Geological Quarterly, 2000, 44 (2): 157–166

Measurements and interpretation of well logs in the Jeziórko sulphur deposit, Tarnobrzeg, Poland

Jadwiga JARZYNA and Maria BAŁA

Jarzyna J. and Bała M. (2000) — Measurements and interpretation of well logs in the Jeziórko sulphur deposit, Tarnobrzeg, Poland. Geol. Quart., 44 (2): 157–166. Warszawa.

Geophysical logs of borehole F-380 drilled through the Jeziórko sulphur deposit near Tarnobrzeg are interpreted in terms of mineral composition and porosity. Measurements were made from a standard set of logs by Geokar Geophysical Co. and from using university prototype logging equipment developed for shallow boreholes. Comparative analysis was made of GR and gamma ray spectroscopy, density, neutron-gamma, epithermal neutron, and acoustic logs. The interpretation yielded values for the volume of limestone, clay mineral content, sulphur content, and porosity while the barite content in the sulphur deposit was determined from a four-log set (GR, neutron-gamma, density, and acoustic). A gamma ray log with the uranium window subtracted, GRS, used instead of GR, gave the distinct drop of shaliness and caused the distinct changes of sulphur content for selected intervals of the section examined. To test the geophysical interpretation, the sulphur content of core samples of limestone was determined by three different techniques: ICP-AES analysis, sample combustion in the LECO automatic analyser and X-ray phase analysis. Clay mineral identification in the overburden was attempted using the Th vs. K cross-plot. Acoustic full wavetrains were used for rapid identification of formation zones with different elastic parameters. The dynamic coefficient of rock elasticity, i.e. the Poisson coefficient, was obtained from P-wave and S-wave velocities, determined *in situ* from acoustic full wavetrains.

Jadwiga Jarzyna, Maria Bała, Department of Geophysics, Faculty of Geology, Geophysics and Environmental Protection, University of Mining and Metallurgy, Mickiewicza 30, PL-30-359 Kraków, Poland; e-mail: jarzyna@geol.agh.edu.pl *(received: October 14, 1999; accepted: Marz 24, 2000).*

Key words: interpretation of well logging, mineral composition, porosity, dynamic elastic parameters, sulphur deposit.

INTRODUCTION

Around Jeziórko near Tarnobrzeg, sulphur-bearing Miocene limestones several dozen metres in thickness occur under a 120 m thick overburden of shaly sands and sandstones, siltstones and mudstones. Exploitation of sulphur as a raw material is preceded by shallow seismics and borehole investigations to identify the deposit structure and to determine the physical parameters of sulphur-bearing limestones and waste rock. Interpretation of well log measurements gives volumes of sulphur and other mineral components, as well as porosity. The results of quantitative well log interpretation are compared with laboratory analyses of sulphur-bearing limestone core samples. The differences between geophysical and laboratory results are sometimes quite substantial.

The aim of the paper is to show how to improve the determination of sulphur content by careful selection of geophysical logs and by detailed quantitative interpretation. Gamma ray spectroscopy is also demonstrated as a new tool to provide information on clay mineral composition in rocks.

BOREHOLE MEASUREMENTS

Measurements in borehole F-380 in the Jeziórko sulphur deposit were made by two logging groups. The Geokar Geophysical Co. from Tarnobrzeg used standard well logging equipment and the university team applied prototype equipment developed at the Department of Geophysics, the Faculty of Geology, Geophysics and Environmental Protection, the University of Mining and Metallurgy, Kraków. The Geokar team used GR, neutron-gamma, density and lateral resistivity logs, A1.0M0.1N and M0.1N1.0A, and a caliper. The university group applied: acoustic full wavetrain, SAM60, gamma ray spectroscopy and spectral density, SO-5-90, epithermal neutron, ODSN-102 and a caliper.

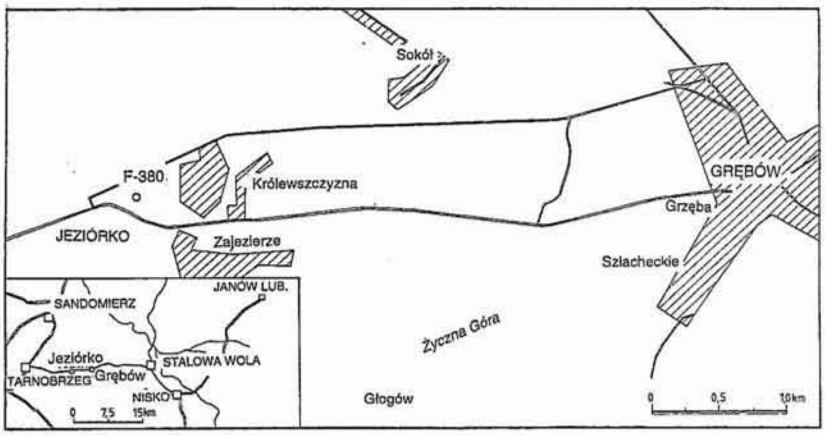

Fig. 1. Location of borehole F-380

Borehole F-380 is sited in exploiting area IX near Jeziórko about 200 m north of the Tarnobrzeg–Stalowa Wola road (Fig. 1). Measurements were made in the overburden at a depth range of 117.0–178.2 m and in the sulphur deposit at a depth range of 178.3–193.2 m. The upper part of the well was cased down to 117 m. The stratigraphy and lithology of rocks profiled in borehole F-380 are shown in Figure 2 (data from the Department of Geology of K&ZPS "Siarkopol", Tarnobrzeg).

The prototype, university density log was made only in the overburden, since the density equipped with a decentralising appliance, could not be moved into narrow sections of the borehole.

Integrated interpretation of well logs recorded by both the UMM team and the Geokar group involved determination of mineral composition (including sulphur content) and physical parameters (including bulk density, neutron porosity and total porosity) of the sedimentary overburden and the sulphur deposit. The main goal of this comparative study was to select an effective combination of logs to obtain values of sulphur content consistent with laboratory results obtained from core samples.

INTERPRETATION OF WELL LOGS IN THE OVERBURDEN

Quantitative interpretation was preceded by macroscopic core evaluation and by the detailed analysis of well-logs recorded with the prototype equipment of the UMM in the overburden, in an open borehole interval of 117.0–178.2 m. The deterministic, domestic GEO system was used for quantitative interpretation. This system employs several logs to determine mineral content and porosity in selected sections of the geological profile with constant lithology. Generally, sets of linear equations of the following type are solved (Hearst and Nelson, 1985):

$$L_k(H) = \sum_{i=1}^{n} C_{ik} V_i(H)$$

where: $L_k(H)$ — result of k-type log as a function of depth (acoustic, density, neutron); C_{ik} — matrix parameter for i-mineral and k-log; V_i — volume of i-mineral at the H-depth; n — number of logs.

In this study shale volume was always calculated from GR using a formula developed for Tertiary clastic formations (Frost and Fertl, 1981). According to the definition presented in the *Society of Professional Well Log Analysts* (1997), shale means "a fine-grained, thinly laminated fissile, detrital sedimentary rock formed by the compaction and consolidation of clay, silt, or mud. The composition is characterized by an appreciable content of clay minerals, or derivatives from clay minerals, and a high content of detrital quartz". The term "shaliness" refers to all clay minerals in clastic rocks and carbonates as well as to lithological types of pelitic (fine-grained) sediments including clays, claystones, marls, mudstones, and siltstones. When log analysts do not define which clay minerals occur in a rock but only want to establish the presence of clay minerals they refer to the "shaly rock" or "shaliness of a rock".

Two main units of clastic overburden (the *Pecten* Beds and the Krakowiec Clays) have contrasting lithologies. The *Pecten* Beds comprise grey and grey-green carbonate siltstones, marls, fine sandy and marly limestone intercalations, while the Krakowiec Clays are made of grey beige and greenish claystones, clay-siltstones and siltstones with fragments of quartzites, quartzitic sandstones, marls and limestones (Czapowski, 1994). Pawłowski *et al.* (1985) and Stoch and Helios-Rybicka (1973) distinguished also mudstones in the Krakowiec Clays. These lithological components could not all be separately distinguishing on the basis of the logging techniques used. A three-component simplified lithology model of shales, mudstones and sandstones was employed. Matrix parameters for individual components were adopted based on published typical values (Roberts *et al.*, 1990; Schlumberger, 1991; Halliburton Logging Services Inc., 1991) and interpreter's experience. A relatively high value of matrix transit interval time for shale was adopted since the formations investigated were never deeply buried (Pawłowski *et al.*, 1985) and are relatively uncompacted (Table 1). The mineral composition of the shales led to high values of neutron porosity and low values of matrix density being assumed. In these overburden shales montmorillonite, hydro-muscovite and mixed-layer clay minerals predominate (Stoch and Helios-Rybicka, 1973), and this was confirmed by a Th-K cross-plot, obtained from gamma ray spectroscopy (see Fig. 3). The sulphur deposit, showing low K and low Th values by this method, contains only small amounts of illite and micas (Stopiński, 1975). Clay minerals with a high content of water in the inter-sheet space show a high neutron porosity.

Results of the quantitative interpretation of selected logs in the overburden are shown in Figure 4. The section interpreted is shaly and contains a high content (*ca.* 25%) of mudstone. At the base of the interval analysed there is a thin sandy bed.

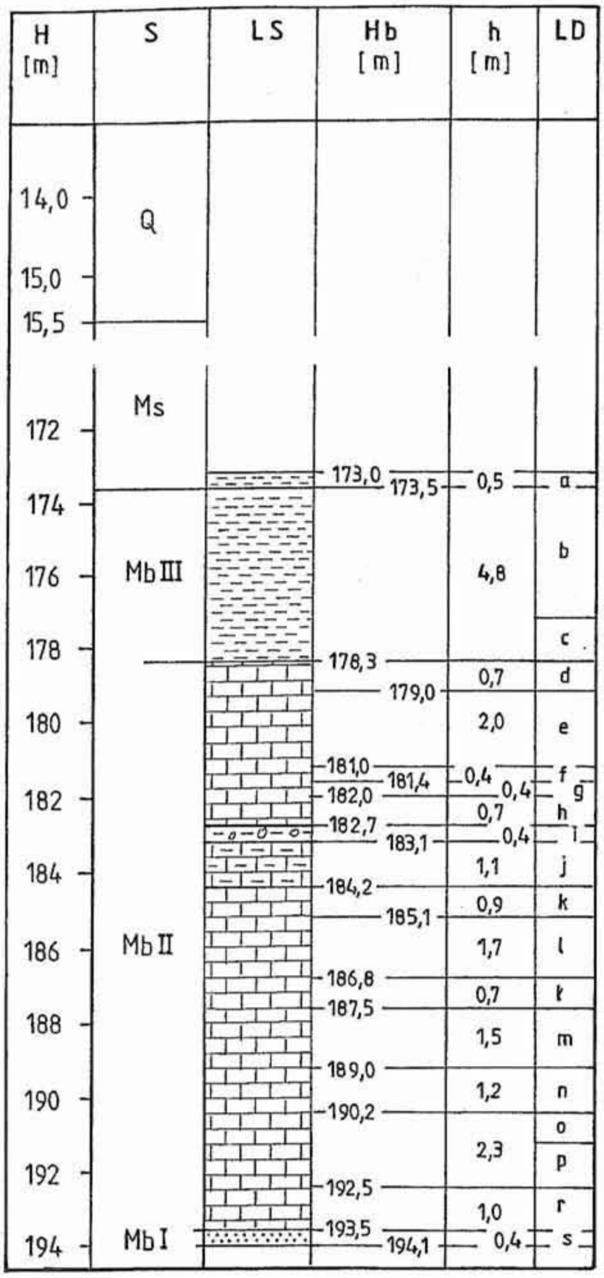

Fig. 2. Stratigraphy and lithology of rocks profiled in borehole F-380

H — depth; S — stratigraphy: Q — Quaternary, Ms — Sarmatian, MbIII—Badenian, *Pecten* Beds, MbII — Badenian, chemical series, MbI — Badenian, Baranów Beds; LS — lithology symbols; Hb — depth to base of interval; h — thickness of interval; LD — description of lithology; a — claystone, b, c — dark grey claystone without sulphur, d, k, ł, h — grey limestone, e — grey limestone, 10% sulphur, f, g — limestone, i — shaly-limestone breccia, j — dark grey marl without sulphur, l, n — grey limestone, 25% sulphur, m — grey limestone, 15% sulphur, o, p — dark grey limestone, 20% sulphur, r — grey limestone, 20% of sulphur, s — sandstone (data from the Department of Geology of K&ZPS "Siarkopol", Tarnobrzeg)

Table 1

Matrix parameters adopted for rocks and mineral components occurring in the overburden (*) and in the sulphur deposit of borehole F-380

Component	Neutron porosity Φ [%]	Transit interval time DT [μs/m]	Density δ [kg/m³]
Shale#	40	500	2400
Mudstone#	0	280	2500
Sandstone#	0	190	2650
Calcite	0	154	2710
Sulphur	-2	510*	2030
Barite	-1	229	4500
Shale	35	400	2400
Mud filtrate	100	630	1100

*value obtained in laboratory

Calculated porosity ranges from 3 to 25% with the greatest values in the interval 163.8–177.0 m. The mean value of overburden porosity is about 15%.

INTEGRATED INTERPRETATION OF THE SULPHUR DEPOSIT

The Geokar team employed three nuclear logs. The university team determined the GR [API] — the total intensity curve, the GRS [API] — an intensity curve without the "uranium window", and epithermal neutron, thermal neutron, and sonic logs.

Results of the Geokar team interpretation are shown in Figure 5a. The GEO system was employed in their interpretation. A multicomponent model of the medium was assumed, and volumes of individual components (limestone, sulphur, shale) as well as porosity were determined. Measurements made by the university team were quantitatively interpreted in several stages. At the first stage, a sonic log in the form of a transit interval time curve, obtained from a full waveform interpretation, was combined with the Geokar measurements (Bała and Jarzyna, 1992, 1996). Using the sonic log as additional data to GR, density and neutron-gamma methods enabled determination of the barite content and improved the accuracy of sulphur content determination. Interpretation of three logs: GR, neutron and density, enabled determination of the three major components, i.e. of shale, limestone and sulphur. An additional sonic equation gave new information as regards barite content. It resulted in changes in percentage of both limestone and sulphur. Results of the interpretation with the GEO system are shown in Figure 5b. Matrix parameters, used in the interpretation and listed in Table 1, were adopted based on Schlumberger (1991) and Halliburton Logging Service Inc. (1991) charts or were obtained from laboratory measurements of selected rock samples (asterix in Table 1 means that the transit interval time of sulphur was measured in the university laboratory).

The results of quantitative interpretation, shown in Figure 5a and b as volumes of mineral components and porosity, are

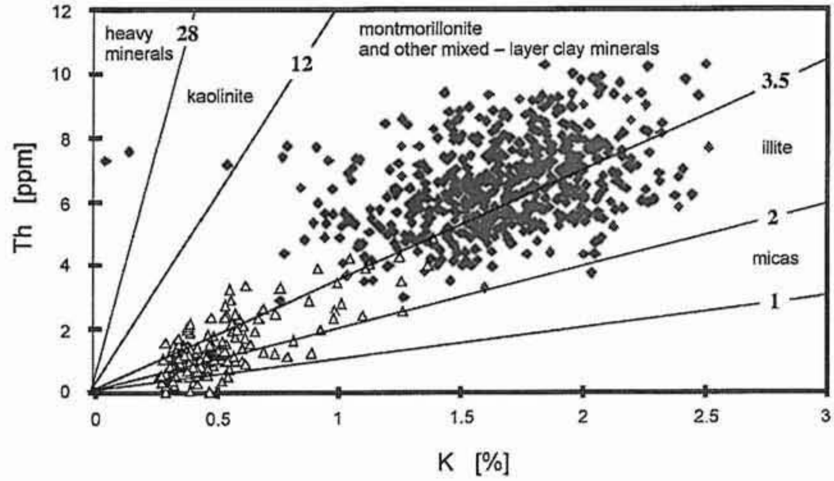

Fig. 3. Th vs. K cross-plot for the overburden and the sulphur deposit borehole F-380; lines annoted with values (i.e. 28, 12, 3.5, 2 and 1) in the internal part of the cross-plot are drawn for constant Th/K values; points corresponding to the overburden are marked with squares, points from the sulphur deposit are marked with triangles

similar. However, a lower sulphur content was obtained with the second interpretation for the lower part of the deposit (Fig. 5b and Table 2). The barite volume, obtained from the integrated interpretation, ranges from 0 to 8.26% with the greatest value in the interval 183.4–183.9 m. No barite peak was identified in the diffraction pattern for a core sample cut at 183.7 m depth (Fig. 6a). However, the ICP-AES ion analysis made for the same sample (Table 4) showed 109.4 ppm of barite ion. Barite occurrence in other samples was confirmed by X-ray phase and ion analysis. In diffraction patterns in Figure 6b peaks (B), corresponding to barite, are distinct. Geophysical interpretation showed substantial barite content at 188.7–189.6 m depth, and this was confirmed by peaks in the diffraction patterns. A high strontium content, of 7367 ppm, was observed 183.7 m and this may indicate the presence of celestine (Pawłowski *et al.*, 1985).

Table 2

Results of GRS, sonic, density, and neutron-gamma log interpretation for the sulphur deposit interval in borehole F-380 (GRS and sonic — UMM, density and neutron-gamma — Geokar)

Depth [m]	Volume [%]				
	Shale	Limestone	Sulphur	Barite	Porosity
178.3178.7	13.98	43.98	19.51	3.8	18.87
179.1	4.26	52.09	24.5	2.32	16.84
180.0	2.5	57.43	26	2.17	12.88
181.1	2.98	56.73	24.95	1.9	14.09
181.4	3.25	55.13	14.87	6.02	20.66
182.3	6.104	54.49	13.57	7.48	21.07
183.1	8.17	44.93	21.44	6.8	20.66
183.4	12.77	39.18	23.69	3.63	20.55
183.9	15.94	34.29	23.88	8.26	17.3
184.2	16.98	47.73	14.51	3.76	21.68
185.1	12	52.28	11.63	2.64	20.99
187.8	3.36	68.82	15.75	0.29	12.97
188.1	1.54	66.1	17.43	1.82	13.59
188.7	1.91	67.73	14.88	0.31	14.71
189.0	3.96	63.26	12.33	4.4	17.3
189.3	4.74	56.68	19.59	1.71	14.06
189.6	4.2	58.83	16.4	5.17	15.36
190.4	4.02	70.99	8.6	0.43	13.44
191.9	3	76.7	5.99	0	15.1

In the next stage, an integrated interpretation of density and neutron-gamma logs, recorded by the Geokar team, and sonic and GRS logs, measured by the UMM team, was made. The results are shown in Figure 5c and in Table 2. A drop of shaliness is observed over the entire interval studied; this is related with the use of the GRS log. An increase in sulphur content is observed at 185–186 m depth while the barite content remains constant.

The next step was quantitative interpretation of density recorded by the Geokar team integrated with logs obtained using the university's prototype logging system. The latter included GRS and epithermal neutron calibrated at Geofizyka Kraków Ltd., Zielona Góra Division. This interpretation showed an increase of porosity and a decrease of sulphur content by comparison with the results obtained in the previous stages (Fig. 5a–c and Table 3).

LABORATORY DETERMINATION OF SULPHUR CONTENT IN ROCK SAMPLES

The sulphur content obtained from well log interpretations was compared with results of laboratory tests on six rock samples cut from cores of the borehole F-380. Laboratory determination of sulphur content was made by ICP-AES (Boss and Fredeen, 1989), and by combustion of samples in a LECO automatic analyser. Both tests were made at the UMM. Moreover, X-ray phase analysis of a number of samples was made of the Oil and Gas Institute, Kraków.

Twenty-seven cores were collected from well F-380 in the interval 175.7–193.1 m. Macroscopic analysis of cores and geophysical data from other boreholes in the Jeziórko area (Geokar Geophysical Co., Tarnobrzeg, pers. comm.) show that sulphur-bearing limestones in the deposit are lithologically variable. Laboratory measurements of acoustic velocity, made on six samples to provide information on elastic formation parameters, confirm also a considerable lithological variability both in the deposit and in the overburden. Six samples cut from cores, representing different parts of the deposit, were used in X-ray diffractometry, ICP-AES spectrometry, and combustion in the LECO analyzer to obtain additional information on sulphur volume (Jarzyna *et al.*, 1997). There were no sufficient funds to cover the cost of a complete laboratory test for 27 cores. On the other hand, a number of possible results would be too small for credible statistical conclusions to be drawn. The results confirmed the presence of Ba ions and other elements in samples, so a separate determination of barite volume is justifiable. The accuracy of the method, sample size, and the site of sample collecting affect the results and, hence, different methods may yield different sulphur contents. Rock material for laboratory tests was taken from cores with a mass of about 2 kg. Rectangular prisms with dimensions of 0.09 x 0.15 m were cut out for acoustic measurements, while 0.5 kg homogeneous powder samples were used in other tests. For the ICP-AES analysis 1 g of homogeneous rock powder was dissolved in acid and then water was added to make a 100 ml volume of solution.

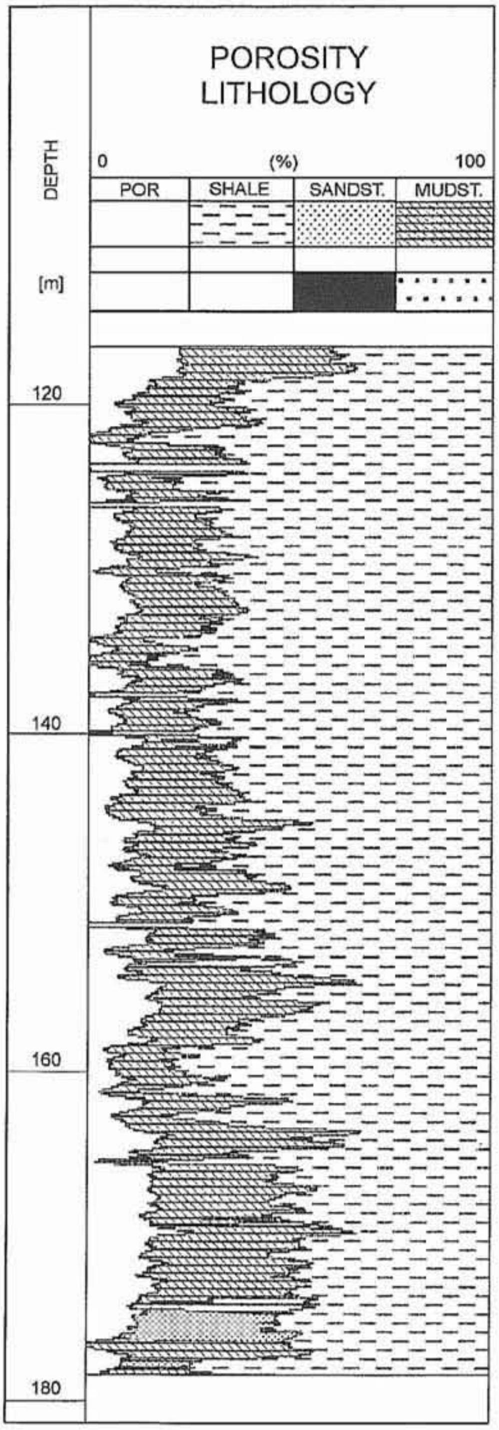

Fig. 4. Results of comprehensive interpretation of GR, epithermal neutron log and sonic log for the overburden in borehole F-380

Table 3

Results of GRS, sonic, epithermal neutron and density logs interpretation for the sulphur deposit interval in borehole F-380 (GRS, sonic and epithermal neutron — UMM , density — Geokar)

Depth [m]	Volume [%]				
	Shale	Limestone	Sulphur	Barite	Porosity
178.3178.7	13.4	47.45	12.38	4.92	25.14
179.1	3.03	52.41	10.51	5.61	28.05
180.0	2.5	58.8	6.13	6.54	26.81
181.1	2.52	57.89	9.65	5.12	25.01
181.4	3.34	56.33	5.7	7.35	27.3
182.3	6.1	55.8	2.22	9.25	29.38
183.1	8.17	46.23	9.79	8.76	29.05
183.4	17.08	40.6	8.67	6.46	31.31
183.9	15.94	35.51	10.48	10.83	26.88
184.2	16.98	45.03	4.81	5.02	29.15
185.1	12	53.64	0.54	3.14	30.22
187.8	2.4	69.67	8.9	0.5	18.74
188.1	1.54	66.71	16.34	1.48	14.42
188.7	1.91	68.54	10.29	0.48	18.42
189.0	3.27	64.2	6.62	5.01	21.47
189.3	4.74	57.48	14.09	5.34	18.12
189.6	4.2	59.44	17.5	4.13	14.69
190.4	4.02	70.57	4.17	0.36	18.35
193.0	2.1	75.90	5.9	0	16.10

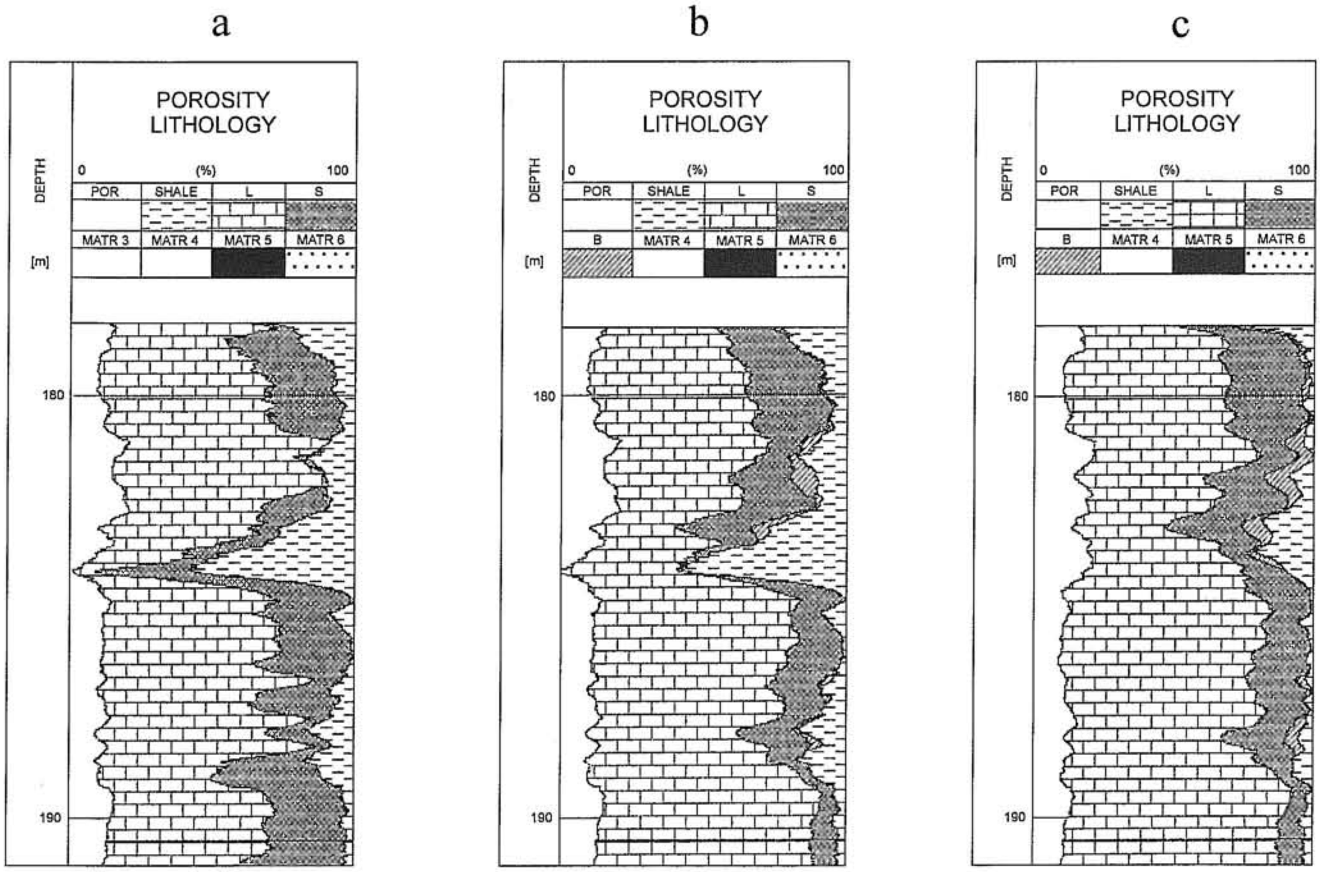

Fig. 5. Lithology and porosity determined for the deposit interval in borehole F-380 from the following logs: **a** — GR, density and neutron-gamma, **b** — GR, density, neutron-gamma and sonic, **c** — GRS, sonic, neutron-gamma and density

L — limestone, S — sulphur, B — barite

RESULTS OF ICP-AES ION ANALYSIS

Inductive Coupling Plasma-Atomic Emission Spectrometry (ICP-AES) was used to evaluate the following ions: S, Ba, Sr, Ca, Mg, Al, Na and K for six selected samples. In Table 4 the volumes of S, Ba and Sr are included; the others did not give essential information on the sulphur deposit. The accuracy of S, Ba and Sr ion content evaluation is good, the error does not exceed 3%. A limitation of ICP-AES in this instance is difficulty in dissolving sulphur-bearing carbonate rocks. Some native sulphur may get into solution and so the sulphur content may be slightly overestimated.

Table 4

Results of laboratory analyses and geophysical interpretation in borehole F-380

No/ Depth [m]	S [%]	Ba [ppm]	Sr [ppm]	S_{900} [%]	S_{1350} [%]	S_t [%]	$S_{geophys.}$ [%]
1	2	3	4	5	6	7	8
5/179.5	18.75	25.6	3045	21.15	3.41	24.7	23.1
6/180.7	14.49	28.7	4473	14.1	3.15	17.15	22.1
9/183.7	3.26	109.4	7367	3.01	1.40	4.485	6.1
19/189.9	37.72	21.5	1114	23.33	6.77	30.654	28.4
19A/190.20	28.31	166.4	1154	24.725	3.78	28.475	24.2
26/193.1	20.52	25.0	2221	24.93	4.82	28.35	24.4

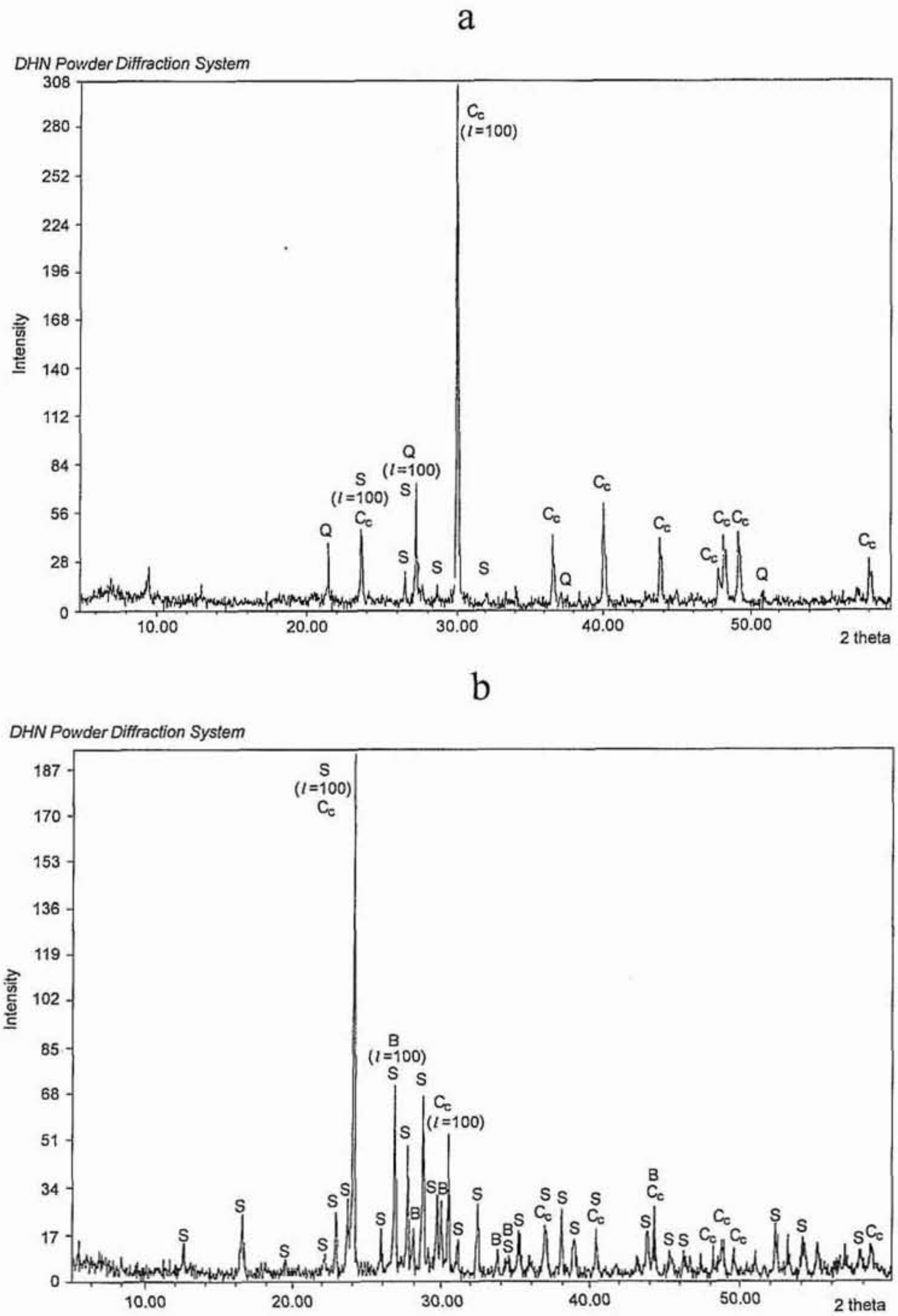

Fig. 6. X-ray diffraction pattern for a sulphur-bearing limestone in borehole F-380: **a** — sample from 183.7 m depth (no barite peaks identified), **b** — sample from 188.7 m depth (barite peaks identified)

C_c — calcite, S — sulphur, Q — quartz, B — barite

RESULTS OF COMBUSTION OF SAMPLES IN THE LECO AUTOMATIC ANALYSER

Sulphur content was determined with the LECO automatic analyser. The method is based on automatic qualitative combustion of a rock sample in the presence of oxygen at temperatures of 900 or 1350°C. Combustion products, devoid of moisture and mechanical impurities after filtering with magnesium perchlorate, are analysed in the infrared detector to obtain sulphur dioxide content. The obtained result is expressed with 0.001% accuracy as a percentage of sulphur in a sample. It was assumed that native sulphur content was obtained from combustion at 900°C, while sulphate content was measured during combustion at 1350°C. To check the results of total sulphur volume

Table 5

Lithology (macroscopically evaluated), velocity of P-wave and S-wave and Poisson coefficient of sulphur-bearing rocks in borehole F-380

Depth [m]	Lithology	Laboratory results		Acoustic full wavetrains interpretation		
		V_{Pav} [m/s]	V_{Sav} [m/s]	V_P [m/s]	V_S [m/s]	ν (Poisson coefficient)
175.70	limestone without sulphur	5145.8	2739.7	4167	2273	0.29
181.70	limestone	4067.3	2400 3.3	3289	2028	0.27
186.85	limestone with sulphur veins clearly visible	4244.7	2447.1	3378	1712	0.33
187.55	limestone	4572.8	2427.1	4167	2404	0.25
190.70	limestone	3966.4	2110.8	3788	2193	0.25
191.00	vuggy limestone	4017.0	2026.7	3906	2155	0.28

measurement, combustion of extra rock samples was performed at 1350°C.

QUALITATIVE EVALUATION OF THE PRESENCE OF SOME MINERALS WITH THE X-RAY PHASE ANALYSIS

The presence of certain minerals in rock samples was qualitatively evaluated with X-ray phase analysis at the Oil and Gas Institute in Kraków. A diffraction pattern for a core sample from a depth of 183.7 m is shown in Figure 6a, and this lacks a barite peak. Figure 6b shows a diffraction pattern for a sample from 188.7 m depth where barite peaks have been identified.

COMPARISON OF LABORATORY ANALYSES AND GEOPHYSICAL INTERPRETATION RESULTS

The results of geophysical interpretations and laboratory analyses for samples from different depths are listed in Table 4. Columns 2, 3 and 4 contain values for sulphur, barium and strontium volume, respectively, determined using ICP-AES. Columns 5, 6 and 7 contain values of sulphur content determined using the combustion method; in column 7 the total value of combustion product at 1350°C is given. The last column gives average sulphur content determined from the integrated interpretation of well logs. Values in Tables 2 and 3, representing mineral composition (shale, limestone, sulphur, and barite) and porosity, were calculated as an average volume of several results obtained in detached depth intervals. The interpretation of well logs using the GEO system was performed with a 0.10 m step, so several samples (4–28) were combined in an average value calculation. The sulphur content shown in column 8 of Table 4 was obtained from the results of integrated interpretation of combined logs (GRS, sonic, epithermal neutron, and density — Table 3).

Results obtained with different methods cannot be directly compared, but are in general agreement. The only direct comparison is between columns 7 and 8 where average total sulphur content is given. The differences between columns range from 6.7% (sample no 5) to 30.8% (sample no 9). These may be explained by inhomogeneous formation structure and by the different volume of rock sample used. Cores used in laboratory studies are of small volume compared to those in the vicinity of a geophysical device, suggesting that geophysical measurements made *in situ* are of greater reliability.

ELASTIC PROPERTIES OF SULPHUR-BEARING LIMESTONES — LABORATORY MEASUREMENTS AND ACOUSTIC FULL WAVETRAINS INTERPRETATION

Laboratory measurement of P-wave and S-wave velocity on cores taken from the overburden and deposit intervals were made using prototype laboratory equipment at the Department of Geophysics, UMM. P-wave and S-wave arrivals were also determined from borehole acoustic full wavetrains recorded at the same depth intervals. Laboratory measurement of velocity was used to verify acoustic full wavetrains recorded with the SAM60 tool. Mean values of laboratory-measured P-wave and S-wave velocity, mean values of transit interval time, and mean values of P-wave and S-wave velocity are listed in Table 5. A Vp/Vs ratio providing information on the lithology is also given in this table.

A discrepancy between P-wave and S-wave velocity values is a result of the strong heterogeneity of the rock medium. Small pieces of cores were used in laboratory measurements of velocity, while the SAM60 tool gathers information from a rock ring with the diameter equal to the hole size, a height of 0.5 m, and a width of a few centimetres. The velocity determined in laboratory is greater than that obtained from arrivals (transit interval times). The rock structure around the borehole is destroyed by drilling, while natural fractures filled with calcite or sulphur also occur there. Laboratory samples, however, were cut of core

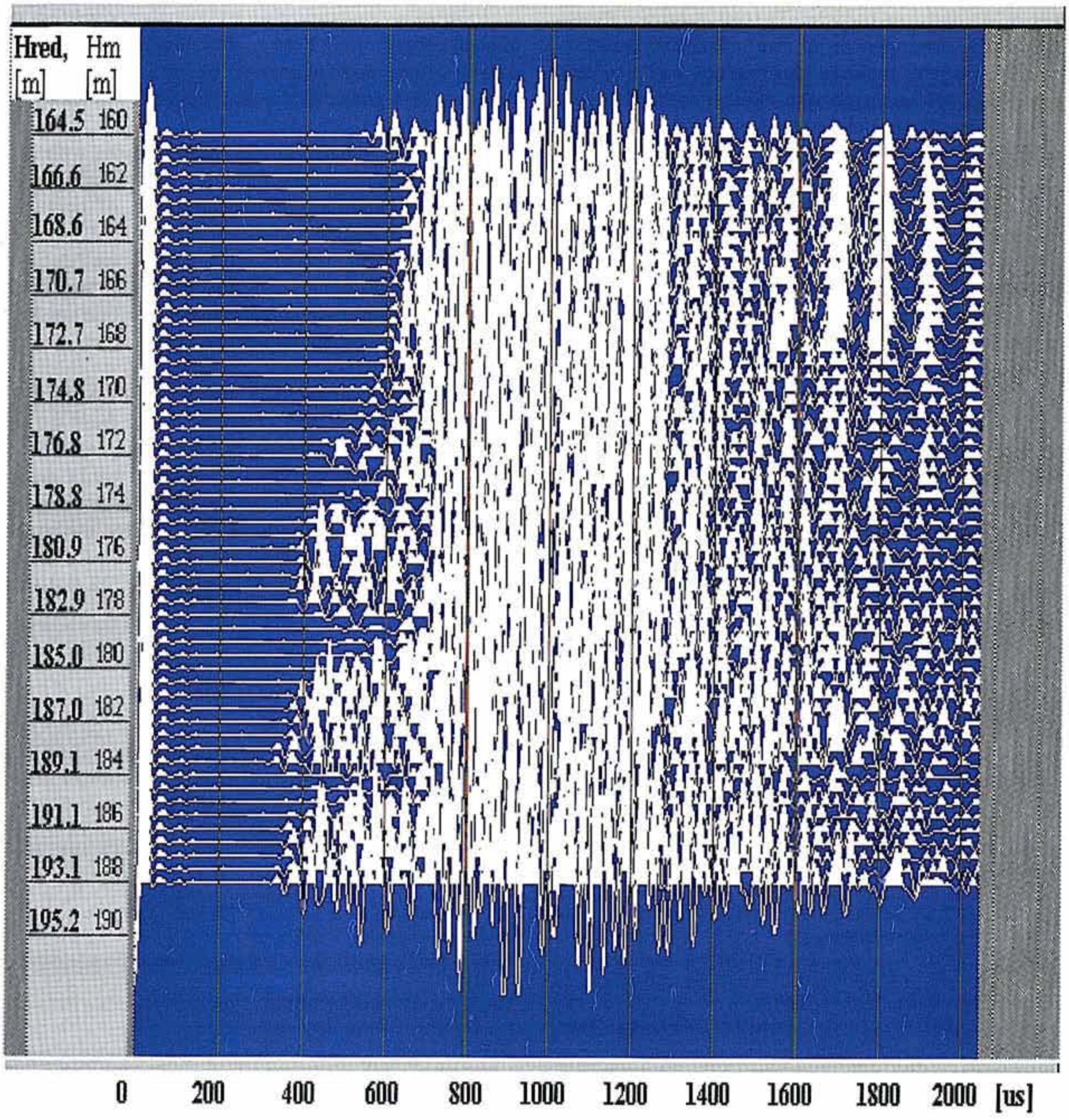

Fig. 7. A group of acoustic full wavetrains recorded with the SAM60 tool (near receiver — T1) in borehole F-380

Hm — depth measured, *Hred* — depth corrected for the shift of the recording point (in the centre of the distance between two receivers) and corrected for the lenght of the geophysical cable; on the horizontal axis time is in the range from 0 to 2000 μs

sections in which no fractures were observed. Nevertheless, values of the *Vp*/*Vs* ratio and the Poisson coefficient confirm the lithology evaluation. The Poisson coefficient ranges from 0.25 to 0.33, the greatest value corresponding to limestone containing sulphur.

Figure 7 shows a group of acoustic full wavetrains recorded with the SAM60 tool in well F-380; changes in the dynamic and kinematic parameters of acoustic full wavetrains recorded in the overburden and deposit are easily seen. These are caused by diverse lithology as well as by the different elastic parameters of shaly horizons, fractured and sulphur-bearing limestones, and hard, compact parts of the sulphur deposit. Such plots enable the qualitative recognition of a rock medium. In addition, the dynamic value of the Poisson coefficient of the formation may be calculated from P-wave and S-wave velocities determined *in situ*.

CONCLUSIONS

As a result of integrated well log interpretation, the mineral composition and porosity of sulphur-bearing formations may be obtained. The application of four independent logs in solving problems of lithology and porosity of a sulphur-bearing formation enabled the determination of five unknowns: limestone content, shale content, native sulphur content, barite content, and porosity. An acoustic log used in addition to standard logs (GR, neutron-gamma and density) enabled barite content to be determined and improved the sulphur volume determination. Barite may be easily distinguished from other mineral components (calcium carbonate, clay minerals and native sulphur) since its matrix parameters (neutron porosity, transit interval time, density) are very different. In addition to celestine, barite occurring in sulphur-bearing limestone may cause an overestimation of sulphur content in laboratory analysis of rock samples and may be the reason for differences between sulphur content determined from laboratory measurements and those from geophysical data. Therefore, the geophysical determination of barite content *in situ* gives useful additional information on a sulphur deposit.

Using gamma ray spectroscopy rather than a standard total intensity log, can help distinguish the effects of shaliness from the effects of uranium accompanying organic matter in a rock medium. Clay minerals may be identified in a Th vs. K cross-plot.

Laboratory analyses give additional information on the mineral composition of the sulphur deposit as regards native sulphur content and volumes of sulphur, calcium, barium and strontium ions, and constrain the reliability of geophysical data interpretation.

Qualitative recognition of a rock medium with different elastic parameters may be quickly made using acoustic full wavetrains. Quantitative interpretation of acoustic full wavetrains can deliver a continuous curve of Poisson coefficient vs. depth from P-wave and S-wave velocities. Dynamic elastic parameters and acoustic image form full waveforms enabling distinction between hard zones and fracture horizons, and sulphur-bearing limestones and barren layers.

Acknowledgements. The authors wish to thank Emilia Grzyb, Marta Boroń, and Zbigniew Wątor from the Geokar Geophysical Co., Tarnobrzeg, Poland, for access to their measurement data from well F-380. Special thanks are due to Tomasz Zorski from the Department of Geophysics, UMM, for his co-operation in field measurements and for interpretation of nuclear logs. The study was sponsored by the Committee for Scientific Research, Poland as project no 9 T12 A 010 10.

REFERENCES

BAŁA M. and JARZYNA J. (1992) — System of automatic interpretation of full waveform recorded during acoustic logging. Acta Geophys. Pol., **40** (2): 49–61.

BAŁA M. and JARZYNA J. (1996) — Application of acoustic full wavetrains for the determination of lithology, reservoir and mechanical parameters of formation. Geophys. Prosp., **44** (5): 761–788.

BOSS CH. B. and FREDEEN K. J. (1989) — Inductive Coupling Plasma-Atomic Emission Spectrometry: Physical Basis, Equipment and Methodisc. Perkin-Elmer Publishing .

CZAPOWSKI G. (1994) — Sedimentation of Middle Miocene marine complex from the area near Tarnobrzeg (north-central part of the Carpathian Foredeep). Geol. Quart., **38** (3): 577–592.

FROST E. Jr and FERTL W. H. (1981) — Prolog Well Site Analysis, Part II. The Log Analyst, January-February: 14–32.

HALLIBURTON LOGGING SERVICES INC. (1991) — Log Interpretation Charts. Houston, Texas, USA.

HEARST J. R and NELSON P. H. (1985) — Well Logging for Physical Properties. Mc Graw-Hill Book Company. New York, USA.

JARZYNA J., BAŁA M., PAŁKA K., ZORSKI T., GÓRECKA N., KNAP W., PONIEWIERSKA H. and SZUWARZYŃSKI M. (1997) — Methodisc of determination of physical parameters of rock formation using prototype equipment for well logging in shallow boreholes. Final report of project Nr 9 T12A01010, by Committee for Scientific Research. Library of Department of Geophysics UMM. Kraków (in Polish).

PAWŁOWSKI S., PAWŁOWSKA K. and KUBICA B. (1985) — Geology of the Tarnobrzeg native sulphur deposit (in Polish with English summary). Pr. Inst. Geol., **114**.

ROBERTS W. L., CAMPBELL T. J. and RAPP G. R. Jr (1990) — Encyclopaedia of Minerals, 2nd Ed. Van Nostran Reinhold Co. New York.

SCHLUMBERGER (1991) — Log Interpretation Charts. Houston, Texas, USA.

SOCIETY OF PROFESSIONAL WELL LOG ANALYSTS (SPWLA) (1997) — Glossary Copyright.

STOCH L. and HELIOS-RYBICKA E. (1973) — Mineralogical description of clays from the overburden of a sulphur deposit at Jeziórko (in Polish with English summary). Kwart. Geol., **17** (1): 106–117.

STOPIŃSKI A. (1975) — Changes in the geological environments as a result of working of the sulphur deposit at Grzybów by the borehole traction method, in the light of micro-gravity studies deposit (in Polish with English summary). Biul. Inst. Geol., **286**: 89–182.