2 METHODOLOGICAL AND INSTRUMENTAL RESEARCH

2.1 SEISMIC METHODOLOGICAL AND INSTRUMENTAL RESEARCH

2.1.1 Dip-moveout (DMO) and prestack migration (PSM)*

NMO transforms non-zero-offset time sections into zero-offset ones with acceptable accuracy if the conditions approximate the criteria of horizontal layering, laterally constant velocity functions and small offsets relative to depth. In the case of complex boundaries and lateral velocity changes other transformation methods are also needed. For this reason, the methods of DMO and PSM have been adopted into our processing package. In the following, the position of these programs in the seismic data processing package is discussed with emphasis on our special solutions.

Conventional data processing includes:

— CMP trace gather,
— velocity analysis,
— NMO,
— stacking,
— migration.

NMO is carried out with the velocity function $V/\cos\theta$ in which V = rms velocity, θ = dip angle of the reflector.

Problems arising with NMO are displayed in *Fig. 72*. At a given CMP and time, the signals reflected with a velocity $V_A/\cos\theta_A$ from point *A* are stacked with the signals arriving from point *B* at the same time with the velocity $V_B/\cos\theta_B$. If $V_A/\cos\theta_A$ significantly differs from $V_B/\cos\theta_B$ problems arise during stacking. If V_A nearly equals V_B and only the dip angles differ, the DMO completely solves the problem; hence, this method eliminates dip effects in the stacking velocity. After DMO, the signals from the two points have to be summed with the same velocity, and this velocity is also suitable for migration. The data processing is in this case as follows:

— NMO,
— common-offset trace gather,
— DMO,
— inverse NMO,
— CMP trace gather,

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- velocity analysis,
- NMO (with velocity functions independent of the dip),
- stacking,
- migration.

The result of DMO is provided by the solution of the following differential equation:

$$P_{ht} = \frac{h}{t} P_{xx},$$

where $P(x, h, t)$ = the measured common-offset time section, after NMO,
x = coordinate of CMP,
h = half of the offset,
t = time.

The solution is $P(x, 0, t)$, the zero-offset time section achieved by the method of finite differences.

If the lateral and vertical velocity changes are significant, V_A can sharply differ from V_B, and the travel paths of events reflected from A and B are different, in this case DMO does not solve the problem. Moreover, stacking after DMO may produce an even lower quality time section than conventional stacking if the difference between $V_A/\cos\theta_A$ and $V_B/\cos\theta_B$ is less than that between V_A and V_B. In this case, PSM has to be applied with velocities V_A and V_B, and the data processing will be re-formed as follows:

- NMO,
- common-offset trace gather,
- 1st step of PSM,
- CMP trace gather,
- inverse NMO,
- velocity analysis,
- NMO,
- 2nd step of PSM,
- stacking.

The following two differential equations give the solution of PSM:

$$P_{\tau t} = \frac{\tilde{V}}{4} P_{xx},$$

where: τ = two-way vertical traveltime,
t = time,
x = coordinate of CMP;

$$\tilde{V} = \frac{V^2}{2}\left\{1-\left[1+\left(\frac{2h}{Vt}\right)^2\right]^{3/2}\right\}\cdot\left[1+\left(\frac{2h}{Vt}\right)^2\right]^{-1/2},$$

where: V = $V(x, \tau)$, rms velocity,
$2h$ = offset,
$P(\tau, t, x)$ = wave field,

$P(\tau=0, t, x)=$ common-offset time section after NMO,
$P(\tau, t=0, x)=$ solution of the differential equation.

The second differential equation is the following:

$$P_{ztt}+\frac{V}{4}P_{xxt}-\frac{V^2}{16}P_{xxz}=0,$$

where: $z=$ depth coordinate,
$P(z, t, x)=$ wave field,
$P(z, t=0, x)=$ solution (the result of PSM).

In the first step, multi-offset time sections are transformed into zero-offset time sections. In the second step, zero-offset time sections are migrated, then, stacking is carried out. Consequently, the input of the second step is represented by the output of the first step. The response of the method can be studied by the application of the so-called 'single signal' model input. The 'single signal' model is constructed by placing Ricker wavelets along a trace at discrete instants. The model is displayed in *Fig. 73* with wavelets every 100 ms. The results of the first step of PSM ($V=3000$ m/s, $2h=800$ m, $x=12.5$ m) are presented in *Fig. 74*. In *Fig. 75* the results of DMO are shown. They are similar to those of the first step of PSM, with a better signal-to-noise ratio although DMO can be used for a narrower dip range.

In our next model diffractor points have been arranged every 150 m in the 150–1200 m depth interval ($V=3000$ m/s). In *Fig. 76* the corresponding zero-offset single-channel time section ($\Delta x=12.5$ m) is displayed. After NMO and the first step of PSM, the time section did not change. The 2nd step of PSM produces the migration of the zero-offset time section *(Fig. 77)*. The $2h=800$ m offset time section of the same diffraction model is shown in *Fig. 78*.The time section after NMO is displayed in *Fig. 79*, and after migration in *Fig. 80*. Here the essence of PSM can be seen. This migrated time section significantly differs from the zero-offset time section (Fig. 77), the diffraction hyperbolae are not focused to one point. The stacking of these two sections leads to a decrease of the signal-to-noise ratio. *Fig. 81* illustrates the transformation of the $2h=800$ m offset time section into a zero-offset time section (1st step of PSM). In *Fig. 82* the $2h=800$ m offset time section is displayed after the 1st and 2nd steps of PSM: it is much more similar to the migrated version of the zero-offset time section (Fig. 77).

Since PSM can be applied to time sections after NMO, its sensitivity to the accuracy of the velocity function has to be studied. Our experiments demonstrated that this method is not sensitive to velocity errors. Furthermore, the sensitivity of the method to the offset has also been investigated. The first step of PSM was performed with $2h=600$ m *(Fig. 83)* and with $2h=1000$ m *(Fig. 84)*. The time sections obtained essentially differ from that in Fig. 74. It can be concluded that PSM significantly depends on offset.

2.1.2 Possibilities to increase the horizontal and vertical resolution in oil and gas prospecting*

In detailed oil and gas prospecting, the demands on the resolution of field seismic surveys are increasing. In the Füzesgyarmat–Szeghalom area (southeastern Hungary) field surveys above a more-or-less known deposit have been carried out for several years. Most of the profiles were located inside or near inhabited areas so that explosive sources were inapplicable.

In 1989 methodoligical experiments were carried out along a profile formerly shot by conventional VIBROSEIS parameters (linear sweep, long vibrator and geophone array), where field conditions allowed explosive sources. It is well-known that VIBROSEIS time sections are usually of lower frequencies, and display more homogeneous frequency distribution and lower resolution than those of explosion seismics in the same areas. The reasoning behind this usually mentions the limitation of the spectrum of vibrators and the high-cut effect of the near-surface low-velocity layers. Besides these two unavoidable factors of the spectrum band limitation there are further high-cut effects which can considerably be decreased by the choice of the source and recording parameters in the field. For instance, the long vibrator and geophone arrays, generally used for the elimination of vibrator ground rolls, have a drastic high-cut effect on the reflection signals at offsets comparable with the investigated depths. A similar effect is produced by the response of the vibrator–ground coupling which sharply enhances the 15–35 Hz interval.

The ground rolls can be eliminated by a special parametrization of the vibrator and recording system known as stackarray. The essence of this system is that the length of both the vibrator and geophone arrays equals the distance between shotpoints, and that shotpoints are located half-way between geophones independently of the wavelength of the ground rolls. In a system like this stacking of the NMO-corrected CDP traces produces such a filtering effect against the NMO-uncorrected coherent noise as a uniformly sampled array of a length corresponding to the maximum offset. Thus, noise elimination is performed during CRP stacking, not during recording.

The most favourable stackarray for signal resolution can be achieved by split spread with equal geophone and vibrator array spacing and no geophone array overlap. *Fig. 85* displays the wave-number response of the spread and array system of the methodological experiment. In Fig. 85/a, in the response of the 60-fold coverage system the alias peaks appear at wavelengths which equal integer multiples of the shotpoint spacing. The response of geophone arrays designed in accordance with the stackarray criteria (Fig. 85/b) have zero values just at these points so that a flat response function, free of alias peaks, is the resulting response (Fig. 85/c).

At the beginning of the experiments the spectrum of the signal of the base was recorded. This spectrum is considerably distorted by the response of the vibrator–ground coupling compared with the theoretical spectra *(Fig. 86)*. If

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the sweep is linear a resonance peak appears in the 20–30 Hz band. We attempted to flatten this peak by an asymmetric combisweep of five members (see *Table VI*) and succeeded to a certain extent (Fig. 86/b).

In *Fig. 87* a conventional Vibroseis record and one with the field parameters described above are displayed. By comparing the records two main differences can be revealed: in the record of linear sweep and long geophone array (Fig. 87/a) there are no ground rolls and the apparent frequency of the reflections tends to be rather constant, 25–30 Hz, independently of the arrival times. In the record displayed in Fig. 87/b ground roll is significantly intensified and the apparent frequency of the reflections is essentially higher; furthermore, the reflection character is much more differentiated than in the previous record. In the traces near the explosion point the high-cut effect of the geophone array is very weak, therefore here it is unambiguous that the difference in the frequency patterns results from the flattening of the resonance peak of the input spectrum and from the enhancement of high-frequency components. Judging from model calculations at large offsets (> 1000 m) the 40 m long geophone array attenuates the high-frequency (70–90 Hz) components by 12–20 dB compared with the short arrays.

In *Fig. 88* the same part of the two Vibroseis and the explosion seismic time sections are displayed. Comparison of the time sections reveals that explosion seismics (Fig. 88/c) unambiguously provides the best vertical and horizontal resolution (for field parameters, see Table VI). The Vibroseis time section of the experimental source and recording parameters (Fig. 88/b) demonstrates an obvious improvement compared with the conventional one (Fig. 88/a). Consequently, the stacking of stackarray records has filtered the ground rolls which clearly developed in the field record (Fig. 87/b), and at the same time the high-frequency content of the records has been preserved.

	Conventional Vibroseis	Methodological experiment (Vibroseis)	Explosion seismics
Number of channels	120	120	48
Sampling rate	2 ms	2 ms	1 ms
Geophone spacing	20 m	20 m	10 m
Source spacing	40 m	20 m	10 m
Coverage	30	60	24
Length of geophone arrays	40 m	20 m	10 m
Length of vibrator arrays	40 m	20 m	
Sweep	18–92 Hz	18–92 Hz 1 × 24–92 Hz 1 × 30–92 Hz 1 × 36–92 Hz 2 ×	
Explosion depth			38 m
Explosion weight			1 kg
Minimum offset	200 m	190 m	25 m
Maximum offset	1380 m	1370 m	255 m

Table VI. Comparison of the source and recording parameters applied in the methodological experiment

The normalized amplitude spectra of *Fig. 89* demonstrate in a quantitative way the differences in frequency content and resolution caused by different source and recording parameters. The comparison unambiguously shows that the explosive source and connected recording parameters result in a spectrum most abundant in high frequencies. If surface conditions do not allow explosives to be used as the energy source, the improvement obtained by the above described field parameters also has to be appreciated.

2.1.3 Integrated processing of well-logging and seismic data on personal computers*

One of the fundamental goals of seismic data processing consists in an integrated interpretation of high-resolution well-logging data and seismic sections. In the spring of 1989, we started elaborating a new personal computer program system which provides flexible and rapid processing for such an integrated interpretation.

The input of the program system is formed by well logs, seismic traces and VSP data. From well-logging data at present we use acoustic transit time, density and neutron porosity logs. The input seismic data are represented by conventionally processed migrated traces. The link between acoustic and seismic data is created by VSP measurements.

The system now has four principal functions (subprograms) which are built in a step-like way:

— seismic–acoustic analysis,
— constructing seislog sections,
— constructing seismic porosity sections,
— computation of seismic attributes.

The program elaborated for the IBM AT/PC is connected to the conventional processing package at the endpoint (migration). Migrated traces can be loaded into the PC through the terminal line. The possibilities provided by the program are demonstrated by the block scheme of *Fig. 90*. Various operations can be chosen from the menu system.

One of the aims of *seismic–acoustic analysis* involves precise identification of the lithology in the seismic sections. This is carried out by using well-logging data. The synthetic seismograms computed from sonic velocities or acoustic impedances are comparable with the corresponding migrated traces and the filtered sonic velocity curve or the filtered acoustic impedance curve with the seislog. In this way, by searching for similar features the high-resolution well-logging data can be correlated with the corresponding features in the seismic section within the limits of the seismic resolution. The other aim of the analysis consists of constructing the acoustic model needed for the seislog and correlating the acoustic and seismic traveltimes (calibration).

Based on the VSP measurements, the program system provides a possibility to calculate the drift curve displaying the difference between the acoustic and

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SEISMIC-ACOUSTIC ANALYSIS

Drift calculation
Transformation from depth to TWT
Spectrum analysis
Computation of synthetic trace
Comparison of synthetic trace with migrated time section
Filtering of sonic velocity or acoustic impedance curve

COMPUTATION OF SEISLOGS

Picking of seismic horizons on migrated time section
Creating step-like sonic velocity curve
Interpolation between boreholes
Producing the low-frequency velocity model by filtering
Calculation of relative seislog
Producing the absolute seislog by superposition

COMPUTATION OF SEISMIC PSEUDOPOROSITY SECTIONS

Calculation of shale content
Computation of effective porosity
Creation of crossplots
Processing of pseudoporosity section

CALCULATION OF SEISMIC ATTRIBUTES

Instantaneous phase
Instantaneous amplitude
Instantaneous frequency
Apparent polarity

Fig. 90. Menu system of the program

seismic traveltimes as a function of depth *(Fig. 91)*. This difference can be taken into account in transforming the well-logs into functions of seismic two-way traveltimes *(Fig. 92)*. The frequency of the wavelet for computing synthetic seismograms can be defined from the spectrum of the migrated traces *(Fig. 93)*.

The program provides the possibility to use either minimum- or zero-phase Ricker wavelets and Klauder wavelets. In the program the seismic traces recorded in the vicinity of the well and the synthetic seismogram can be called on the screen together *(Fig. 94)*. Finally, the low-frequency velocity component needed for the absolute seislog can be constructed by filtering the sonic velocity curve.

In order to *computate the absolute seislog section* the migrated section can be called on the screen where seismic sequences can be selected by moving the cursor *(Fig. 95)*. The sonic velocity curves can be transformed into a step-like form in accordance with the sequences selected. By interpolating between the wells, a step-like thick-layer velocity model can be constructed the low-frequency filtering of which results in a low-frequency velocity model *(Fig. 96)*. By superimposing the relative seislog computed by the program we set the absolute seislog section.

The third subprogram of the program system makes the *construction of a porosity section* possible. Comparing the available acoustic parameters with the neutron porosity results in various crossplots. Furthermore, it is possible to calculate the clay content and the porosity corrected for the clay content. As an example, a clay content–effective porosity crossplot is demonstrated *(Fig. 97)*. Finally, from the clay content and the velocity–porosity relationship the absolute seislog, regarded as a pseudovelocity section, can be transformed into a two-component porosity section.

The fourth subprogram calculates *seismic attribute sections* by Hilbert transformation and median filtering. The instantaneous phase, the amplitude strength, the instantaneous frequency and the apparent polarity sections can also be computed.

An EGA monitor makes the coloured imaging of the seismic sections possible both in time- and depth-section forms. In *Fig. 98* an absolute seislog, a porosity corrected for the clay content and an amplitude strength—depth section are seen. To help interactive interpretation, several sections can be called on the screen simultaneously *(Fig. 99)*. If a seismic horizon is selected in the instantaneous phase section, for example, it will be marked automatically in all other sections, and the horizontal variation of the parameters (velocity, porosity, amplitude strength, etc.) can be displayed along the seismic horizon.

We express our thanks to P. Szabó and Gy. Táborszky for elaborating the terminal connection between the R–61 computer and the PC and to L. Zilahi Sebess jun. for his assistance in compiling the program system for the processing of well-logs.

2.1.4 In-mine reflection measurements in multiseam brown coal deposits*

The theoretical background of in-mine reflection measurements was first elaborated in the FRG and Great Britain. In both countries most of the productive complexes can be approximated by a three-layer model (roof/coal/

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bedrock). In Hungary, however, the brown coal seams are usually interrupted by unproductive layers of various thickness, producing a 'sandwich' structure. In such conditions the processing and the interpretation of seam wave seismics do not correspond to the three-layer theory in which results can be achieved by enhancing and enveloping the Airy phase.

Therefore, as the first step, the dispersion properties of the seam waves in sandwich-type coal seams were investigated. Two three-layer models have been studied *(Fig. 100)*: in the first (I) the thickness of the coal seams varied while in the second (II) the quality, i.e. their acoustic impedance, was different. From the dispersion curves *(Fig. 101)* it can be seen that the modes and especially the Airy phases of the modes cannot be recognized from their frequencies. Thus, the basal and higher modes cannot be distinguished by frequency filtering which was formerly successful in the data processing.

Besides the dispersion curves, the vertical amplitude distributions are also characteristic of the seam waves. In the sandwich-type models these are quite interesting *(Fig. 102)*. While the low frequency of the basal mode is distributed uniformly in the three coal seams, the energy of the individual modes becomes dominant in various coal seams with increasing frequencies. This means that although the individual modes cannot be separated by their frequencies they can be distinguished in space. In other words, the wave form depends on the coal seam in which the detectors are placed. This is demonstrated by the synthetic seismograms of *Fig. 103*. In the computations it was supposed that the detectors were placed in the median planes of the individual coal seams with 5 m spacing with the offset to the first sensor being 100 m.

The phenomena described are decisive in the course of data processing and interpretation. If the precise location of the source and detectors within the given thick multiseam deposit is unknown—which is most likely—the data cannot be processed in the usual way. CDP stacking becomes impossible since stacking is based on the similarity of the signals to be stacked, which condition is not met. The problem can be solved in two ways. One of the possibilities is to compress the dispersive signals. This needs relatively precise knowledge on the dispersion curve which generates innumerable further problems. Moreover, precise data are needed on the parameters of the coal deposit (thicknesses, velocities, densities) which are, on the one hand, difficult to obtain but, on the other hand, are almost impossible to define due to the lateral inhomogeneities of the coal seams. That is why this way is difficult to follow.

The other possibility of data processing and interpretation seems to be very simple and fruitful, as modelling proves. In this case the high frequencies are removed by a high-cut filter, and the relatively low-frequency interval of the spectrum is preserved. Since this interval—as can be seen in Fig. 102—is present in each coal layer it can be recorded independently of the position of the detectors inside the coal seam. The low-frequency data obtained in this way are further processed as was done in the case of the three-layer model. Of course, it has to be taken into account that the resolution is decreased and the signal-to-noise ratio worsens due to the high-cut filter.

After the theoretical considerations two in-mine reflection profiles *(Figs. 104* and *105)* are discussed. These two sections are of lower quality and more noisy compared with formerly published results. Despite this fact, two large faults have been discovered which call attention to the danger of karst-water inrush. Obviously, there is no need to stress the importance of this result.

Since most of the coal deposits in Hungary belong to the same sandwich-type model the outlined procedure forms the basis for the application of reflection seismic methods. This is important for both exploitation and in-mine safety.

2.1.5 Refraction tomography: A methodological experiment*

The seismic velocity tomography program [Hermann et al. 1982] was used mainly in mines [Körmendi et al. 1986], but several attempts were made to use it for the processing of areal (3-D) refraction measurements [Bodoky et al. 1983]. Based on all our former experience, in 1989 we performed a new experiment in connection with a shallow refraction survey. The aim of the experiment was to investigate the block structure of the limestone in a quarry with relatively thin cover.

It is known that in 2-D seismic velocity tomography based on a geometrical optical approximation (wave propagation along curved raypaths) the velocity distribution within the area 'enclosed' by the profiles is determined from the traveltimes of transmission waves along numerous raypaths which cross each other. Two important fundamental conditions are that the observation system is co-planar and the raypaths follow the measurement plane. It is obvious that these conditions are not met in refraction seismics. *(Fig. 106)*: the raypaths step out of the SG plane of measurements, and the T_S and T_G times of propagation in the low-velocity layer are added to the T_R time which is characteristic for the velocity of the refractor. These correction times have been determined from the shallow refraction profiles $\overline{AB}$, $\overline{BC}$, $\overline{CD}$ and $\overline{DA}$ which formed the primary task of the prospecting *(Fig. 107)*.

In the course of the tomographic measurements we shot the observation systems on the lines $\overline{AB}$ and $\overline{AD}$, each with 24 geophones, by a hammer from 27 shotpoints on profiles $\overline{BC}$ and $\overline{CD}$ using the stacking capabilities of the shallow seismic instrument ESS–01–24 (in principle, 888 arrivals without the direct arrivals from the near sources).

The resulting map is presented in *Fig. 108*. Data of the refraction profiles (Fig. 107) are in good correlation with the tomographic map, but are not equal. The refraction profiles give the velocities of head waves at relatively small offsets, while in the tomographic survey offsets are much longer so that waves penetrate deeper into the layer thus propagating faster. In contrast to refraction profiling the tomographic map does not provide the thickness of the low-velocity layer. Therefore, this method does not substitute refraction profiling but extends its information content.

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By mapping the velocities the fresh, non-tectonized and well-preserved rocks of higher velocity can be separated from the weathered, altered, fractured or less consolidated blocks. A linear structure has been supposed on the basis of the presence of a velocity gradient perpendicular to the NE–SW direction in the tomographic map. The two areas divided by this fracture are of different composition or consist of rocks that have been subjected to various environmental effects. In order to reveal concrete local reasons for the anomalies of the velocity map, further geological investigations would need to be carried out.

For references, see Hungarian text.

2.1.6 Investigation of the resistance of buildings to vibrations*

In the course of Vibroseis measurements in inhabited areas the danger of vibration damage in buildings frequently arises. It was for this reason that studies on the resistance of buildings to vibrations were started in 1989.

The precise determination of the vibration effect produced on buildings and the elaboration of a suitable measurement method were the goals of the methodological study. The most important questions to answer: whether resonance can arise in an ordinary building-ground system (e.g. one-family house) in the Vibroseis frequency range or not and if yes, how much the amplitude of the vibration within the building exceeds that in the ground. From published data it was clear that within the vibrator–building distances studied neither dispersion induced spectrum distortion nor the effect of reflected waves is to be expected.

First of all the instruments used for the experiment had to be calibrated. Therefore, the transfer characteristics of the whole recording system, channel by channel, starting with the geophones and ending with the digital recording, were determined by a high-precision B&K vibration meter. We succeeded in linearizing the transfer above 8 Hz by correction filters.

In the course of the field measurements we tried to discover the resonance effect in a single-story house and by determining *P*- and *S*-wave velocities in the superstructure, obtained primary data for the computer modelling of resonance by the finite-element method. The field observation system consisted of groups of three-component geophones with 4.5 Hz eigen-frequency, of ELGI's shallow-seismic instrument ESS–01–24 and of a Failing 1100–CB vibrator. Based on the spectra of noise records we found the resonance frequency of the mechanical fastening elements of the geophone groups on the walls to be beyond the studied frequency range *(Fig. 109)*. The configuration of the observation system is seen in *Fig. 110*. The vibrator generated vertical monofrequencies in the 4–40 Hz range and the velocity of the vibration was recorded at observation points *A*, *B*, *C* and *D*. The maximum amplitudes were recorded at point *B* in the *x* direction. Their spectra constructed from recorded amplitudes at the individual

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source frequencies are presented in *Fig. 111*. Maxima in the ranges around 8 and 16 Hz of one octave distance represent the resonance frequency of point *B* of the house and its first harmonics (the peak at 4 Hz results from the nonlinearity of the observation system).

A general analysis of the phenomenon is planned to be performed in a computer model. To check the suitability of the available software a two-dimensional finite-element model was constructed from the real velocities measured in the given house–ground system. The geometry of this model is presented in *Fig. 112* in which the velocities measured in the real system are indicated. Generating similar frequencies such as those in the field measurements resulted in the spectra of *Fig. 113*. This system, despite its geometry significantly differing from the real one, also resonates in the 10–20 Hz frequency range. Furthermore, it can be stated that upwards on the wall the amplitudes recorded on the resonance frequency increase. This frequency belongs to the first mode vibrations the mode of which is at the foot of the wall.

For the purposes of further investigation of the problem a three-dimensional computer model is to be constructed in which the points represent the shape of the real house with response characteristics measured in the real system. The model will offer possibilities to study the effect of vibrations which are impossible to generate in the study area for technical or safety reasons.

2.1.7 Developing an instrument for vertical seismic profiling*

The demand for a special instrument for vertical seismic profiling has grown lately. The sophisticated multichannel (48, 96) seismic stations are suitable for VSP, but too expensive and clumsy. The difficulties are increased if the wells are in areas of poor access where helicopters are needed for transporting equipment. The portable 12–24-channel shallow seismic instruments with their small size, weight, consumption and lower price are the most attractive for VSP.

The construction parameters and fundamental characteristics of ELGI's ESS–01–24 shallow seismic instrument formed a suitable basis for the development of a special VSP instrument. After specifying the technical demands, the construction parameters of an experimental instrument were determined in 1988, then, after some field experiments they were fixed, and the zero series of the instrument ESS–01–08/VSP was produced in 1989. From the construction of the ESS–01–24 the 10–2000 Hz transfer frequency range, the filter set for recording and field display, the electric circuits of the digital memory and tape recording, the construction of the controls, check and display as well as the cassette unit have been preserved.

In harmony with the VSP technique the sampling intervals have been completed with the 2 and 4 ms steps, and the number of channels has been reduced from 24 to 8. By increasing the capacity of each channel the record length reaches a maximum of 16 sec. By using a divided memory, filtering,

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display on the screen, recording on magnetic tape and printing became possible. Abandoning the formerly used thermosensitive field registration we have chosen the more flexible matrix-dot-printer for producing field seismograms.

To increase the information content of the measurements the instantaneous floating point (IFP) gain control was adopted as the most important change. It results in an increase of 42 dB in the dynamic range of the record. Another essential change which made work and transportation easier consists in the arrangement of the central electric circuits and the peripherals in a single small and compact unit *(Fig. 114)*. Only the matrix-printer forms a separate unit.

In co-operation with the company VNIIGIS (Oktiabrskiy, USSR) which produces the VSP sondes, we have developed a complete VSP station (SVK–1VSP) consisting of an ESS–01–08/VSP instrument, sondes of various diameters and the manipulator for the sondes.

Technical parameters

Number of channels	8
Frequency range	10–2000 Hz
Amplification	24–60 dB in 12 dB steps
Range of the instantaneous floating-point (IFP) gain control	42 dB in 6 dB steps
Noise level	max. 0.5 μV
Distortion	max. 0.3%
Crossfeed	−80 dB
Sampling rate, frequency range, record length	4 ms 10–62.5 Hz 16.384 s 2 ms 10–125 Hz 8.192 s 1 ms 10–250 Hz 4.096 s 0.5 ms 10–500 Hz 2.048 s 0.25 ms 10–1000 Hz 1.024 s 0.125 ms 10–2000 Hz 0.512 s
Low-cut filter	72 dB, 22 dB/octave
Delay	max. 10 s in 0.01 s steps
A/D converter resolution	12 bits with sign
Data format	16 bits
Memory capacity	48 Kwords
Recording	magnetic cassette
Display in the field	monitor and matrix printer
Supply voltage	12 V, 8 A
Temperature rating	5–40 °C
Size and weight	
seismic instrument	560 × 400 × 320 mm, 25 kg
printer	500 × 350 × 150 mm, 12 kg

2.2 GEOELECTRIC METHODOLOGICAL AND INSTRUMENTAL RESEARCH

2.2.1 Downward continuation of electromagnetic field*

In the most widely used interpretation method of ground electromagnetic measurements it is supposed that the halfspace is layered, and the electrical parameters of the buried layers are to be determined. There are only a few interpretation methods for models more complicated than one-dimensional. One of them might be the downward continuation of electromagnetic fields. We began to examine the theoretical bases of this method in ELGI in 1989. This technique can be applied when the surficial layer is homogeneous from the electrical viewpoint, and an anomalous parameter distribution to be detected exists at a given depth *(Fig. 115)* which, of course, influences the ground observations. Such a task might be, for example, searching for a pipeline or void detection. By applying downward continuation we expect that the individual anomalies become more separated and the position (depth, horizontal extension) of the causative body of the anomalies can precisely be delineated.

Mathematically, downward continuation of electromagnetic fields means the following: Let us suppose that every component of the electromagnetic field is known on the surface of the earth, i. e. according to the coordinate system shown in Fig. 115, in the $z=0$ plane. The conductivity, σ, of the underground region, marked with Ω is also known. We are looking for that solution of the Maxwell equations in the Ω region, which at the boundary $z=0$ coincides with the values observed on the surface. Here we will examine the vertical magnetic component only but similar expressions are valid for the other components too. From the results of ground measurements that electromagnetic field value which could be measured at a depth can be determined using the following formula when the causative body is three-dimensional:

$$H_z(r') = \frac{1}{4\pi^2} \iint\limits_{-\infty}^{+\infty} \left[h_z^0 \mathrm{ch}(\eta_n z') + i(k_x h_x^0 + k_y h_y^0) \frac{\mathrm{sh}(\eta_n z')}{\eta_n} \right] \mathrm{e}^{-i(k_x x' + k_y y')} \mathrm{d}k_x \mathrm{d}k_y \qquad (1)$$

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* E. Prácser

h_z^0 means the spatial Fourier transform of the electromagnetic field which can be written in the form of

$$h_z^0 = \iint\limits_{-\infty}^{+\infty} H_z^0 \mathrm{e}^{i(k_x x + k_y y)} \mathrm{d}x\mathrm{d}y$$

After that the vertical magnetic component for a two-dimensional case

$$H_z(r') = \frac{1}{2\pi} \int\limits_{-\infty}^{+\infty} \left[h_z^0 \mathrm{ch}(\eta_n z') + i k_x h_x^0 \frac{\mathrm{sh}(\eta_n z')}{\eta_n} \right] \mathrm{e}^{-ik_x x'} \mathrm{d}k_x \tag{2}$$

where superscript 0 refers to ground measurements, and $r' = (x', y', z')$ means a point within the region Ω, and

$$k_n^2 = i\omega\mu\sigma_n, \qquad \eta_n = \sqrt{k_x^2 + k_y^2 - k_n^2}$$

These formulae use the spatial Fourier transform of the field components. These are multiplied by certain exponential terms depending on the depth, then inverse Fourier transformation of the whole expression is performed. This can be interpreted so that the downward continuation of electromagnetic fields is a filtering. When a depth of 0 is substituted into the formulae to check them, it can be seen that the integrals yield the correct values on the surface, since the inverse Fourier transformation is applied to the Fourier transforms.

To compute formulae (1) and (2) programs were written for an IBM AT/PC. Computation of Fourier transform is performed by FFT. We have checked the programs by means of some simple models. In *Fig. 116* analytic continuation of a magnetic dipole in free space, in *Fig. 117* downward continuation of the field of a magnetic dipole in a homogeneous halfspace can be seen. Three curves belong to both models; in Fig. 116 H_z is plotted as a real quantity, and in Fig. 117 the real part of H_z is shown. Curve *a* represents results of ground measurement, curve *b* shows what would be measured at a depth, and curve *c* is obtained from downward continuation of ground measurements. Curves *b* and *c* completely coincide in the figures which demonstrates that downward continuation yields correct results. Curves *a* and *b* are results of theoretical calculations. The dipole moment of the source is unity for both cases, this is the reason for the low values appearing on the vertical axis. z_d means the depth of the virtual source below the surface and z_f the level to which the downward continuation was performed. In these examples calculations refer to the total electromagnetic field, and the magnetic dipole takes over the role of anomalies which are present in practical applications, in contrast to the practical applications where the secondary field is essential. Unfortunately, no mathematical modelling programs are at our disposal by means of which checking of the method corresponding more closely to the practical conditions could be carried out.

On the other hand, the applied program is suitable for checking the results of theoretical calculations. If a two- or three-dimensional model calculation is carried out for different levels, then data for the upper level can be continued analytically downward to the lower level, and from the conformity of the two different data sets referring to the lower level conclusions concerning the exactness of the theoretical calculation can be drawn too. Thus, in practice we check whether results of model calculations satisfy the Maxwell equations. Downward continuation can be carried out to that depth to which the halfspace is homogeneous from the electrical viewpoint. This depth is the depth $z=d$ which can be seen in Fig. 115. This feature of the method allows us to estimate the depth of the anomalies in the halfspace (e.g. the depth of a pipeline in a two-dimensional case). Downward continuation should be carried out to ever increasing depths until the results obtained from downward continuation become obviously incorrect and then this depth can be considered as the depth to the given object.

Some words should be said about the practical applicability of the method. As can be seen from the formulae for carrying out the downward continuation, it is necessary to fully know the electromagnetic field on the surface (the absolute value and phase of each component). In a three-dimensional case, when a high number of data measured over an area is required, only sufficiently automatic receivers with data logger can be considered as suitable. In a two-dimensional case the method can be used with significantly less data too because measurement along a line is also sufficient. It might cause a further problem that the integrals which are the basis of the method are taken over an infinite interval, thus the measurements should be carried out over an area of suitable size. A too dense grid is not expedient for the measurements because the signals disturbing the measurement become more enhanced. In other words, the less dense sampling filters out the disturbances of higher spatial frequency. For greater depths the effect of these disturbances is enhanced by the calculations using integrals (1) and (2) because the depth is an exponent in these formulae. It is expedient to choose one quarter of the investigation depth as the sampling interval.

Measurement might be carried out in an arbitrary frequency band, depending on the geological conditions. The type of source is not essential from the theoretical viewpoint; on the other hand, it is important that each component should be measured rapidly and accurately. The main point is the development of the secondary field, and the type of generation which produces this secondary field plays a less important role. Of course, it is advisable to choose such a source the primary and secondary fields of which could be more easily separated. Downward continuation can be carried out together with the primary field but this is not expedient because the presence of the primary field makes recognition of anomalies difficult. In a two-dimensional case a line source can be used, while in a three-dimensional one measurements can be carried out within or beside a large loop.

Moreover, the stability of the downward continuation should be examined because the formulae representing the solution to the task are ill defined from the mathematical viewpoint, i.e. a small deviation in the input data might cause considerable error in the result. Therefore a modified, more stable method should substitute for the original one which provides a theoretically exact solution. This modified method provides a solution close to the exact one for accurate input data, at the same time it is much less sensitive to the possible errors in input data.

2.2.2 Residual profiles derived from electromagnetic soundings*

We carried out experimental measurements over the known anthracite deposit in the vicinity of Trebisov (Czechoslovakia) with the Maxi-Probe EMR-16 electromagnetic frequency sounding equipment, in cooperation with Geofyzika n.p. Brno, závod Bratislava. The aim of the experiments was to decide whether ground electromagnetic measurements can be used to trace the numerous, thin individual anthracite layers within the anthracite formation, with a view to correlating the individual seams between the drillholes.

Methodologically we had to cope with two phenomena that made the solution difficult:

a) the uppermost, highly conductive anthracite layer might cause a very strong inductive shielding effect because of which the deeper lying layers cannot be detected from the surface.

b) the individual anthracite layers within the formation are so close to each other that their effects cannot be separated but one single anomaly characterizing the anthracite formation as a whole is manifested.

Transformed $\varrho_a(h)$ curves obtained from data of electromagnetic sounding-profiling measurements can effectively be applied in investigating laterally very inhomogeneous geological formations and in recognizing anomalies caused by bodies at different depths. To be precise, the main point of the $\varrho_a(h)$ apparent resistivity-depth transformation is that for certain model families the well separated effects of the individual layers can directly be recognized on the transformed curves—this is the basis for graphical interpretation—and in addition, these effects appear at apparent depths h which approximate closely the real burial depths.

This situation is demonstrated in *Fig. 118,* in which the effect of two thin, 10 Ωm layers can be seen, and the depth to the upper thin layer is fixed, while that to the lower one increases. It can be seen that the effect of the lower layer is separated in those cases when the distance between the two layers is sufficiently large (curves 2, 3 and 4). On the other hand, when the layers get close to each other (curve 5) the effects merge. (Curve 1 shows the effect of the upper layer only.) Therefore we developed the method of residual curves, and using this the effects of layers lying close to each other can be separated.

In the case of the transformed curves that can be seen in Fig. 120 the response curve of the homogeneous halfspace was used to define the apparent resistivity [Soininen and Oksama, personal communication]. A detailed description of this apparent resistivity definition can be found in the paper of Aittoniemi et al. [1987]**. Direct recognition of the anomalous behaviour is made

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** For reference, see Hungarian text (p. 161) possible by the fact that the transformation straightens the sounding curve measured over a homogeneous halfspace. If we apply a transformation based on this definition we see from the soundings measured over the anthracite formation—as shown in the depth section in *Fig. 119*—that a single anomaly develops. This single anomaly merges the effects of the individual layers and it prevents answers being given to the questions raised.

Generalization of the apparent resistivity definition brings us closer to the solution *(Fig. 120)*. Transformation of apparent resistivity was generalized in the following manner: the homogeneous halfspace curve (curve for $n=1$ layer) used earlier to define the apparent resistivity ϱ_a was replaced by the curve for $(n-k)$ layers response curve, where $k=1, 2, \ldots, n-1$. When $k=n-1$ the original definition is obtained. The $\varrho_{(n-k)}(h)$ curves derived in this way might be called residual curves because, for example, transformation of an n-layer curve using an n-layer curve provides a straight line, transformation using $(n-1)$, $(n-2)$, ... layer curves the residuals showing the effect of the lowest, of the lowest two, etc. layers are obtained. Thus, for example, in Fig. 120./b the theoretical curve corresponding to the 8-layer geoelectric model of the drilling TR–62 (see in Fig. 119) was transformed using a 6-layer (curve A), 4-layer (curve B), and 2-layer (curve C) response curve. According to this curve A reflects only the effect of the lowest anthracite layer, curve B the effects of the two lowermost anthracite layers, and curve C contains effects of all three anthracite layers.

It can be stated that apart from some smaller overshots the starting depths H_A, H_B and H_C of the anomalies appearing on the theoretical residual curves closely coincide with the real depths of the anthracite layers. Apparent resistivity relations of the residual curves reflect qualitatively the real resisitivity distributions, thus, conclusions concerning the real resistivity relations can be drawn with the help of the residual curves.

An obvious way of utilizing the method can be formulated in the following manner. Let us determine at one point—preferably at a drillhole—the best fitting n-layer model. As long as we succeed in determining a model closely approximating the real one, then using the n-layer response curve corresponding to this for defining ϱ_a the transformed curve will be approximately straight. Now let us use the same n-layer response curve at other points of the profile to transform the sounding curves. If the model changes along the profile the residual anomalies reflect the model deviations qualitatively in the usual manner, on the other hand, the depths where the anomalies appear suitably reflect the real depth relations in the $\varrho_a(h)$ domain.

The residual profile in *Fig. 121* is given as an example. This profile (Fig. 121) was obtained using the response curve of the 9-layer model that was determined by fitting and based on the data of the geoelectrical model corresponding to drillhole TR–63. It can be seen that this response curve really makes the sounding curves straight in the vicinity of this drillhole. At the same time a definite conductivity surplus appears at drillhole TR–62; this surplus may be connected with the extension of the uppermost layer.

2.2.3 Application of direct inversion of transient soundings to solve a groundwater prospecting task*

We carried out transient measurements in Cuba in 1988, on the shore of Batabano Bay *(Fig. 122)*, to investigate the aquifer that provides the water supply for the capital city. The task was to distinguish the fresh water and brine–saturated layers, and to detect the infiltration of high salinity water from the sea. The aquifer consists mainly of porous carbonate rocks—limestone, dolomite—but sandstone can be found in it too. The exact hydrological parameters are unknown. The permeable layers are covered by Quaternary coral limestone. The thickness of this is 20–80 m, its resistivity is 400–600 Ωm, these parameters are known from vertical electrical soundings. Because of the high resistivity of the overburden the aquifer could not be investigated by means of the direct current method. The task seemed to be resolvable using transient electromagnetic soundings though it should be taken into account that if the sequence is approximated by a Q-type model it causes difficulty in the treatment of the model.

The investigation was carried out using a quadrangular transmitter loop, with central induction loop (CIL) array. We measured 13 soundings along a 5 km long profile, using the features of the EM–37 instrument, at the frequencies 2.5 Hz (LOW) and 25 Hz (HIGH), at every station. To avoid the initial distortions appearing at early times a 50 × 50 m loop was used for measurements at 25 Hz, and to reach a sufficiently deep penetration a transmitter loop of 175 × 175 m was used at 2.5 Hz. The transient curves recorded in this way cover the time interval from 89 μs to 70 ms. It took only 3 days to perform the field survey.

Originally the measurements were interpreted using two inependent methods, the break point (TRH) method, and interactive inversion. In 1989 we developed a new processing method: the transformation known as direct inversion produces a depth–resistivity distribution in the layered halfspace. The method can effectively be used to represent the results of measurements in colour or in gray scale. This is not only spectacular: it provides a more easily interpretable image for the user. To test the new method we repeatedly interpreted the measurements of Batabano. The obtained results partly confirmed, partly made the earlier ideas more accurate.

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* L. Sőrés

Interpretation by interactive inversion

The program (that can be run on an IBM AT) fits the theoretical curves to the measured data by modifying the model interactively. The direct problem is solved by Fourier transformation, with the filtering method of Anderson. The interpretation results of the Batabano survey are shown in *Fig. 123.* On the top three characteristic sounding curves can be seen. Agreement between measured and calculated values is excellent. The only a priori information used was the resistivity of the upper layer. The layer resistivities are estimated values. Slightly different — equivalent — models, of course, might be supposed but this does not influence the basic structure of the sequence. The curves are relatively insensitive to the resistivity of the lowermost layer but it is certain that a higher value than that above should be considered.

At the bottom of Fig. 123 the constructed sounding section can be seen. The resistivity of the first layer — coral limestone — is 500 Ωm. The 20 Ωm and 50—60 m thick second layer extends along the whole profile terminating at the last station. If we suppose that the resistivity of the layer is determined by the resistivity of the pore water then this zone very likely corresponds to a layer saturated with fresh water. Below this a 100—150 m thick layer of 1.5 Ωm resistivity can be found which gives place to an even lower resistivity (0.5 Ωm) rapidly thickening layer in the close vicinity of the sea. Changes in the thickness and resistivity equally reflect saline water saturation which is the result of sea water intrusion. Below that — downward from 250—300 m — a higher resistivity formation can be detected. This increase in resistivity can supposedly be explained by the decrease in rock permeability.

Between soundings 1 and 5 a layer of transitional resistivity (4–6 Ωm) should be inserted between the second and third layer in order to ensure optimal fitting. We have good reason to suppose that this was created by fresh and salt water being mixed because of the effect of the high-yield wells operated in the vicinity of station 2. It is easy to imagine that from the deeper layer saline water intrudes to the place of the water pumped out from the depth of 70—80 m and as a result of this water masses earlier separated by virtue of their densities get mixed. An important result of the survey was to draw the attention to that potential danger.

Returning to the interpretation of the section, a different sequence can be seen below station 0. We succeeded in detecting a thick 38 Ωm resistivity layer below which saline water and a zone of increased resistivity can be found. Based on the resistivity distribution it seems that the fresh water and mixed water are unable to intrude into this layer. In that case the change between stations 0 and 1 indicates the northern boundary of the water-bearing formation.

Interpretation with direct inversion

At the top of *Fig. 124* transformed curves of the direct inversion can be seen. The axial section of resistivity is 2 Ωm for each curve. The direct inversion method almost completely eliminates the shielding effect of the overburden. The curve of station 12 suggests that the resistivity is also very low at greater depth. This low value seems to be reasonable at the station closest to the sea. On the other curves the minimum zone of 1.5 Ωm at a depth of 150—200 m can clearly be traced and this zone exactly coincides with the previously described saline water bearing layer. The resistivity increase that can be seen at the lower part of the curves is the effect of the basement.

The curves start at a depth of about 100 m therefore it is not to be expected that we can determine the resistivity of layers lying above that depth. It is mentioned that the initial steeply decreasing part reflects the higher resistivity of the near-surface layers.

The gray-scale image at the bottom of the figure clearly shows the position of the layers of different resistivity in the section. Agreement between the results of two diverse methods is acceptable (see the lower boundary of the wedge-shaped mixed water zone). The impermeable formation which borders the aquifer in the north appears as a strong dark spot, similarly to the previous results. *Figure 125* is shown in order to enhance the similarities. Results of interactive and direct inversions are presented together on two very dissimilar sounding curves.

Based on the results we can state that the method which has been developed can very well be applied to represent the resistivity distribution for layered models. The transformed resistivity values are more sensitive to the changes than the traditional apparent resistivities. In many cases the resistivities obtained through transformation are close to the real resistivity values, thus they provide good initial guesses for more accurate inversion procedures (e.g. Marquardt inversion).

2.2.4 Application of airborne geophysical measurements in bauxite prospecting*

Airborne geophysical measurements have been carried out since the early 1950's. At first they played an important role in prospecting for ores and radioactive materials, and in the regional mapping of larger areas. The aim of the airborne measurement series which was carried out with Soviet cooperation in our country in 1965—68 was of this kind too. The intention was to obtain reconnaissance information rapidly on the radioactive and magnetic features of large areas.

With improving sensitivity and accuracy of instruments and with the increasing number of measured parameters airborne measurements have become a useful tool in geological mapping and prospecting for non-metallic raw materials. The airborne measurement carried out in 1977 with Czechoslovakian assistance aimed at the prospecting of a non-metallic raw material, alginite.

The present situation of bauxite mining necessitates preparation of intensive prospecting for near-surface bauxite deposits over a large area. Therefore

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bauxite mining experts and ELGI considered that the first stage for ground geophysical measurements should be replaced by airborne survey. The first airborne measurements for bauxite prospecting purposes took place in 1986 — by the Bulgarian Specialized Airborne Geophysical Enterprise *(Fig. 126)*. Measurements were carried out over several areas of the country. Two such measurements in the vicinity of Pápavár and Halimba, were specifically for bauxite prospecting. The Bulgarian airborne geophysical system was mounted in an MI–8 helicopter and consisted of a MADACS type gamma ray spectometer and a MAP–5 proton-resonance magnetometer: navigation was performed visually, and the location map was constructed on the basis of video records.

In 1987, we, too, tested the airborne electromagnetic method in the framework of Austro–Hungarian scientific cooperation. A DIGHEM–II type electromangetic system was mounted in an MI–8 helicopter of the Hungarian Army; visual navigation was used and film strips provided the basis for location map construction.

The conclusion drawn from the 1986–87 experimental measurements was that to solve bauxite exploration tasks a complete airborne geophysical measuring system should be assembled which is able to measure as many geophysical parameters as possible simultaneously. Reliable detection of bauxite lenses which are economically still valuable in spite of their small lateral extension requires application of an up-to-date navigation system. The integrated airborne geophysical measuring system *(Fig. 127)* which is the property of the Österreichische Geologische Bundesanstalt (Geological Survey of Austria) and was completed with a suitable radio positioning system (MICROFIX) met the above requirements. The airborne measurements performed in 1989 are discussed in section 1. 2. 3. 1.

Compared with traditional (non-seismic) ground measurements, airborne measurements yield a very large amount of data: the number of data from an area of several 10 km^2 may reach a figure as high as 10 million. Therefore interpretation of airborne measurements requires suitable data processing and interpretation programs. Although measurements and basic data processing are carried out by the same company we have developed several programs meeting particular demands *(Fig. 128)*. Development of a data base management program for the data base containing the airborne geophysical data, and associated processing and visualizing programs is currently in progress.

In the following, the geophysical methods used in the airborne measurements will be dicussed in detail. Examples chosen from the 1986–87 experimental measurements demonstrate the utilization of the individual methods in bauxite exploration.

Airborne gamma spectrometry

Airborne radiometric instruments measure natural radioactive radiation. In addition to the total gamma energy, radiation is generally recorded in three energy windows, these are: uranium (U^{238}), thorium (Th^{232}) and potassium (K^{40}). In the course of processing, the percentage, by volume of the individual elements is determined after taking into account the measured background radiation and the known calibration constants; the various ratios (U/Th, U/K and Th/K) are also calculated. In bauxite exploration the amount of thorium and potassium is the most significant. From experience the thorium content is higher and the potassium content is lower over a near-surface bauxite lens *(Fig. 129)*.

Airborne electromagnetic measurements

Airborne electromagnetic methods have many different versions. Passive methods use an electromagnetic field which exists independently of the measurement (e.g. airborne VLF measurement). When active methods are applied the electromagnetic field is generated by a special transmitter which is on-board an aircraft or on the ground. Based on a preliminary surves of the literature, the application of a multifrequency system with active field generation, dipole–dipole array (Slingram type), and helicopter-towed bird seemed to be the best means of solving shallow bauxite exploration tasks. The sytem of the Canadian DIGHEM company is of this kind and it was this that we chose.

In this system two induction coil pairs can be found in the bird suspended by a 30 m long cable from a helicopter. In the bird there is a horizontal plane transmitter coil transmitting at 3600 Hz, and a vertical plane transmitter coil transmitting at 900 Hz. Both coil pairs are in the so called "maximum coupling" position. i.e. the plane of the receiver coils is orthogonal to the magnetic field at that place; in other words the mutual induction coefficient between the transmitter and receiver coils is maximal. The system measures the in-phase and out-of-phase components of the "secondary" magnetic field due to the currents induced in the ground, normalized to the "primary" magnetic field which is directly generated by the transmitter, at both frequencies.

The first step in data processing — similarly to other elentromagnetic methods in general — is calculation of apparent resistivity: i.e. resistivity and separation from the bird of that homogeneous halfspace should be calculated which, for the induction at the given frequency and given coil array, produces a magnetic field equal to the measured one [FRASER 1978]. The program has been developed to allow one to calculate the apparent resistivity defined in this way for arbitrary layered models on an IBM AT computer. Analysis of apparent resistivity values calculated for different models facilitates the interpretation of measured profiles.

In bauxite exploration airborne measurements are utilized for geological models in which the depth to the high resistivity basement varies between a few m and 60–80 m. We suspected even during the interpretation of field measurements that resistivity calculation based on the homogeneous half space model can provide misleading results in many cases over shallow parts of the area, and its dependence on the flight altitude may cause difficulties too. As a check the real airborne measurements were replaced by calculation of the magnetic field over layered models, and apparent resistivity transformation was carried out starting from these computed values.

To calculate the apparent parameters (resistivity and conductivity) a simple model should have been found which not only approximates closely the mentioned geological structure but is also less sensitive to the increase in flight altitude. Because the overburden is thin and of low resistivity, it can be substituted by a thin conductive sheet [Kaufmann–Keller 1983]. When this model is used the conductive sheet is characterized by one parameter, the admittance (S). The vertical magnetic dipole is described by the formula:

$$H_z = \frac{M}{4\pi}\left\{\int_0^{\infty} J_0(\lambda r)\lambda^2 e^{-2\lambda h} R_0(\lambda, S)\, d\lambda - \frac{1}{r^3}\right\}$$

where M = the dipole moment
$R_0(\lambda, S)$ = the kernel function depending on the admittance (S) of the sheet
J_0 = zero order Bessel function of the first kind
r = transmitter–receiver separation
h = separation between the transmitter and receiver coils and the conductive plate.

This formula deviates from the formula valid for the layered model [Kardeván–Prácser 1984] only in the definition of the R_0 kernel function. The applicability of the method was checked by replacing the real measurements by calculations which were processed by applying the thin sheet approximation instead of the homogeneous halfspace. Our experience up till now shows that the thin sheet interpretation is advantageous when the thickness of the overburden is small because the obtained apparent conductivity value only slightly depends on the flight altitude and its value closely approximates the real conductivity of the overburden. It is expected that this interpretation procedure will become a matter of routine in the future.

Result of the experimental electromagnetic measurements in 1987

Interpretation of apparent resistivity maps is similar to that of the VLF mapping, i,e. in areas of high resistivity the basement lies near the surface, and the low resistivity values indicate basement depressions.

In *Fig. 130* results of ground VLF and airborne electromagnetic measurements are compared. Similarly to the VLF maps, according to the previously discussed regularity, the airborne EM map indicates the area where the high resistivity basement lies near the surface with high resistivity and with relative minimum depressions of the basement. Apparent resistivity values, however, significantly exceed those belonging to the VLF measurements over the depressions, and the shape of the anomaly is more blurred. The reasons for these are the different nature of induction and different altitude of measurements.

A typical profile of the Gézaháza resistivity profiles of airbone measurements is shown in *Fig. 131* in which not only parts of the area with bedrock outcrops can be delineated but conclusions can also be drawn concerning the quality of the overlying formations — in our case, for example the very low resistivity suggests Oligocene formations. From the application of two different frequencies we except to obtain information from different depths. In this profile, for example as an effect of the Oligocene formations apparent resistivities belonging to the shallower penetration ($f = 3600$ Hz) are more strongly reduced. Of course, the applied resistivity transformation is based on a 1-D model, thus resistivity lows over the depressions should be interpreted taking that into account. Thus, in the middle of the profile the depression of small alteral extent does not give rise to a definite minimum, although Oligocene formations can be found in the overlying sequence. On the other hand, definite minima indicate the graben-like 2-D structures in the profile.

In the area of experimental measurements carried out in the vicinity of the village of Szár we succeeded in detecting several low resistivity spots *(Fig. 132)* which proved to be promising for bauxite. We found a close correlation between the airborne geophysical parameters and the basement depth data from drillholes and outcrops using regression of non-linear polynomials. Based on the airborne EM measurements and depth calculations by regression we located depression *(Fig. 133)*. Holes drilled on these intersected commercial bauxite.

The main stages of the investigation at Somlyóvár are shown in *Fig. 134*. At the beginning of the investigations the geological map and data of some earlier drillholes were known *(Fig. 134/a)*. In both resistivity maps of airborne measurements the low resistivity zone in the middle of the area is outlined. Here, where the basement lies deeper we performed vertical electrical soundings and bauxite geophysical penetration measurements. We have proved relationships between the parameters obtained from airborne and ground geophysical measurements, and geological data using the regression method. By means of these relationships we constructed the depth map of the bauxite's bottom which was continuously updated as prospecting drillings advanced. The axonometric view of the depth map of the last stage, completed with the extension of bauxite, can be seen in *Fig. 134/c*. Several drillholes suggested on the basis of airborne EM parameters and depth calculation intersected commercially viable bauxite *(Fig. 134/e.)*.

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2.2.5 Development of in-mine geoelectric gradient profiling*

Together with experts of the Bakony Bauxite Mines Enterprise and Fejér County Bauxite Mines, we have developed a method which is a combination of DC in-mine gradient profiling (IGP) and drilling from the entry. The main aim is to determine the depth and morphology of the bedrock below the entry. The earlier practice was to determine the morphology of the under- and overly-ng formations by means of drillings 5 m apart from the opening entry. The newly elaborated method allows significant reduction in the number of drillings. The IGP measurements and data processing for a 50 m long section of the entry can be carried out in one day.

The first stage of the procedure is the geoelectric measurement and processing. In the measurements an *AB* current electrode separation is chosen which is 4–10 times larger than the average deposit thickness *(Fig. 135)*. Along an entry section the length of which is equal to about half of the *AB* separation, values of potential gradient are measured with the *M* and *N* potential electrodes. The *MN* separation is at least five times less than the average deposit thickness. If the entry section to be investigated is longer, profiling is carried out by changing the site of the whole array, with some overlapping stations.

In the course of data processing the ratio of the theoretical (E) and real, i.e. measured field strengths (E_M) normalized to ϱ_2, the σ_a apparent conductivity parameter is calculated:

$$\sigma_a = \frac{1}{\varrho_2} \frac{E}{E_M} = \frac{k \cdot \overline{MN} \cdot I}{\Delta V_M} \tag{1}$$

where ΔV_M is the potential difference measured at point P, $\overline{MN}$ is the separation of the potential electrodes, I is the current, ϱ_2 is the resistivity of the second layer in the theoretical model (average resistivity of the deposit), and K is the geometric and model factor. The value of K depends on the parameters of the electrode array and the theoretical model:

$$K = F(\varrho_1, \varrho_2, \varrho_3, H, D, r, x, y, z) \tag{2}$$

For our example we have chosen an ideal three-layer model *(Fig. 136)*. The meaning of the variables in equation (2) is also demonstrated by using Fig. 136. The resistivity of the layers and average thickness of the deposit are given based on data of holes drilled from the surface in the vicinity of the entry (Fig. 135/a).

Function F is determined by solving the forward problem for the field of sources placed in the second layer.

The σ_a curve roughly reflects changes in the real thickness of the deposit (Fig. 135/b). Its values, however, could be modified by the values of the resistivity of the deposit, and the overlying and underlying formations. In spite of this, the curve follows the changes in the deposit thickness, and it is suitable for marking out sections with maximum or minimum thickness in order to locate the best sites for in-mine drillings.

* A. Simon

The second stage of the method is drilling and depth calculation. In characteristic, generally extreme sections of the σ_a curve, reference holes are drilled into the under- and overlying formations from the entry (Fig. 135/c). At these sites we get to know the real deposit thickness. At the points between the boreholes the deposit thicknesses H_i are determined using the correlation between the values of σ_{ai} and H_i. The relationship expressing the correlation is given by:

$$\sigma_{ai} = C(x_i, y_i, z_i) \cdot H_i \tag{3}$$

and the function $C(x, y, z)$ is known as the transfer function. Its values at the reference boreholes are calculated using relationship (3). At points between the boreholes they are given graphically using the previous values (Fig. 135/d Using the C_i values the deposit thicknesses are calculated from equation (3). The boundary of the overlying formation is constructed from the data of reference boreholes. Because this boundary is not an unconformity horizon we should not consider sudden morphological changes (except at the places of faults), thus data of reference boreholes are satisfactory for constructing this horizon. Subtracting the deposit thicknesses from the level of the overlying formation, the level of the underlying formation is obtained. Finally, using the levels of over- and underlying formations and the material of drill cores the vertical section of the deposit is constructed (Fig. 135/e).

In 1988 and 1989 we carried out experimental measurements along 14 entry sections with different deposit conditions (geological model), the total profile lengths was about 600 m. Judging from the data of checking boreholes between the reference boreholes errors in determining the depth to the underlying formation do not exceed ± 10% of the real deposit thickness.

2.2.6 Magnetotelluric instrumental research*

A serious problem in utilizing the magnetotelluric method is the need to enhance the components of the natural electromagnetic field containing the geological information in the presence of man-made noises, the level of which sometimes significantly exceeds that of the signals. Recently the remote reference processing method which can be applied in synchronized magnetotelluric measurements has become wide-spread as a means of increasing the reliability of processing. The main point of the method is that in the case of simultaneous measurement of a minimum of two stations the spectral power density functions $\sum EE^*$, $\sum HH^*$, $\sum EH^*$, used in processing MT measurements can be replaced by functions $\sum EE_r^*$, $\sum HH_r^*$ and $\sum EH_r^*$ where E_r^* and H_r^* represent the complex conjugates of the respective components at the remote station. If the nature of the noise is independent at the two stations, the spectrum of the noise is eliminated from the spectral power density functions which are the bases of processing; i. e. the accuracy of the processing can be singnificantly improved. When the reference method of processing is applied, the systematic error which necessarily appears in determining the impedance tensor in single station measurements because of the autocorrelation functions can be eliminated too.

To realize the previously discussed processing method the VMTR–10 magnetotelluric data acquisition and processing system has been developed which allows simultaneous measurement of two stations with real-time or quasi real-time processing. The layout of the measuring station is shown in *Fig. 137*.

Layout of the equipment

The measuring system consists of three main parts:

The central unit (I) comprises a ruggedized IBM AT/PC compatible computer and a digital data acquisition unit. The digital unit allows one to digitize 16 analog channels; the resolution of the A–to–D converter is 16 bits. To represent the analog signals an analog recorder can be connected to the central unit.

The analog unit (II) consits of channels which are necessary to measure three magnetic (H_x, H_y, H_z) and two electric (E_x, E_y) components. The analog channels perform amplification and band filtering of low-level signals coming from the field sensors, and elimination of 50 Hz noises by a notch filter. The scheme of two five-channel analog units is identical. The analog units can be located 5 km apart from the central unit, by cable connection.

Two kinds of sensors are used to pick up the electric and magnetic components. The electric components are measured with non-polarizing low-noise lead/lead chloride electrodes (5 pieces/unit), and the magnetic ones with permalloy-core induction coils (3 pieces/unit).

Operation of the measuring system

The central unit — after being turned on — automatically tests all parts of the system. The remote analog unit does not have any control knob except for the power supply switch. Control of the unit, together with the setting of the measuring parameters are performed by a series of digital signals sent from the central unit. The digital control line ensures a bidirectional contact, the central unit receives information on the state of the analog unit (power supply, overload).

The filtered and amplified (maximum ± 5 V) analog signals reach the central unit through a cable. After sampling and multiplexing the signals are digitized and transferred to the memory of the computer, and here data processing begins. During measurement of low frequency band where the speed of data acquisition is much lower than that of data processing, real-time processing can

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be achieved; in high frequency bands requiring a short recording time data processing is slower than acquisition. The total time necessary to measure one MT sounding curve is considerably longer than the time of data processing, therefore data processing can practically be considered real-time.

Main technical data of the measuring system

Analog unit:

Number of channels (*E* and *H*)	5 (2 + 3)
Input amplifier	symmetrical
Common mode noise rejection	120 dB
Input impedance *E*–channel	1 MΩ
H–channel	10 MΩ
Frequency bands 1	0.001–0.02 Hz
2	0.01–0.2 Hz
3	0.1–2 Hz
4	1–20 Hz
5	10–200 Hz
Notch filters	50 Hz, 150 Hz,
Temperature drift	0.2 μV/ °C
Input-reduced noise *E*–channel	< 0.1 μV
H–channel	< 0.1 μV
Sp cancellation	automatic
Gain setting	programmable
Power supply	rechargeable batteries for 48 hours of continuous operation
Temperature range of operation	0 to 55 °C
External dimension	280 × 400 × 400 mm (waterproof polyurethane box)
Weight	10 kg

Central unit:

Ruggedized IBM AT/PC in the following configuration
- 80 286 processor
- 80 287 math processor
- 1 Mbyte RAM
- 27 Mbyte Winchester disk
- 1.2 Mbyte floppy disk drive
- 0.72 Mbyte microdrive
- 60 Mbyte streamer storage
- built-in monochrome (Hercules) or external colour (EGA) monitor
- complete ASCII keyboard
- matrix printer

A–to–D converter	16 bit
Conversion time	50 μs
Sampling rate	10 times lowpass cutoff frequency for bands 1 to 4, 5 times lowpass cutoff frequency at band 5

Control and user's programs

The complete program package of the measuring and processing system consists of three major parts:

- measurement control and data acquisition
- data processing
- inversion and interpretation.

Measurement control and data acquisition are actually the system software of the measuring and processing system. Its major functions are:

- testing the instrument
- measurement control, setting of measurement parameters by means of a menu system
- control of remote unit
- optimization of time sharing between data acquisition and processing.

The most important routines of data processing:

- fast Fourier transformation of time series
- calculation of power density spectrum functions
- data classification by means of multiple and partial coherency
- determination of the complex impedance tensor using the remote reference method. As reference any component can be used.
- calculation of transformed values and polarization directions
- display of processing results on the screen
- making numerical and graphical documentation of final processing results.

Special storage mode of processing data allows subsequent improvement of results.

Possibilities for inversion and interpretation

- 1-D interacive inversion
- 1-D direct inversion using the Marquardt algorithm
- 2-D modelling based on the multigrid method.

Different parts of the program package are written in Assembler, Professional Fortran, Pascal and Basic languages.

2.3 WELL-LOGGING METHODOLOGICAL AND INSTRUMENTAL RESEARCH

2.3.1 Development of the microlambda method*

One of the most important tasks in petrophysical investigations of fractured magmatic, metamorphic and sedimentary reservoir rocks is to locate interstices in the rock which are filled with non-solid material, and to analyse them qualitatively and quantitatively. These interstices may be three-dimensional (pores) or quasi two-dimensional (fractures). From the hydraulic point of view these may be open, suitable for fluid transport, or closed. The method and equipment developed for direct detection of fractures was named microlambda.

Physical basis of measurement

In microlambda measurements current flows in through current electrode A1 and guard electrode A2, and flows back through the remote electrode *B (Fig. 138)*. Within the current funnel a Faraday cage develops in which the potential is constant for compact rock. This potential is measured at electrode *K* with respect to remote electrode *N*. The voltage U_{MK} is zero because current does not flow within the closed Faraday cage, and therefore there is no potential drop. When the electrode array arrives to a fracture the Faraday cage opens out, the fracture absorbs the current I_1, therefore the ratio I_1/I_2 increases, and within the Faraday cage the current density component parallel to the pad brings about the voltage impulse U_{MK}. For measurement purposes the ratios U_{MK}/U_K and I_1/I_2 (calculation of ratios ensures independence of rock resistivity), *R*, logarithm of the apparent resistivity, and hydraulic conductivity *H* deduced from these are recorded.

Mathematical modelling of measurement

We determined mathematically the measuring characteristics of the microlambda device for the case when the resistivity R_t of the rock matrix is constant, the ring-like electrode system — the thickness of which is finite and is located on the wide insulator pad virtually stretched out in a plane — is in contact with the mud cake of thickness t_{mc} and resistivity R_m.

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For homogeneous rock ($t_{mc}=0$) at point (r, z) the value of potential generated by the current I flowing from a circular infinitely thin electrode with a radius a is deduced from the formula describing the potential of a point-like electrode, with appropriate treatment of the elliptic integrals that appear. The result of this is

$$\Phi_a(r, z) = \frac{I\varrho}{2\pi^2} \frac{2}{\sqrt{(a+r)^2+z^2}} \cdot K\left(\frac{2\sqrt{ar}}{\sqrt{(a+r)^2+z^2}}\right) \tag{1}$$

where K is the elliptic integral of first kind, the Legendre form of which is

$$K(m) = \int_0^{\pi/2} \frac{1}{\sqrt{1-m^2 \cdot \sin\psi}} \mathrm{d}\psi \tag{2}$$

If $t_{mc}>0$ the potential of the infinitely thin ring of radius a is again obtained from the potential field of the point-like electrode for a two-layer model. The result of this, using the Bessel multiplication theorem, is

$$\bar{\bar{\Phi}}_a(r, z) = \begin{cases} \Phi_a(r, z) + I\varrho \cdot \displaystyle\int_0^{\infty} \frac{k_{tm}}{e^{2\lambda t_{mc}} - k_{tm}} \cdot (e^{-\lambda z} + e^{\lambda z}) \cdot J_0(\lambda a) \cdot J_0(\lambda r)\, d\lambda \\[2ex] \Phi_a(r, z) + I\varrho \cdot \displaystyle\int_0^{\infty} \frac{k_{tm}}{e^{2\lambda t_{mc}} - k_{tm}} (1 + e^{2\lambda t_{mc}}) e^{-\lambda z} \cdot J_0(\lambda a) \cdot J_0(\lambda r)\, d\lambda \end{cases} \tag{3}$$

where $k_{tm} = (R_t - R_m)/(R_t + R_m)$, $\Phi_a(r, z)$ is the function (1), and J_0 is the zero-order Bessel function.

Formulae (1) and (3) describe the field of the infinitely thin electrode for homogeneous and two-layer models. The distribution of total current $I = I_1 + I_2$ flowing through electrodes A1 and A2 of the microlambda sonde can be determined for homogeneous space using formula (1).

Although the rings are relatively thin, if one varies a in (1) in accordance with the inequality $r_{bi} < a_i < r_{ki}$ ($i = 1, 2$) the estimation $0.429 < I_1/I_2 < 0.508$ is obtained for the currents. Therefore to describe a field of rings with finite thickness and with parameters r_{bi}, r_{ki} the following definition is used which means modification of the potential field:

$$\Phi_{r_k, r_b}(r, z) = \begin{cases} \Phi_a(r_b, 0) = \Phi_a(r_k, 0) & \text{if } \Phi_a(r_k, 0) \leqq \Phi_a(r\ z) \\ \Phi_a(r, z) & \text{otherwise} \end{cases} \tag{4}$$

Definition (4) should be interpreted in the following way: Point a is chosen for a given ring of r_b, r_k so that the infinitely thin ring determined by a should generate an identical potential at points $(r_b, 0)$ and $(r_k, 0)$. Within the equipotential surface connecting these points the potential $\Phi_{r_b, r_k}(r, z)$ is considered constant; outside it the potentical is taken equal to $\Phi_a(r, z)$.

Definition (4) is valid with mathematical rigour when the surface of the electrode is identical with the equipotential surface connecting points $(r_b, 0)$ and $(r_k, 0)$, but (4) is a very good approximation of the potential field corresponding to out flat electrodes shown in *Fig. 138*. It is noted, that if a is defined according to (4) and applied to formula (1) a is very near to $(r_b + r_k)/2$, while if applied to formula (3) $a > (r_b + r_k)/2$ when $R_t \gg R_m$; even so, when $R_t = \infty$ and $t_{mc} \rightarrow 0$, $a \rightarrow r_k$. Using definition (4) the value $I_1/I_2 = 0.470$ is obtained for the current ratio in homogeneous space.

Based on the above potential theoretical considerations a program package was developed to calculate and present results for two-layer models. These programs were run for $I_1 + I_2 = 1$ A; $R_m = 1$ Ωm, and in the parameter ranges 0.02 cm $< t_{mc} <$ 0.7 cm and $1 < R_t/R_m < 10{,}000$.

In *Fig. 139* the current line image generated by the microlambda sonde can be seen for 7 mm mud cake thickness and for an R_t/R_m value of 10. It can be stated that the bulk of the total current (88%) flows away through electrode A2, and it tries to remain within the mud cake. In *Fig. 140* the dimensionless U_{MK}/U_K parameter is plotted as a function of the ratio R_t/R_m, for different resistivity values.

Realization of the instrument

The instrument used for microlambda measurements consists of the following main electronic units: a 200 Hz/50 W sine wave generator in the surface unit; electronic circuit in the sonde amplify and rectify the signals U_{MK}, U_K, I_1 and I_2 and send them to the surface as direct current; a matching amplifier and a fourth degree low-pass filter mounted in the surface unit receive these signals. Signals of the surface unit are directly transferred through the intelligent unit KFU manufactured in ELGI to the DRESSER–3600 logging truck.

In another solution signals of the surface unit arrive to a Sharp PC–1600 computer according to the standard RS–232 through the analog-to-digital converter PRC–12 of ELGI. This computer performs arithmetic operations and data storage as well. The character of data recorded in this way depends on the geologic conditions. This character is shown in *Fig. 141* which is constructed based on mathematical modelling and other potential theoretical considerations. It can be seen in the figure that $U_{MK}/U_K = 0$ and I_1/I_2 is low in compact rocks. If the rugosity of the borehole wall increases, the value of $I_1 = I_2$ increases too but $U_{MK}/U_K = 0$ remains valid. The hydraulic conductivity H derived from them is zero in both cases. At a closed fracture U_{MK}/U_K gives an impulse but not I_1/I_2, thus the indication from curve H is insignificant. On the other hand, at a hydraulically open fracture the effect of U_{MK}/U_K is strengthened by I_1/I_2, thus curve H indicates only the commercially viable fractures.

Experimental measurements with the system started in 1987. Up to now we have measured logs in various domestic wells in the vicinity of the settlements Szeghalom, Dorozsma, Ásotthalom and Dombegyház, and in the Kontinental Tiefbohrung (Windisch–Eschenbach, FRG), and they have also been processed too. These logs correlate well with other logs (induced polarization, microlaterolog, dual laterolog, etc.), and with the fracture detection of the COMWELL B. R. integrated interpretation (see the Annual Report of ELGI for 1984). The fracture log is in agreement with the drill cores taken from the parameter wells at Szeghalom. The most reliable check is provided by the layer testings where the comparison unambiguously demonstrated that at depths with good inflow high amplitudes were obtained too, and at depths where there was no influx the level of the *H* curve remained low. In addition to the mentioned qualitative relationship there is a certain quantitative connection between the *H* curve (hydraulic conductivity) and the results of hydraulic measurements (layer testing). In *Fig. 142* the relationship is shown between the results of layer testing in five intervals in the Ásotthalom–É–8 well from 2016 to 2097 m (horizontal axis) and the square root of the area under the *H* curve (vertical axis). It can be seen that the relationship is linear. It is obvious that the *H* curve is a function of the geometry of the fracture system; the yield, however, depends on other parameters (pore pressure, viscosity, etc.) too. In a short interval of a well it is possible that the non-geometrical parameters are constant which allows one to reduce the number of layer testings.

2.3.2 Well-logging mini centre based on an IBM AT compatible personal computer*

In 1989 we developed the mini centre based on an IBM AT compatible personal computer. Its configuration is shown in *Fig. 143;* it consists of the following units:

- IBM AT compatible computer with the following specification
  1 Mbyte memory
  41 Mbyte Winchester disk drive
  CENTRONICS parallel interface
  84-key keyboard
  1.2 Mbyte floppy disk drive
  battery operated clock, calendar
- EGA colour monitor with 14-inch screen
- EPSON FX–1000 matrix printer
- HP–9475 six-pen flat colour plotter
- COROLLPRESS–88 409.6 mm wide colour raster plotter
- RA–06/A semi-automatic digitizer with a surface of 1050 mm × 677 mm for on-line transfer of analog measurements into the computer
- CM–5300 on-line half-inch magnetic tape recorder to input field measurements and to ensure connection with the mainframe computer

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- CM–5302 half-inch magnetic tape recorder for off-line operation of COROLLPRESS
- PK1 magnetic cassette tape reader to enter field measurements
- punched tape reader to enter previously digitized materials into the computer.

Hardware and software matching of the above units has been carried out thus re-writing of the following well-logging data-processing programs from the previously used HP–9825B computer also became possible:

- program package which allows entering data of digital field measurements into a disk data storage from magnetic tapes of different type and format
- program for interactive operation of the RA–06/A semi-automatic digitizer
- programs for presentation of measured and calculated curves on the screen, printer or plotter
- programs for filtering and smoothing of curves
- programs for interactive depth matching of curves
- programs for calculating the relationship between frequency and mean value distribution of different parameters
- program for calculation of shaliness using different methods
- program for determination of permeability using different methods
- program for lithologic sectioning by utilizing the statistical method
- program for calculation of rock components at sampling points using the least squares method
- program for calculation of grain size
- program for determination of the calorific value, ash content and humidity of coal
- program allowing the interactive treatment of acoustic waveforms.

The present hardware configuration and the existing software ensure a good possibility for performing up-to-date, computer aided interactive well-logging interpretation which depends on the type of raw material.

In *Fig. 144* well-logging measurement material obtained in a coal prospecting borehole and represented by the mini centre, and the result of the lithologic sectioning based on the well-logging curves can be seen. As measurement material, we used resistivity curves obtained with sonde RO–H of 40 cm spacing, RO–R of 10 cm spacing and the W40 Wenner array sonde, together with the KAPPA induced polarization, the CAL (caliper), DENSITY and TG (natural gamma) curves. Depending on the amplitude values of the measured curves, low density and low radioactive radiation suggest the presence of coal; low resistivity, high radioactivity and high resistivity, high density, low radioactivity refer to clay and sand respectively.

The half-inch magnetic tape units guarantee the connection with mainframe computers too. Thus, for example, it is possible to represent data obtained with the ASOIGIS system in colour on the COROLLPRESS plotter operating in the mini centre. As an example of this, *Fig. 145* gives the result of the computerized processing of the well-logging measurement material from a water prospecting well. In the first column to the left the natural gamma GR and self-potential SSP logs can be seen; the second column shows resisitivity logs of sonde RS 40 cm and RL 160 cm; the third column contains the density ROB and density-porosity FID logs calculated from gamma–gamma measurement, and the neutron–porosity FIN log calulated from the neutron–neutron measurement.

In order to determine the rock components, after constructing and interpreting the probability distributions, the so called ‘crossplot’, is performed by solving the equation system set for each sampling point of the previously listed logs using the least squares method. The fourth column demonstrates the result of this, where FI is the effective porosity. SAND is the sand-, SILT is the silt-, and CLAY is the clay-content in per cent by volume. In the fifth column are plotted the FI, the producible water, FIAD, the water bound in clay, and SOLID, the solid rock matrix again in per cent by volume. In the last column the permeability PERM can be seen which is proportional to the amount of producible water in unit time, and obtained as a result of the application of Wyllie’s formula.

2.3.3 Development of an up-to-date well-logging data acquisition system based on an IBM AT compatible personal computer*

In 1989 ELGI developed a new generation of well-logging equipment. The equipment performs simultaneous measurement of numerous geophysical parameters — their number is limited first of all by the number of detectors. Such equipment sends the data to the surface, processes them simultaneously with the measurements, and displays and stores them. Depending on its configuration and the applied sonde set the system is suitable for solid mineral and CH prospecting as well. The K–500C type equipment is designed for shallow well-logging while the K–5000C serves for CH prospecting. Sondes of ELGI developed earlier can be used with this system. The main parts of the system *(Fig. 146)* are:

A) A ruggedized IBM AT compatible computer with special expansion cards developed in ELGI. This controls the system and performs processing simultaneously with the measurements using the appropriate algorithms. This processing means depth matching of data from different detectors, filtering of signals from the individual detectors, calculation of density and porosity, and correction of measured data for caliper, mud resistivity, mud density, etc. It allows data storage in a data base by real-time preprocessing. The operator controls the system through the keyboard using the menu system appearing on the monochrome monitor (measurement selection, calibration, depth setting, range setting, sonde opening and closing, etc.). The logs appear on a colour (EGA) monitor, on a matrix printer, and if necessary also on a 12-channel recorder. Data can be stored on floppy disk (3 1/2″, 5 1/4″), hard disk (20 or

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60 Mbyte) and on streamer (100 Mbyte) too. The communication card ensures data transfer from and to the sondes. The system can be expanded according to the user's demands but it can be made more simple too. The system runs under an operational system developed by ELGI which fits to the DOS.

B) Surface matching unit which is controlled by a microprocessor. Its tasks are to establish the correction between the computer and the sondes through the switch matrix controlled from the operator's menu system, to supply the downhole devices with current and to solve the physical data transfer. It allows simple matching of 'alien' systems through its 8 analog inputs. The matching unit is controlled by the computer through one of its serial data transfer lines (RS232).

C) Depth recording system. This performs the following tasks which are connected to the winch control: measurement of logging depth and cable speed, correction using a magnetic marker, measurement of cable tightness, etc. Data transfer between this and the IBM AT is performed through the second serial data transfer line (RS232) of the latter.

D) Downhole data acquisition and data transfer unit. This unit is microprocessor controlled and uses CMOS components; it is mounted in a Dewar heat prevention sytem. Outside the Dewar system the power supply unit can be found which provides the nesessary supply voltages for the data acquisition circuitry and the sonde train. The data acquisition unit is connected to the members of the sonde train through a bus system made of 13-pole connectors, this system ensures a bidirectional data transfer between the members of the sonde train and the data acquisition unit. The data acquisition unit is capable of processing analog and impulse-like signals arriving from the members of the sonde train (to digitize them and, based on the information, to send back commands to the members of the sonde train, and to transmit data to the surface in digital form). Connection between the unit and the surface is maintained through one conductor in half-duplex mode of operation. If necessary, members of the sonde train can be operated individually, without the data acquisition unit. *Figure 147* shows logs obtained with a gamma–gamma, caliper, natural gamma and neutron–neutron combination sonde (diameter 43 mm) developed for solid mineral prospecting.

Main parameters of the system

Maximum allowable pressure: 80 MPa

Maximum allowable temperature: 150 °C

Speed of data transfer: 40 kBaud on a 5000 m-long cable (80 kBaud under development)

Developed members of a sonde train:

- natural gamma sonde
- gamma–gamma and caliper (cal) sonde
- neutron–neutron sonde (pressed against the wall)
- laterolog sonde
- microlaterolog sonde (with motor-operated pad)

Some possible sonde trains:

- gamma–gamma–cal/neutron–neutron/natural gamma
- microlaterolog/laterolog/natural gamma/SP

The following sondes are being developed:

- spectral gamma–gamma
- spectral natural gamma
- multi element acoustic.

2.3.4 Development of a combined pressure gradient–temperature measuring sonde*

In a producing well the pressure gradient — except for the productive level — can be interpreted by means of Bernoulli's law. By determining the density of the fluid filling the well it is possible to gain knowledge on the phase conditions, to solve such important problems of production like position of the oil–water contact, changes in gas–water ratio with depth, etc. The pressure gradient measured at the productive level, in addition to the fluid density, reflects that pressure anomaly too which is caused by turbulent friction, by changes in direction and hydraulic collision of the formation fluid, depending on the structural features of the well (diameter, slotting, etc.), and leakage characteristics of the zone around the well. The pressure anomaly formed at the production level is small. The highest possible value is not more than a few tenths of a bar. Pressure gradient measurement is an ideal tool for studying the pressure anomaly, and this is justified not only by the high resolution requirement (< 50 Pa) but also by the fact that the pressure gradient ($\mathrm{d}p/\mathrm{d}z$) is a basic parameter in the various formulae.

An integral complement to the pressure gradient measurement is the temperature measurement. This is, on the one hand, necessary for temperature connection and it provides, on the other hand, further information on the operation of the well. By developing the combined pressure gradient–temperature measuring sonde, the set of production geophysical tools has been enlarged thus providing an excellent possibility for determining the ratio and position of the fluids (water, gas, oil) filling the well, and a better understanding of the operation of the well–layer system.

The operation principle of the combined pressure gradient–temperature measuring sonde can be followed using the block scheme shown in *Fig. 148*. The pressure gradient measuring sensor (1) operates on the principle of piezo-resistance, and it is placed in a Wheatstone bridge. The zero position of the bridge is balanced and compensated for temperature. The output voltage of the bridge, which is proportional to the differential pressure, is amplified by a high-stability amplifier (3). The output voltage of the amplifier reaches to a voltage-to-frequency converter (4), thus the output frequency is proportional to the pressure gradient.

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The temperature sensor (2) is a special integrated circuit, placed in a pressure-tight case the time constant of which is 1.5 s in fluid. Signals of the temperature sensor (which is a DC voltage) are also processed by a voltage–to–frequency converter (4). Signals of both the temperature and pressure channels are led into a logic circuit (5) which completely eliminates the interaction (coincidence) between the impulses from the two channels.

The information on pressure and temperature reaches the surface through a line amplifier (6) in the form of positive and negative impulses using a single conductor (8) which at the same time leads the current necessary to supply the sonde to the electronic circuitry of the sonde. For maximum stability both the pressure and temperature channels operate from a high-stability power supply (7) which, by means of a transmitter, rectifiers and stabilizers, produces the different operating voltages from the direct current arriving from the surface.

In *Fig. 149* it can be seen that the sonde measures the pressure difference between levels 1000 m apart in the investigated well. This measurement technique reduces the disturbing effect of any possible large-size bubbles in density determinations, in addition the numerical value of the pressure difference obtained in this way equals the average specific weight of the fluid filling the investigated well section. Technical data of the sonde

Measuring range:	pressure	10 KPa/m
	temperature	150 °C
Resolution:	pressure measurement	≤50 Pa
	temperature	≤0.05 °C
Maximum allowable	temperature	150 °C
Maximum allowable	pressure	65 MPa
Sonde diamater		43 mm

Cable system: single core, loop resistance max. 200 Ω capacitance max. 0.5 μF