ALP07 profile, as a part of the ALP2002 project was carried out in order to define the contact between the Dinarides and the Pannonian segment. The profile ALP07 stretches in Croatia in the WSW–NNE direction from Istra to the Drava river at Hungarian–Croatian border.

Four layer model was established based on a tomographic inversion by using the Hole method. This model was used as initial model for forward seismic modelling by the Ray Tracing method and final seismic model was defined. A two-dimensional gravity modelling along the profile was also performed due to reducing the ambiguity of geophysical interpretation.

Geological model was constructed based on both models, seismic and gravimetric. Two types of crust are defined, the Dinaridic and the Pannonian crust, between which there is a relatively wide Transition zone. Troughs in seismic model at the level of Mohorovičić discontinuity are interpreted as major breaks in the lithosphere. The Dinaridic crust is divided into two parts: upper and lower crust. Upper crust is characterized by low seismic velocities and densities, but lower crust by high velocities and densities. The Pannonian crust can be seen as unique layer characterized by low seismic velocities and densities.

Keywords: Pannonian Basin, modelling, tectonics, inversion, ray tracing

1. Introduction

The Alps, particularly their eastern part together with the Carpathian range, Pannonian Basin and the Dinarides form very complex tectonic relations, whose explanation is attempted to explain through the system of tectonic plates. They are considered the southern edge of the relatively stable European lithosphere. The Dinarides and the SW part of the Pannonian Basin are located in the edge part of the exploration area of the ALP2002 Seismic Experiment [BRÜCKL et al. 2007], where key data can

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be obtained only through 2-D interpretation. For this reason, a profile which nearly vertically crosses the Dinaridic range and also covers a part of the Pannonian Basin was formed in order to define one of the most important contacts in the exploration area, i.e. the contact between the Dinarides and the Pannonian Basin. The profile is marked as ALP07, with its full length located in Croatia (*Fig. 1*).

Seismic modelling, both forward and inverse was performed on the profile, for purposes of determining the structure of the Earth's crust and upper mantle, and the relation of the Adriatic microplate and the Pannonian Basin of the Eurasian plate. Additionally, a 2-D gravity modelling along the profile was performed as well for purposes of reducing the ambiguity of geophysical interpretation.

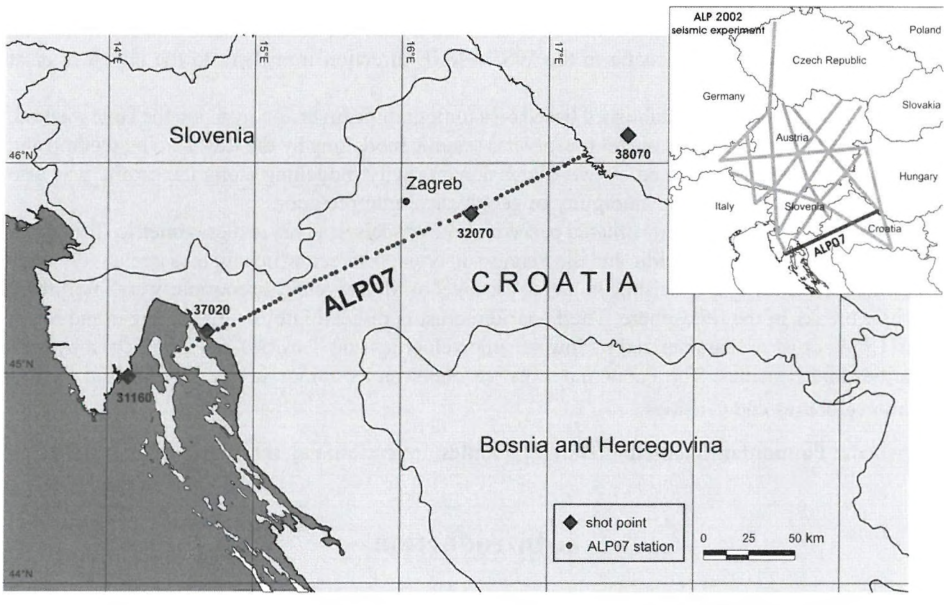

Figure 1. Locations of the receivers and shot points along ALP07 profile
1. ábra. Az észlelési pontok és a robbantópontok helyzete az ALP07 szelvény mentén

2. Data acquisition and processing

Texan instruments with geophones are placed in prior determined and checked microlocations. Microlocations are carefully selected to reduce natural noises. On the profile, there are 72 installed receivers in relatively dense distribution, at distances from 3 to 4 km, and four shot points: in

Hungary, along the border with Croatia (38070), at Ivanić Grad (32070), in Tribalj at Crikvenica (37020) and in the area of Koromačno in Istra (31160). Measurements were conducted during three nights, from 2 to 5 July 2002.

It can be generally stated that higher quality data were obtained from the shot points located in the Pannonian Basin (38070 and 32070) than from the points located in the Dinarides (37020 and 31160), as expected prior to the measurements. Namely, from the earlier deep refraction exploration projects it is known that shot points located in carbonates, i.e. generally mountain massifs, give more modest data than those located in clastic deposits, i.e. sedimentation basins. The shot point in Hungary (38070) gives the most complete data on the deep structures and the Mohorovičić discontinuity, considering that it was somewhat distanced from the first receivers and served as the main support for seismic modelling (*Fig. 2*).

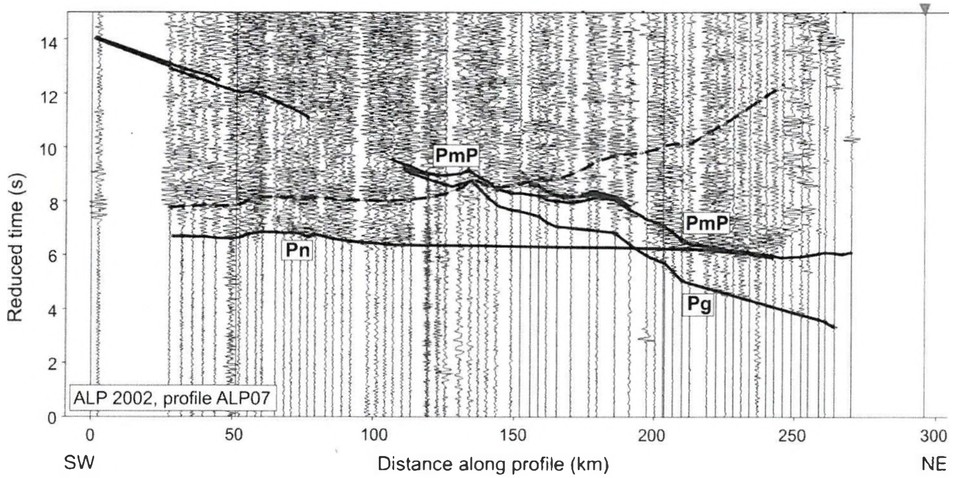

Fig. 2. Forward ray-tracing modelling of the seismic record for SP 38070. Marked are the main seismic phases *Pg* (refracted waves from the crust), *Pn, PmP* (refracted and reflected waves from the Mohorovičić discontinuity); reduction velocity is 8 km/s

2. ábra. A 38070 sz. robbantópont szeizmikus szelvényének sugárkövetéses módszerrel végzett előremodellezése. Jelöltük a *Pg* (a kéregről beérkező refraktált hullámok), *Pn, PmP* (refraktált és reflektált hullámok a Mohorovičić diszkontinuitásról) fő szeizmikus fázisokat; a redukciós sebesség 8 km/s

3. Seismic and gravity modelling

In the first interpretation phase, automatic tomographic inversion was performed by using the Hole method based only on first arrivals [HOLE 1992]. Four layer model was established which was used as initial model for forward seismic modelling by the Ray Tracing method [ČERVENY, PŠENČIK 1983]. At the very beginning of interpretation by forward modelling, it was evident that the relief of the underlying clastic deposits, i.e. bedrock, and applied velocity function strongly influence the interpretation of the deeper horizons in the crust. Therefore, the boundary was defined on the basis of data obtained in the framework of petroleum geology explorations [SAFTIĆ et al. 2003].

On the seismic model of the ALP07 profile, the depths of the Mohorovičić discontinuity are the deepest in the area of the Dinarides and equal about 40 km (*Fig. 3*). The depths in the area of the Pannonian Basin range from 30 to 20 km, and are the smallest at the profile's end. The boundary depth changes suddenly, thus making evident the uneven relief. The uplift on the profile in the positions about 140 km is defined by clear *Pn*-arrivals at the beginning of the profile, in the positions up to 110 km (Fig. 2). A very sharp trough in the positions about 245 km is defined by reflected rays from the Mohorovičić discontinuity (*PmP*-arrivals).

Low seismic velocities were generally obtained in the upper crust, about 6 km/s, but with lateral velocity changes. Thus, a very shallow anomaly with high seismic velocities at the beginning of the profile in the area of Istra and Adriatic coast stands out, and also a deeper anomaly in the positions 145–210 km, which is located under the Sava depression. These anomalies are also observed on the tomographic profile. The boundary of the Conrad discontinuity, the boundary between the lower and upper crust, is located at the depths from 12 to 17 km. Its depth gradually increases from the beginning to the middle of the profile, only to disappear as a clear boundary at the profile's end in the area after Ivanić Grad, in the position 220 km.

In the lower crust under the Dinarides, there are relatively high seismic velocities (6.6–7.1 km/s), whereas the velocities in the area of the Pannonian Basin at the profile's end are very low, only about 6 km/s. The velocities' distribution on the profile actually shows that there is no need to divide the crust in the area of the Pannonian Basin into two parts, the lower and the upper part, but rather consider it as a unified zone. On the profile

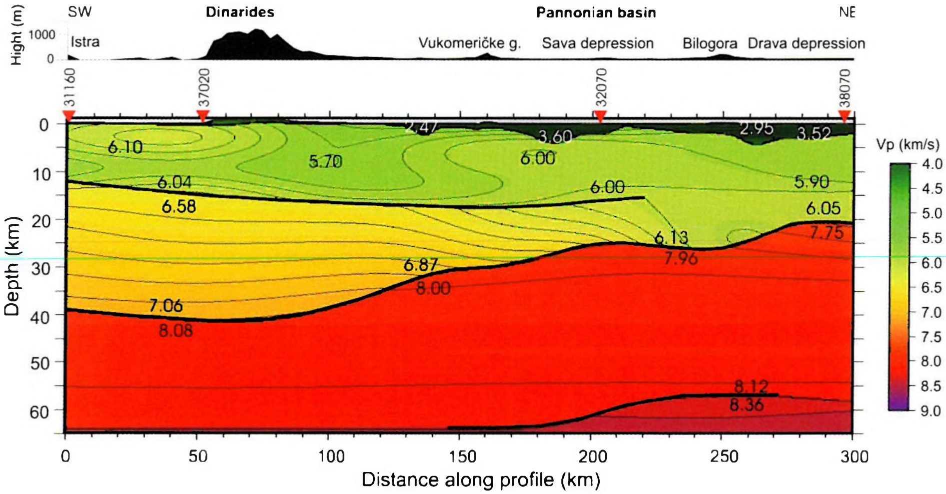

Fig. 3. Two-dimensional velocity model along the ALP07 profile obtained from forward seismic modelling. Shot point locations are marked by red triangles.

3. ábra. Kétdimenziós sebességmodell az ALP07 szelvény mentén szeimikus előremodellezéssel. A robbantópontokat piros háromszögek jelzik

ALP02, whose final part stretches through the Pannonian part of Croatia, a multi-layer crust was interpreted [BRÜCKL et al., 2007]. However, the profile stretches along the edges of the ophiolite zone, thus the profile ALP07, which stretches approximately vertically to the ophiolite zone, offers more representative data.

Two-dimensional gravity modelling was performed along the seismic profile ALP07 by using the software based on the Talwani method [TALWANI et al. 1959]. The data for the gravity profile were taken from the gravity map of the SFRY [FEDERAL GEOLOGICAL INSTITUTE 1972]. The main purpose of gravity modelling was to reduce ambiguity in geophysical interpretation. It was expected that gravity modelling would assist in the definition of the characteristics of individual layers and zones determined by seismic modelling. However, some phenomena on the seismic profile attained a new meaning, so it was proven very useful for the determination of the final geophysical and geological model.

Considering that seismic data have a much higher resolution, the boundaries of individual layers and lateral boundaries of the initial model were taken from the seismic model. The densities were also determined on the basis of seismic velocities, mostly by using experience and empirical formulas. In order to achieve an acceptable conformity between measured and theoretical gravity data, densities of individual layers, but also within the layers, were changed. The greatest changes were in the area of determination of lateral changes of densities in the upper crust. In the Pannonian part of the model the greatest changes were necessary. The results showed that there was no need to change the depth of boundaries determined by seismic forward modelling.

Gravity modelling confirmed that in the area of the Dinarides the crust consists of two parts, and that the lower crust is characterized by high densities (2.84 g/cm^3). In the area of the Pannonian Basin, at the profile's end, the crust is virtually unified, with relatively low densities (2.43 g/cm^3). The trough in the Mohorovičić discontinuity in the position 245 km was also confirmed. Already the seismic model showed the existence of a transition zone, which was much more evident in the model of densities, where it can be placed in the positions from 130 to 255 km.

4. Geological model

Based on the both, the seismic and the gravity modelling, two types of crust can be defined: the Dinaridic and the Pannonian (*Fig. 4*). The Dinaridic crust is comprised of two parts, the lower and the upper crust, whereas the Pannonian crust is virtually unified. The Dinaridic upper crust is characterized by low seismic velocities (about 6 km/s) and low densities (about 2.6 g/cm^3), while the lower crust has high seismic velocities (6.5–7.1 km/s) and high densities (2.84 g/cm^3). The Pannonian crust is characterized by similar seismic velocities as the upper Dinaridic crust, but still lower densities (2.43 g/cm^3). Between these units there is a relatively wide transition zone, i.e. contact zone. On the gravity model, it is somewhat wider than on the seismic model, but due to the clearer picture of the lateral boundaries, the gravity model was used as the basis for determination of the zone's width, thus the boundaries were set on the positions from 130 to 255 km, therefore the width equals 125 km. The southern boundary of the zone corresponds with the southern marginal fault of the Pannonian Basin, and the northern boundary (255 km) with the Drava fault (Fig. 4). The faults in the Sava depression are related to the appearance of rocks of the highest densities in the transition zone.

The troughs in the Mohorovičić discontinuity are obtained by seismic forward modelling. They probably indicate to breaks of the crust and the upper mantle. Three main breaks on the Mohorovičić discontinuity were analysed, at the contact of the core and the upper mantle. The first one is located in the position 125 km, and shows the highest jump in comparison to all breaks. The other two breaks are located under the Sava (182 km) and Drava (258 km) depressions, and are characterized by lower jumps.

Based on geometric relations and the fact that the Adriatic microplate is thrusting into the Eurasian plate, as confirmed by the data from geodetic and geodynamic measurements, it can be concluded that the Adriatic microplate at the level of the Mohorovičić discontinuity subducts under the Pannonian segment. The results of both types of modelling indicate the conclusion that there are different velocities of movement as a result of different viscosities of individual parts of the lithosphere, the upper and lower crust and the upper mantle. Thus such a great width of the transition zone as a contact point of the two crusts with substantially different characteristics, in which there are the greatest changes in seismic velocities and densities.

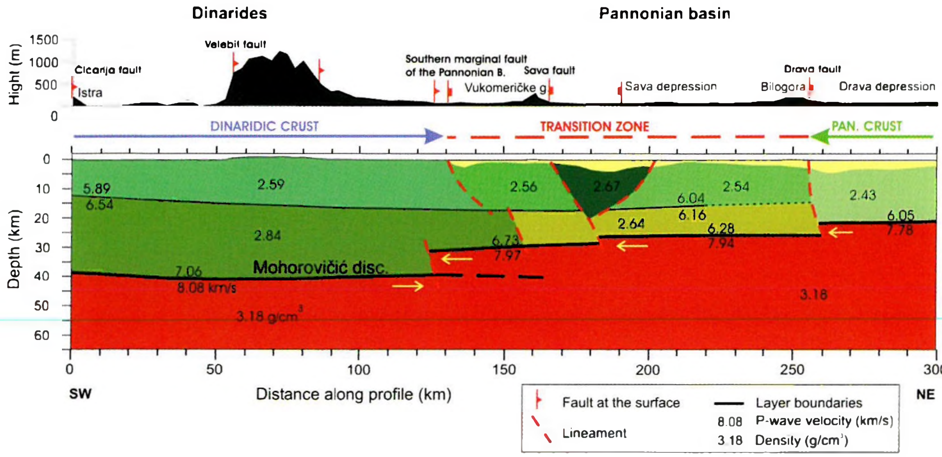

Fig. 4. Two-dimensional geological model of the crust and upper mantle along the ALP07 profile

4. ábra. Kétdimenziós sebességmodell az ALP07 szelvény mentén szeimikus előremodellezéssel

5. Acknowledgements

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A litoszféra szerkezete Horvátország területén a Dinaridák és a Pannon medence találkozásánál

Franjo ŠUMANOVAC, Jasna OREŠKOVIĆ, Saša KOLAR, Alp2002 munkacsoport

Az ALP 2002 projekt részeként az ALP07 szelvény kétdimenziós értelmezését, azért készítettük el, hogy meghatározzuk a Dinaridák és a Pannon szegmens közti határvonalat. Az ALP07 szelvény Horvátországban NyDNy–ÉÉK irányban Isztriától a magyar–horvát határt képező Dráva folyóig terjed.

A Hole módszer használatával tomografikus inverzión alapuló négyréteges modellt készítettünk. Ezt a modellt használtuk kiinduló modellként a sugárkövetéses módszerrel végzett előre-

modellezésnél, és meghatároztuk a végső szeizmikus modellt. A kétdimenziós gravitációs modellezést szintén elvégeztük a szelvény mentén annak érdekében, hogy csökkentsük a geofizikai kiértékelés bizonytalanságát.

A geológia modellt mind a szeizmikus, mind a gravitációs modell alapján megszerkesztettük. A kéregnek két típusát határoztuk meg, a Dinarid típusú és a Pannon kérget, melyek között egy relatív széles átmeneti zóna van. A szeizmikus modellben a Moho diszkontinuitás szintjén a vetődéseket a litoszférában húzódó fő törésekként értelmeztük. A Dinarid típusú kéreg két részre osztható, felső és alsó kéregre. A felső kérget kis szeizmikus sebesség és sűrűség jellemzi, míg az alsó kérget a nagy sebesség és sűrűség. A Pannon kéreg egységes rétegnek tekinthető, amit kis sebesség és sűrűség jellemez.