Case study of a geophysical investigation with seismic refraction tomography and the OhmMapper to estimate the brine content of a Salar/Salmuera

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K-UTEC AG Salt Technologies was contracted to prepare mineral resource/ore reserve estimations for a potassium project in the northern part of Peru. The final phase of the project did include a classification of the deposit and the estimation of mineral resources and ore reserves according to the BVL-Code. For this purpose the project was subdivided into three phases:

- In the first working step a comprehensive research and acquisition of relevant and available data was executed to evaluate the geographical, geomorphological, geological, hydrogeological, hydrometrical and economic conditions of the Salmueras area. Based on this data review an extensive exploration concept was developed.
- Implementation of the exploration programme (field work), summary of all gained data and preparation of an intermediate report.
- Evaluation of the deposit, mineral mesource/ore Reserves estimation and preparation of the final report.

After the review of all available and relevant data, an exploration concept for the Salmueras was prepared. This exploration concept was executed on site between summer 2010 and spring 2012.

The wide experiences of K-UTEC AG (www.k-utec.de) with potash projects and other brine-evaporation projects in South America were highly relevant for the Salmueras project. K-UTEC AG as an engineering company specializing in salt geology, processing and exploration has the capability for interdisciplinary and close cooperation with specialists in the field of geology, geophysics and salt-processing. This ensures consideration of all essential facts, from the exploration to the processing plant design, which is crucial for a profound deposit evaluation.

The final results based on the information and data gained during the exploration program include:

- Geological and topographical mapping of the concession area
- Geophysical investigations
  - 32.0 km seismic exploration
  - 29.4 km geoelectric exploration
- 48 drillings between 10 and 102 m depth with overall
  - 1146.65 m cores
  - 196 Brine Samples
  - 468 Solid Samples
- 5 Pumping Tests
- Piezometer measurements

Further information which was taken into account:

- 193 brine samples from surface pits in depths of 0 to 2 m
- Climate, hydrological and geological data from different reports.

The temperatures in the desert which contains the Salmuera, show a very low range of changes due to the moderating effect of the nearby Pacific Ocean. The desert is one of the most arid ones on earth because of the upwelling of cold coastal waters and the subtropical atmospheric subsidence.

During El Niño years, flooding in the desert regularly occurs. In the years 1997/98 a very strong El Niño phenomenon causes precipitation from January until April of 799 mm instead of 16 mm annually. The normally bone-dry desert was transformed by the intensified rainfalls into a great lake. The run-off from the floods poured into the coastal area of the desert, where there had been nothing but arid hardscrabble waste for 15 years suddenly created the second largest lake in Peru: 145 kilometres long, 30 kilometres wide, and three meters deep, with occasional parched domes of sand and clay poking up from the surface.

Geological Setting

The basin of the Salmuera is bounded by the Andes Mountains in the eastern direction, by the Amotape horst structure in the northern to northwestern direction and by the Illescas Mountains in the western direction. To the South it is limited by the coastline and the Pacific Ocean.

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A Paleozoic basement of metamorphic rocks represents the border to the western direction. A Mesozoic Andeantype suite of magmatic rocks forms the basement of the onshore basin consisting of slightly metamorphosed, volcaniclastic assemblages and intrusive batholiths (Wine et al.).

The Precambric and Paleozoic basement rocks are detected in depths of 1500 to 2500 meters. Cenozoic sediments of the basin were deposited within at least four transgressive cycles with hiatuses during the Paleocene to middle Eocene, Oligocene, middle Miocene and late Miocene (Republica Del Peru, Sector Energia y Minas, Instituto Geológico Minero y Metalúrgico (1980)). These four transgressive cycles, which can be found in the basin area as well as in the Salmueras area, can be described as seen in Table 1.

Geophysical investigations

Objective targets and task formulations

The tasks for the geophysical investigations were the structural exploration of the salt sea (Salar/Salmuera) and the closing of information gaps of the geological and hydrogeological exploration. Geophysical methods can give a continuous overview about the brine conditions (the thickness and the depth below the surface, the size etc.). Furthermore, it is possible to detect additional aquifer layers in the underground. It can be visualized parameters, which can give a hint of different salinities (resistivity) in the underground as well as structural barriers, which could divide the possible existing aquifer layers.

The data review of the investigation area contained the review of more than 50 reports, studies and other sources. The background of the reports and studies were mostly the exploration of oil and gas or the exploration of groundwater for drinking water. The reviewed reports assumed a brine layer depth not more than 5 m to 7 m with some possible gaps from former riverbeds.

Methodology

For the geophysical investigation of the Salmueras two different geophysical methods were chosen. First, the seismic refraction tomography gave a good overview of the structure of the brine zone. As a second method a geoelectrical method with the special equipment of the OhmMapper was applied. Both investigation methods were carried out on the same profile lines.

The seismic investigation was worked out using a so-called *Landstreamer* with 96 active seismic channels (geophones) and a vibrator or a sledge hammer as a seismic source. The reason for using the *Landstreamer* is the large length of the profiles and the desert surface which allows the pulling of the lines. The vibrator as seismic source was selected to give good quality data results, a falling weight drop as an alternative variation source was not accessible.

The investigation step with the fast capacitive coupled geoelectrical device (*OhmMapper*) could be pulled with a high velocity up to 3 km per hour behind a car. The positioning was done with a DGPS (accuracy ± 0,5 m). This capacitive coupled geoelectrical investigation has only a limited penetration depth up to 10 m/15 m. But the data density is very high.

Geophysical equipment and effort list

Seismic investigation:

- Seismic registration units (type Geode – Geometrics Ltd) with 24 channels each, power supply and all-terrain-laptop) including communication cable and triggering cable and connector,
- 96 geophones with the Landstreamer cables
- Seismic source (p-wave vibrator or sledge hammer)
- DGPS to get the position of the investigation points/profiles
- Two all-terrain-vehicles for pulling the Landstreamer cables with the geodes etc.,
- Five people to operate the investigation (One operator and four assistants and drivers).

The previous estimation of up to 2 km measured profile length per day was a good average for the field work. One additional day was spent before starting the seismic investigation to carry out a seismic parameter test.

Geoelectrical investigation with the capacitive coupled device OhmMapper:

- OhmMapper (Geometrics Ltd) with five channels
- DGPS to get the position of the investigation points/profiles
- All-terrain-vehicle to pull the OhmMapper stream
- Three people (including the car driver, the operator and one technician)

Transgressive cycle/Formation	Lithological Description
Miramar	Sandstone and Quartzite
Zapallal	Sandstone and Quartzite, Limonite and clayish Sandstone, interbedded with Calcilith
Montera	Bentonite and Diatomite, Sandstone and Quartzite, interbedded with Calcilith
Mancora- Heath	Sandstone and Quartzite, Bentonite and Diatomite, Conglomerates on the base
Basement	Granodiorite complex, Phyllite, Quartzite, Shists and Mica shists

***Table 1** Lithological Description of transgressive deposit compositions in the investigation area.*

The previous estimation of up to 15 km measured profile length per day could be fulfilled.

Investigation in the field

All investigation profiles (seismic as well as the geoelectric) were positioned by a DGPS made by Leica, type GS09.

The base station was always located on a known station (for example a well) and gave the correction data to the rover on the truck with the equipment.

Refraction seismic tomography

As mentioned before, the refraction seismic tomography was carried out with four registration units called 'Geode' of the company Geometrics. The equipment was carried by a car; the 96 geophones on the registration unit were pulled by two cars (Figure 1) to enhance the investigation progress. The geophone spacing was 5 m, the shot point station was 30 m.

At the beginning, a vibration source (Figure 2) was used to initiate the seismic signals. Different bandwidths (between 10 Hz and 360 Hz) of the vibration signal were tested. Some single shot results looked promising, but it changed already on the next shot point. The data quality of the vibration correlated signal for the differing underground conditions was not good enough; therefore a sledge hammer (Figure 1) was used as a seismic source for the exploration subsequently.

Geoelectrical investigation

The geoelectrical investigations were executed with an OhmMapper TR5 (Figure 3), which consists of one transmitter unit to send the signal into the ground and five receiver units to observe five data sets at once. The main advantage of the equipment is the fast exploration progress. The maximum investigation depth is between 10 m and 15 m, which seemed adequate taking the so far gained data into account. The newer drilling results showed that the brine base is often deeper than 15 m. So the geoelectrical exploration depth of the geoelectrical investigation is too low in some cases.

Data quality

Refraction seismic tomography

The data quality differs between the different profiles. Often the quality was even different on the same profile depending on the underground (mud, sand or a mixture of both). The weather conditions influenced also the quality quite strong, especially the wind. During some daily hours it was almost not possible to get good quality data.

As mentioned before, the data quality using the vibration source was very bad. The investigation of these profile parts had to be repeated in the second exploration campaign.

The following data examples (Figure 4 to Figure 7) show the different conditions of the data quality. The quality depends a lot on the underground as well on the weather conditions and the source, as described before.

The data quality was controlled immediately after the measurement at each shot point. If the data quality was not sufficient, the shots were repeated. Furthermore, at each shot point the registrations were stacked up to a number of 10 single shots.

Geoelectrical Investigation

The data quality of the OhmMapper exploration changed also for different underground conditions. The muddy underground had a high conductive condition, which is responsible for lower penetration depths of the geoelectrical investigation. High conductive underground leads to errors during the data logging and data gaps.

Figure 1 *Investigation car with the registration units, the GPS unit and the Landstreamer.*

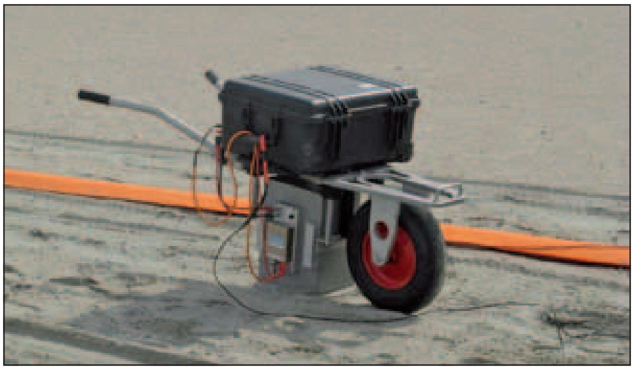

Figure 2 *Vibration source (ELVIS III P8 of the company Geosym GmbH).*

Figure 3 *OhmMapper in the field behind the investigation truck.*

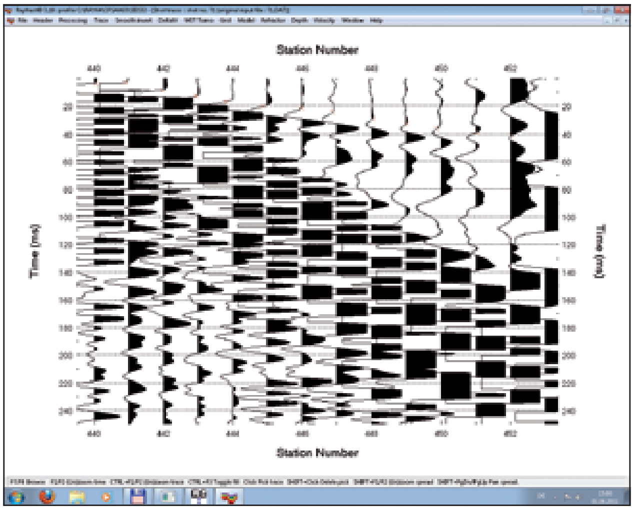

Figure 4 *Heightened data example from a hammer shot.*

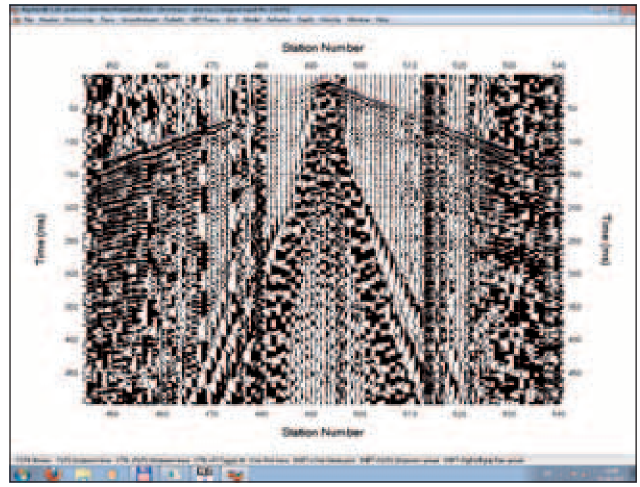

Figure 6 *Example of a good shot point situation with signal over the whole layout length.*

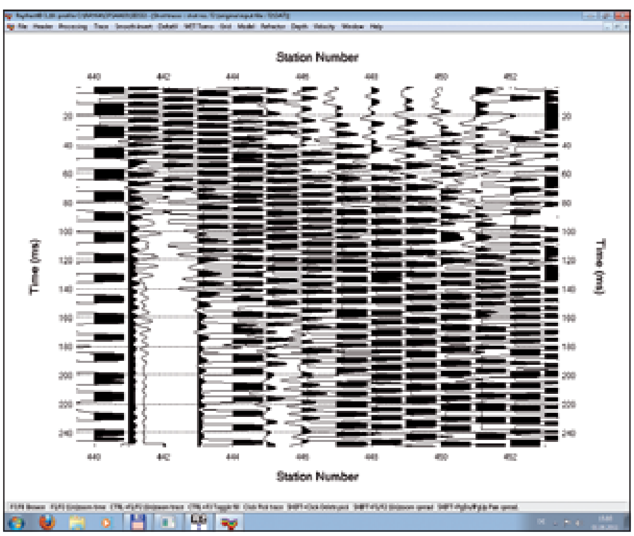

Figure 5 *Heightened example of a vibration shot on the same shot point.*

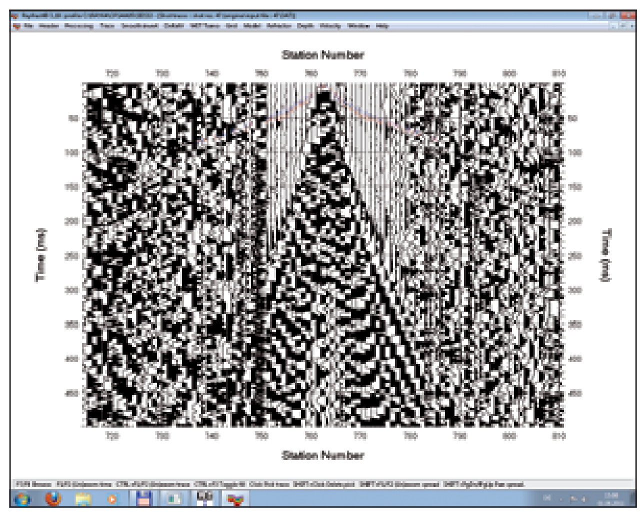

Figure 7 *Example of a poor shot point situation with signals visible only a few geophone stations because of noise by wind and the underground.*

Results and interpretation of the geophysical data

The velocity distributions of the sections show the different weak and stiff areas in the underground. The weak (or low velocity areas) correspond with brine zones. The stiff area (high velocity area) in Figure 8 describes the tight and dam layers. The example in Figure 8 shows great differences in thickness of more than 10 m on a length of about 100 m within the same layers.

The OhmMapper inversion results show the distribution of the resistivity. Areas with very low resistivities (Figure 9) indicate the occurrence of brine with a high salt content.

The thickness of the overburden sand layer is 0 m to 3 m thick, which could be worked out in a good quality with the results of the OhmMapper.

Seismic refraction tomography

The processing, velocity calculation and modelling of the seismic section was executed with the software package Rayfract (www.rayfract.com). The theory behind the iterative modelling software package is given on the internet platform of Rayfract. The results differ in the resulting RMS error, but stayed always below 4 %. The final model has been made using the software package Surfer (www.goldensoftware.com).

The seismic inversion results were calibrated with the borehole information. Furthermore the seismic results were compared with the calibrated results of the geoelectrical investigation of the OhmMapper. These combined information (seismic, geoelectric and boreholes results) lead to the maps of the brine distribution.

Geoelectric tomography

The OhmMapper inversion results show the distribution of the resistivity. Areas with very low resistivities (Figure 9) indicate the occurrence of brine with a high salt content. Also with this method the variation of the brine layer thickness can be visualized.

The example shows the OhmMapper exploration for a near-surface layer up to 15 m depth. For the task of the estimation of the brine volume and mineral distribution until a depth of 35 m and more, the applicability of the OhmMapper is limited. The data was processed and inverted with the software packages DC2DInvRes and BERT (www.resistivity.net).

Resulting depth model

The resulting calculation of the depth of the embankment layer with the data of the geophysical investigations (seismic refraction tomography and OhmMapper investigation) as well as the data of the boreholes was shown.

The data of the embankment layer were picked and transformed in the correct geographic co-ordinates. For the embankment depth calculation of the area a variogram analysis were performed to avoid statistical errors resulting from the higher data density on the geophysical profiles.

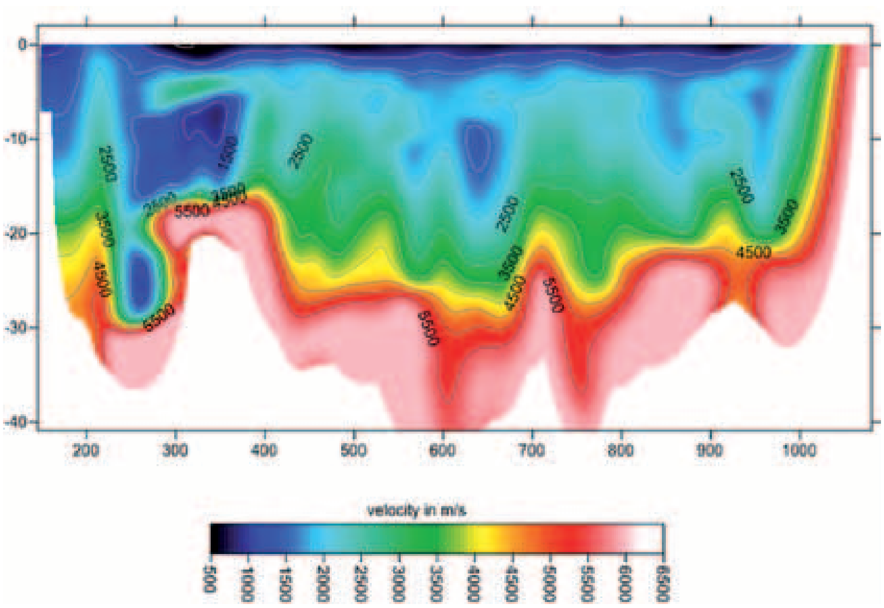

Figure 8 *Velocity distribution of the underground on one profile.*

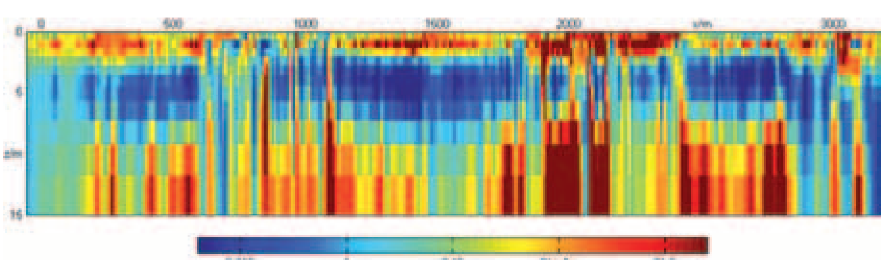

Figure 9 *OhmMapper inversion result profile 1 to 2.*

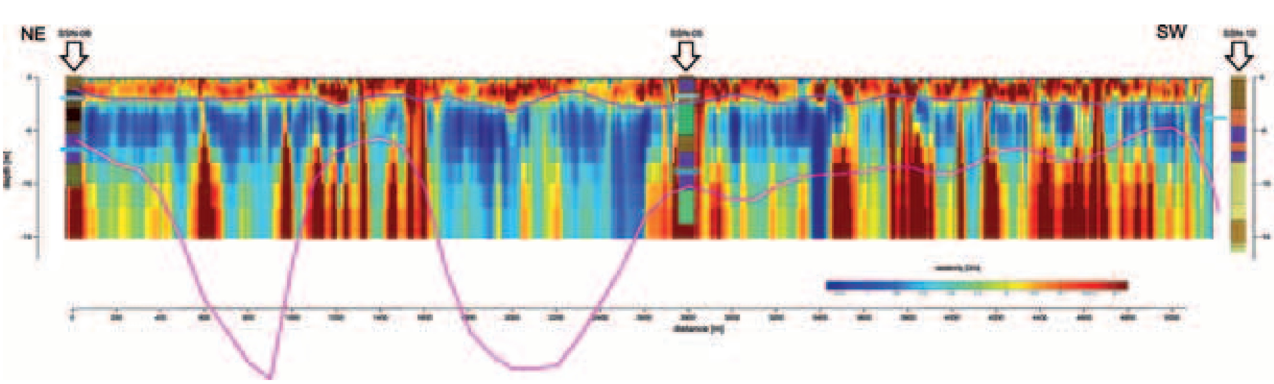

Figure 10 *OhmMapper inversion result with additional borehole information (brine top and base interpretation).*

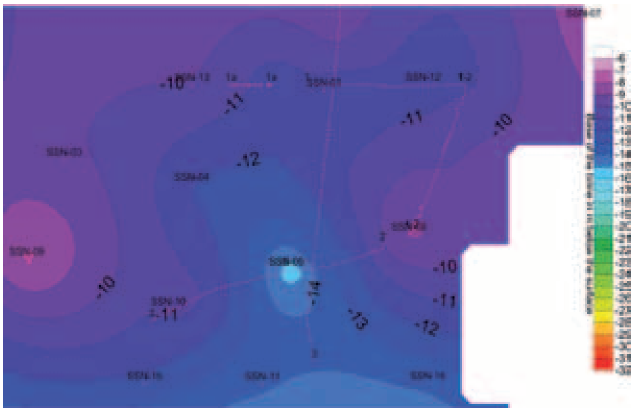

Figure 11 *Cutout of the depth map of the embankment layer after the geophysical exploration, the borehole exploration and topographic correction.*

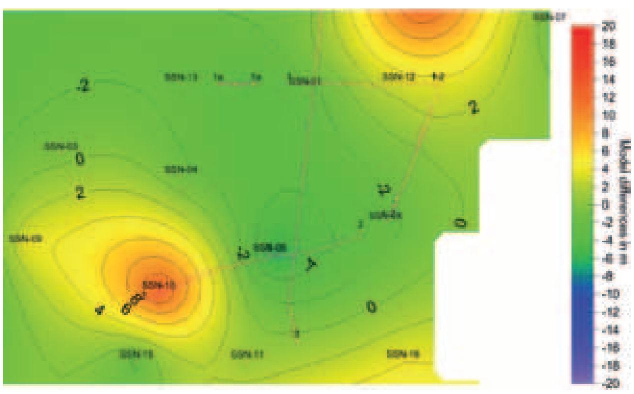

Figure 12 *Cutout of the depth map difference between the geophysical model and the borehole model for the embankment layer.*

The data input from the base of the brine was smoothed by reducing the number of picked data. The reason is to get an overview of the brine base. The mentioned channels, which could be seen in the data results, give just a trend for the depth for the calculation process.

The result of the calculation shows a classification of the concession area in three parts. One area has the lowest depth up to 15 m (Figure 11). Other areas have a depth up to more than 32 m. The distribution of the geophysical exploration profiles is mostly also the area with the highest variation in small ranges. A lot of areas are only covered with boreholes, which causes smaller exploration grades and the limitation of the accuracy of the resource and reserve calculation.

The data of the bottom and the top of the brine layer in the explored area were used as the geometrical base for the brine content calculation. Additional information coming from the chemical analysis and hydrogeological exploration about the qualitative mineral content and porosity were involved as well.

Error estimation

Errors in the geophysical exploration as well as in the borehole exploration will cause errors in the volume, resource and reserve calculation.

The geophysical exploration data were calibrated on the borehole data as long as they were available. Because of poorer quality data on some profiles (because of seismic noise for example by wind), some areas had to be interpolated for the embankment depth. The noise in the original data leads also to higher RMS error in the iterative modelling of the seismic sections. The average error of the seismic modelling was about 2%.

The calculation of the depth of the embankment layer was based on a statistical iteration calculation (Kriging algorithm). The Kriging algorithm was corrected by a variogram analysis, which cannot avoid errors on the model boundaries because of the lack of available data.

Value of the geophysical data

In Figure 12 the value of the geophysical data is demonstrated. With a volumetric model based just on the geological soundings, the results would differ much more from the reality. The difference between a boreholes based geological model to the combined geophysical-geological model reaches for this case study up to ±20 m in layer thickness.

Summary

The geophysical exploration of the Salmueras in the northern part of Peru was part of the geoscientific exploration. The geophysical results of the acoustic and electrical petrophysical parameters in the subsurface were one part of the modelling of the brine distribution in the Salmuera.

The refraction seismic results gave information about the structure, channels and the embankment layer in the subsurface. With help of this information for the investigated areas a hydrogeological barrier could be excluded.

The OhmMapper results gave quite good information about the top of the brine layer in the underground. The information about the base of the brine layer was limited because of the limited depth penetration of the instrument as well of the decreasing of the sensitivity and resolution of the geophysical method.

The combined geophysical results could support the limited number of geological soundings to get a more sophisticated brine model.

References

Wine G., Martinez E., Monges C., Calderon Y. & Galdos C. [2004] Trujillo basin off Peru contains numerous promising structures, Oil & Gas Journal, 102 (20) 45–51.

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