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Amplitude Versus Offset (AVO) analysis for geothermal exploration in the Little Hungarian Plain

Research topic area:

Intergraded seismic and well logging techniques

Thesis of doctoral dissertation (PhD)

by

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I. INTRODUCTION

A multiscale geothermal exploration, started in 2012, resulted successful pairs of production and injection wells near to the city of Győr located on the Little Hungarian Plain, a sub-basin of the Pannonian Basin. The first step of the investigations was a reinterpretation of all archived geological, hydrogeological, and 2D seismic data that was available on the study area. The second step was an additional 2D seismic data acquisition, processing, and interpretation along new profiles. The third phase of the exploration was shooting a local 3D seismic survey planned based on the previous data. At the end, all previous information was integrated and interpreted together for picking out target locations for drilling and well logging. This step-by-step exploration (Kovács et al. 2019) became profitable after hitting a deep geothermal reservoir in the carbonate basement with three pairs of production and injection wells by 2018. Former Geological and Geophysical Institute of Hungary (MFGI), Geo-Log Ltd., and PannErgy Plc. were the partners in this successful geothermal exploration.

The high-quality seismic and well log data gave the opportunity to initiate special local investigations. In 2019, former Mining and Geological Survey of Hungary (MBFSZ) started to study the application possibility of the Amplitude Versus Offset (AVO) analysis for geothermal exploration. At this point, in a framework of a long-standing educational cooperation between MBFSZ and University of Miskolc, I was offered to join the methodological development and that was the beginning of my PhD research in this exciting topic.

AVO analysis have been successfully utilized in the hydrocarbon exploration for more than three decades, however their benefits in the geothermal exploration are recognized just recently. Lithology and rock physical parameters are similar for both type of reservoirs, consequently AVO should work not only to detect hydrocarbons; but to indicate hot water bearing porous geological formations. Of course, the depth is very crucial regarding the high temperature. In my PhD dissertation, I intend to call the attention that inversion techniques based on seismic and well log data (for example AVO inversion and Simultaneous Model-based inversion) can be beneficial for the geothermal exploration.

AVO methodology is based on the anomalous behavior of the pre-stack reflected amplitudes observed from fluid bearing rocks. Ostrander (1984) was the first who demonstrated that AVO responses from both the top and base of a porous gas sand show anomalous (increasing) trends unlike the AVO responses observed from other lithological boundaries showing normal (decreasing) trends. AVO analysis was introduced in the hydrocarbon exploration in the late 80's and after that the number of productive wells increased significantly not only in the Gulf of Mexico (Allen and Peddy 1993) but all around the world. Later, several authors proved that utilizing the pre-stack amplitude variations, AVO also works for fractured carbonate formations to indicate hydrocarbon bearing porous zones (Harvey 1993, Lynch et al. 1997, Li et al. 2003). Parallel with the above studies, the question came up whether AVO can be applied for other lithological investigations beyond the hydrocarbon exploration, for example to estimate rock properties in the depth rage of the middle crust (Pratt et al. 1993, Simon 1998). Takács and Hajnal 2000 and Takács et al. 2021 went even deeper and demonstrated the successful utilization of AVO processing focused on the vicinity of the crust-mantle boundary beneath SE Hungary.

After Goodway (2001) discussed detailed relations between the AVO analysis, Lamé parameters, and the lithology; Russell (2006) pointed out the importance of Elastic Impedance inversion for lithology interpretation. The Lamé parameters (incompressibility and rigidity) are much more characteristic for lithology interpretation and porosity detection than the P- and the S-wave velocity parameters, or even their ratio. The new seismic tool (Simultaneous Model-based inversion) based on the joint inversion of pre-stack reflected P- and S-wave amplitudes, was added to the toolbox of hydrocarbon exploration.

In the last decade, only a few authors studied the benefits of AVO analysis for geothermal exploration, however the number of publications is growing in this topic. Aleardi and Mazzotti (2012) investigated a geothermal reservoir located in the fractured intrusive basement of the Larderello-Travale geothermal field, Italy. They concluded that AVO responses from the fractured zones of massive basement can be different from the well-known amplitude responses of clastic sediments. The authors declared that „we need to derive a new AVO attribute which may highlight fracture locations in this peculiar rock type". Russell (2020) underlined the potential of AVO inversion and analysis in the geothermal exploration and concluded that adaptation of the methodology can be very promising for geothermal reservoir development. Recently, Allo et al. (2021) published their study on the utilization of neural networks in the characterization of a carbonate geothermal reservoir located in the Paris Basin, France.

II. ACCOMPLISHED INVESTIGATIONS

Focusing on a high temperature geothermal reservoir located in the Triassic basement of the Little Hungarian Plain, Hungary, I draw several conclusions that can be useful for further investigations in other study areas. I utilized properly pre-processed seismic and well log data for my study and demonstrated that a hot water bearing fracture zone in the dolomite basement can be successfully mapped by joint seismic and well log inversions (pre-stack Amplitude Versus Offset and Simultaneous Model-based inversions, as well as a subsequent Lambda-Mu-Rho transformation). True amplitude seismic data pre-processing and seismic well tie were essential steps before the inversion processes. I summarize the most relevant results as follows.

By modelling theoretical AVO responses in my study area, I concluded that the AVO response of the investigated geothermal reservoir (located in the carbonate basement) is different from the usually increasing response of a gas bearing clastic sandstone. The amplitude versus incident angle variations from the investigated carbonate reservoir shows clearly decreasing trends in the range of 0°–30° incident angles. My result fits Aleardi and Mazzotti's (2012) previous general conclusions very well, even though they studied fractured geothermal reservoirs in the intrusive basement of the Larderello-Travale geothermal field, Italy.

Carried out an accurate seismic well tie, very good fit between the calculated synthetic and real seismic traces was reached with a correlation coefficient value of 0.807. The P-wave acoustic impedance log inserted in the closest vertical seismic cross-section showed excellent fit between the well log and seismic data after the seismic well tie.

Traditional post-stack P-impedance inversion on the properly pre-processed 3D seismic and well log data provided an appropriate P-impedance model to indicate the investigated hot water bearing dolomitic fracture zone located in the Triassic basement. The inverted model resulted in anomalously low acoustic impedance values at the fractured interval revealed by a production well. However, the obtained model was not helpful to understand the horizontally variable lithology of the carbonate basement. For this reason, I carried out other modern pre-stack inversion procedures.

Scaled Poisson's Ratio Change AVO attribute model derived from the pre-stack seismic amplitudes indicated decreasing values at the top of the fractured carbonate zone and increasing values at its base. This feature of the Poisson's ratio is very characteristic for the fluid saturated zones in any porous geological formations. P-wave impedance, as well as P- and S-wave velocity ratio attribute obtained by the pre-stack Simultaneous Model-based inversion were also useful to map the hot water bearing porous zones of the basement. However, separation of the dolomite fracture zones, and the Triassic marl was not very successful by the above-mentioned inverted rock physical attributes. None the less, the P- and S-wave velocity ratio turned out to be as a good indicator for both the fracture zones and their complex lithological surroundings in the pre-Cenozoic basement.

The results of the above-mentioned pre-stack AVO and Simultaneous Model-based inversions provided the opportunity to carry out Lamda-Mu-Rho (LMR) transformation, which yielded to get two more characteristic rock physical models related with the Lamé parameters (Elastic Impedances – Lambda*Rho and Mu*Rho). Comparing those typical elastic parameters, Lambda*Rho proved to be the best amongst all inverted models in my study area, both from the viewpoint of fracture indication and lithology discrimination in the Triassic basement. My conclusion fits to Goodway's (2001) essential statements which were taken on a wide range of geological formations.

Most of the inverted rock physical models calculated and studied in my PhD dissertation were useful to identify and map the fractured zones containing high temperature hot water in the Triassic basement of my study area located in the Little Hungarian Plain, Hungary. Tracking the surrounding lithological formations, for example the Triassic marl was a more difficult task but it became successful after utilizing a subsequent LMR transformation. All inverted rock physical models obtained by the presented inversion procedures are evaluated from practical viewpoint in Table 5.

There are several practical benefits of the inverted rock physical models that I presented in my dissertation. They revealed the complex lithology of the Triassic basement and the hot water bearing reservoir system located in its fracture zones. Based on my new results, I concluded that three production wells drilled in the study area years before my recent investigations hit the western part of the geothermal reservoir. According to the investigated models, the major volume of the reservoir is in the eastern direction from those wells, and it has a vertically cyclic fabric of the porous zones. The methodology that I presented in my PhD dissertation is based on sophisticated joint seismic and well logging inversion algorithms, adopted from the hydrocarbon exploration, and can help with the well planning in future geothermal investigations.

Table 5 Evaluation of the inverted rock physical models obtained in the study area

Procedure / Rock physical model	**Detection of the fracture zone**	**Discrimination of the lithology**
Post-stack P-impedance inversion - P-wave impedance (Z_P):	 - Medium	 - Poor
Pre-stack AVO inversion - **Scaled Poisson's Ratio Change (Δσ)**:	 - **Excellent**	 - Poor
Pre-stack Simultaneous Model-based inversion - P-wave impedance (Z_P): - S-wave impedance (Z_S): - Density (ρ): - **P- and S-wave velocity ratio (V_P/V_S)**:	 - Medium - Poor - Poor - **Excellent**	 - Poor - Poor - Poor - Good
Lambda-Mu-Rho transformation - **Lambda*Rho (λρ)**: - **Mu*Rho (μρ)**:	 - **Excellent** - Poor	 - **Excellent** - **Excellent**
Cross-plotting - **Velocity ratio (V_P/V_S) versus P-wave impedance (Z_P)**: - **Mu*Rho (μρ) versus Lambda*Rho (λρ)**:	 - **Excellent** - **Excellent**	 - **Excellent** - **Excellent**
Spatial mapping - **Scaled Poisson's Ratio Change (Δσ)**: - **P- and S-wave velocity ratio (V_P/V_S)**: - **Lambda*Rho (λρ)**:	 - **Excellent** - **Excellent** - **Excellent**	 - Poor - Poor - Poor

III. NEW SCIENTIFIC RESULTS

- **Thesis 1** on the AVO modelling:

I proved that AVO response of a geothermal reservoir located in the fractured carbonate basement can be very different from the usual response of any gas sands located in clastic sediments. Both the top and the base of a clastic gas sand usually have increasing AVO responses. I built up a seven-layer rock physical model based on the well log data of my study area (Little Hungarian Plain) and demonstrated that the AVO response of the investigated Triassic geothermal reservoir had peculiar characteristics. On the one hand, AVO responses both from the top and the base of the dolomite fracture zone show decreasing amplitudes with the offset (incident angle). On the other hand, the AVO responses from the base of the investigated fractured reservoir show anomalously low angle of crossover (less than 30°) together with negative intercept value (zero offset reflection coefficient). For this reason, introduction of a new AVO attribute, combination of angle of crossover and intercept, would be helpful for geothermal investigations in case of exploration of the deep dolomite basement.

- **Thesis 2** on the seismic well tie:

I obtained excellent correlation coefficient (0.807) between the synthetic and observed seismic traces by an accurate seismic well tie, even though the well logging (i.e. the acoustic log) intersected variable geological formations in the Pliocene, Miocene, and Triassic sequences. I concluded that there are at least three different reasons for the initial misfit between the time-converted (uncorrelated) well logs and the observed seismic data. The causes are the different frequency range used for the acoustic logging and for the surface seismic observation, the weakened rocks caused by the drilling, and the missing velocity information between the surface and the starting point of the acoustic logs. A simple depth-to-time conversion of the well logs will result in poor correlation between the log data and the surface seismic section. Precise seismic well tie (correlation) is a must before performing any seismic inversion procedure that utilizes the well log data.

➢ **Thesis 3** on the post-stack P-impedance inversion:

I applied traditional post-stack P-impedance (Z_P) inversion on the true amplitude pre-processed 3D seismic and correlated well log data and concluded that this relatively simple inversion procedure provided surprisingly appropriate P-impedance model to detect a hot water bearing fractured dolomite zone of the Triassic basement of my study area. The top and the base of the fracture zone were known from well logging, and the inverted seismic model resulted in anomalously low P-impedance values at the location of the fractured interval revealed by a production well. However, the obtained rock physical model was not very helpful to discriminate the horizontally very variable lithology in the carbonate basement (fractured dolomite, friable dolomite, and Triassic marl). For this reason, I decided to perform subsequent pre-stack AVO and Simultaneous Model-based inversions to investigate the basement in detail.

➢ **Thesis 4** on the **pre**-stack AVO inversion:

I carried out pre-stack AVO inversion on the true amplitude pre-processed 3D seismic and correlated well log data. I concluded that Scaled Poisson's Ratio Change ($\Delta\sigma$) is a very helpful AVO attribute for detecting high temperature water bearing carbonate formations even in the Triassic dolomite basement of my study area. The Scaled Poisson's Ratio Change AVO attribute indicated decreasing values at the top of the fractured carbonate zone and increasing values at the base of the zone. This feature is very characteristic for the fluid saturated zones located in any geological formations. On the other hand, this pre-stack rock physical attribute allowed to get more detailed insight in the horizontal lithology variations of the pre-Cenozoic basement of the area of investigation than the earlier calculated post-stack P-impedance inversion did.

➢ **Thesis 5** on the pre**-stack** Simultaneous **Model-based inversion:**

The pre-stack Simultaneous Model-based inversion provided several additional rock physical attributes for my investigation on the study area. I concluded that the pre-stack P-wave impedance (Z_P) data proved to be more detailed than the post-stack one produced beforehand. It indicated the Triassic fracture zone very well; however it still didn't allow distinguishing the fractured dolomite, friable dolomite, and marl inside the basement. On the other hand, the S-wave impedance (**Z_S**) attribute could not be helpful to indicate the fractured zone at all because S-wave does not propagate in porous media. Neither the obtained density (**ρ**) attribute turned to be a good porosity indicator, likely because deriving density information from seismic data is a very difficult task. However, I derived the P- and S-wave velocity ratio (**V_P/V_S**) from the above rock physical attributes and pointed out that it was a very good indicator to separate the Triassic fracture zone from the Triassic marl.

➢ **Thesis 6** on the Lambda-Mu-Rho (LMR) transformation:

I analyzed several rock physical attributes (P- and S-wave impedances, density, Scaled Poisson's Ratio Change, V_P/V_S ratio, as well as the Lambda*Rho and Mu*Rho parameters) obtained by three different inversion algorithms and a subsequent LMR transformation applied on the same, properly pre-processed 3D seismic data and well logs. I compared all results of the conventional post-stack P-impedance inversion, the modern pre-stack AVO inversion, and the novel pre-stack Simultaneous Model-based inversion utilizing the available seismic and well log datasets. I was focusing on a known geothermal reservoir located inside the Triassic basement and concluded that three of the calculated rock physical parameters, namely the Scaled Poisson's Ratio Change, the V_P/V_S ratio, and the Lambda*Rho attributes provided the best results for porosity indication and lithology discrimination inside the very complex carbonate basement of my study area.

➢ **Thesis 7** on the cross-plotting and spatial mapping

I provided useful lithological information based on cross-plotting and spatial mapping of several rock physical parameters (Scaled Poisson's Ratio Change, P-impedance, V_P/V_S ratio, Lambda*Rho, and Mu*Rho). On the one hand, fractured dolomite, calcareous marl, and dolomite were successfully discriminated in vertical sections. On the other hand, I concluded that three production wells drilled before my recent analyses were planned very accurately based on the only available conventional migrated stacks at that time. Based on the novel inverted rock physical models, all production holes hit the western part of a complex Triassic reservoir in a fault zone; and the major volume of the reservoir system is in east direction from the wells. It has a cyclic structure which was supposedly evolved by the variation of the see level. The methodology that I presented in my dissertation can help with well planning in future geothermal investigations.

IV. LIST OF RELATED PRESENTATIONS AND PUBLICATIONS

CONFERENCE PRESENTATIONS

1. Emad Nageh Masri, Ernő Takács: AVO inversion for a geothermal reservoir located in the carbonate basement, INVERZIÓS ANKÉT, University of Miskolc, 2022
2. Emad Nageh Masri, Ernő Takács: Characterization of a Carbonate Geothermal Reservoir by the Inversion of Seismic Reflection Amplitudes, EAGE GET 2022, Netherlands, 7-9 November 2022 (Scientific Poster)
3. Emad Nageh Masri, Ernő Takács: Characterization of a Carbonate Geothermal Reservoir by the Inversion of Seismic Reflection Amplitudes, EAGE GET 2022, Netherlands, 7-9 November 2022 (Conference proceedings)
4. Emad Nageh Masri, Ernő Takács: True amplitude pre-processing of the 3D seismic data, SEISMIC ENCOUNTER, Budapest, 23-25 September 2022. (Scientific Poster)
5. Emad Nageh Masri, Ernő Takács: Application possibilities of AVO inversion for geothermal exploration, SEISMIC ENCOUNTER, Budapest, 23-25 September 2022. (Scientific Poster)
6. Emad Nageh Masri: AVO investigation of a known geothermal reservoir in the pre-Cenozoic basement's fractured carbonate formations, Northwest Hungary", az 52. Ifjú Szakemberek Ankétjára ,Orosháza- Gyopárosfürdő, 25-26 Március 2022.
7. Emad Nageh Masri: AVO study on a known geothermal reservoir in the fractured carbonates of the pre-Cenozoic basement, NW Hungary", DOKTORANDUSZOK FÓRUMA, Mikoviny Sámuel Földtudományi Doktori Iskola, 2021
8. Emad Nageh Masri: Geothermal reservoirs and AVO analysis, a preliminary case study from northwest Hungary, DOKTORANDUSZOK FÓRUMA, Mikoviny Sámuel Földtudományi Doktori Iskola, 2020.
9. Emad Nageh Masri, Ernő Takács: The possibilities of Amplitude Versus Offset (AVO) analysis in geothermal exploration, INVERZIÓS ANKÉT, University of Miskolc, 2020
10. Emad Nageh Masri: AVO modelling of a geothermal reservoir located inside the Mesozoic basement of the Pannonian Basin, RAW MATERIALS UNIVERSITY DAY, University of Miskolc, 2020.
11. Emad Nageh Masri: Application of Amplitude Versus Offset analysis and Hilbert attributes in the Komádi area, eastern Hungary, DOKTORANDUSZOK FÓRUMA, Mikoviny Sámuel Földtudományi Doktori Iskola, 2019

JOURNAL ARTICLES

1. Masri E.N. and Takács E. (2023): Simultaneous model-based inversion of pre-stack 3D seismic data targeting a deep geothermal reservoir, Northwest Hungary Acta Geodaetica et Geophysica Q2
2. Masri E.N. and Takács E. (2022): AVO study on a known geothermal reservoir located in the fractured carbonate formations of the pre-Cenozoic basement, NW Hungary. Acta Geodaetica et Geophysica Q2
3. Emad Nageh Masri, Ernő Takács: AVO response modelling for a Geothermal Reservoir Inside the carbonate basement of the little Hungarian Plain MŰSZAKI FÖLDTUDOMÁNYI KÖZLEMÉNYEK, (Technical Earth Science Publications), 2020

   "The described article was *carried out as part of the EFOP-3.6.1- 16-2016-00011 "Younger and Renewing University – Innovative Knowledge City – institutional development of the University of Miskolc"*
4. Emad Nageh Masri: Amplitude Versus Offset analysis – A possible useful tool for geothermal exploration, MŰSZAKI FÖLDTUDOMÁNYI KÖZLEMÉNYEK, (Technical Earth Science Publications), 2020

   "The described article was carried out as part of the EFOP-3.6.1- 16-2016-00011 "Younger and Renewing University – Innovative Knowledge City – institutional development of the University of Miskolc"

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