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Three Dimensional Geological Model of Pohang EGS Pilot Site, Korea

Tae Jong Lee[1], Yoonho Song[2], Deok-Won Park[3], Jaesoo Jeon[4], and Woon Sang Yoon[5]

[1,2,3]Korea Institute of Geoscience and Mineral Resources (KIGAM), 124 Gwahang-no, Yuseong-gu, Daejeon 305-350, Korea

[4,5]NexGeo Inc., 5F, Junghwa B/D 39, Yangjae-Daero 66-gil, Songpa-gu, Seoul 138-800, Korea

[1]megi@kigam.re.kr, [2]song@kigam.re.kr, [3]pdw@kigam.re.kr, [4]hygeojs@nexgeo.com, [5]gaia@nexgeo.com

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ABSTRACT

Geothermal investigations of Pohang site has been carried out for more than a decade, since Korea Institute of Geoscience and Mineral Resources (KIGAM) had launched a geothermal development project for a large scale space heating in 2003. Several surface geological and geophysical surveys, including seismic, gravity, magnetic and magneto-telluric (MT) have been conducted during that period. A total of five deep boreholes have been drilled so far, some of which were drilled for exploration purposes and the others for production of geothermal water. After the Korean EGS pilot project was launched in 2010, well PX-1 was drilled. It reached a depth of 4,127 m by October 2013. Well PX-1 is recorded as the deepest well ever drilled in Korea. The drilling results showed that the area has a flat-layered structure with some plutonic intrusions. Specifically, the Heunghae Basin, which is the main target for the geothermal exploration, is covered with Quaternary alluvium deposits underlain by thick Tertiary sediments which is quite uncommon in Korea. The basement rock of granite or granodiorite appears at a depth of around 2,200 m. According to the geophysical surveys carried out (gravity, magnetic and MT) it is expected the presence of lineaments and fractures mainly running NNE-SSW together with crossing conjugates fractures at the southern part of Heunghae Basin. In this study, we first collected and correlated all the data generated by these surveys with the drilling results, and then it was integrated as a common 3D geological model using commercial software GoCAD™.

1. INTRODUCTION

Korea does not have high enthalpy geothermal resources related to volcanic or tectonic activity. The geology of Korea is characterized by a basement of old rocks covered by very thin sedimentary layers. The most recent volcanic activity has been reported in the year 1007 A.D. in the Jeju Island, South Sea of Korea. However, in that zone there are some anomalous regions that shows high geothermal gradient and Pohang is one of such regions that show high heat flow and geothermal gradient. The geothermal anomaly in the Pohang area has been reported in 1960s from several deep drilling projects for oil exploration.

Based on the anomalous geothermal regime the low-temperature geothermal development project in Pohang has been performed by the Korea Institute of Geoscience and Mineral Resources (KIGAM) for 6 years from 2003-2008 (Song et al., 2006a; Lee and Song, 2008). Intensive geological and geophysical surveys such as airborne gravity, magnetic, radioactive, geochemistry and magneto-telluric campaigns have been performed to delineate possible fractures which can transport deep geothermal water to near surface. Four exploration wells have been drilled to figure out the geological and geothermal structure of the target area. Well logging from the four wells commonly showed a geothermal gradient higher than 30 °C/km, while national average of geothermal gradient is about 25 °C/km (Lee and Song, 2008). Assessment of geothermal resources in Korea (Lee et al., 2010) showed that the temperature at 5 km depth of the Pohang area is expected to be about 180 °C, which is the highest temperature expected in South Korea within the 5 km depth so far.

Based on the scientific results, the government and industry decided to launch a proof-of-concept project for enhanced geothermal systems in Korea in December 2010. During the following 4 years of EGS research, more data was collected including seismic reflection, measurements of physical properties of rocks and core samples, and drilling of well PX-1. This well was planned for injection or production and reached a depth of 4.127 km, which is the deepest well ever drilled in Korea. In this article, we summarize all the results above mentioned. Next, we will integrate them as a common 3D geological model of the pilot site and the surrounding area.

2. GEOLOGY OF THE POHANG SITE

Figure 1 shows the geologic map and a schematic 3D diagram of the geological structure of the Heunghae Basin deduced from the geological/geophysical surveys and the drilling results of 5 wells. The area is located in the Tertiary Pohang Basin, which overlies Cretaceous sedimentary rocks, biotite-granite intrusions and Eocene volcanic tuffs. The Heunghae Basin, which is the main target of the geothermal exploration program, is covered with Quaternary alluvium underlay by thick Tertiary sediments, which is quite uncommon in Korea. A thick Tertiary semi-consolidate mudstone (S-MS) covers the area, it thickness varies from more than 400 m in the south to about 200 m at the northern part. Below the S-MS unit, a 1,000 m thick Cretaceous sedimentary layer of sandstones and mudstones interlayered with volcanic intrusions or eruptions is present. Then, below these sedimentary rocks a sequence of andesites and crystal tuffs is underlay by a Paleozoic granodiorite which forms the basement of the basin. A radiometric age dating of a granodiorite core recovered from a depth of 2.2 km from well BH-4 results in an age of 268±4 Ma.

Figure 2 shows geological columns, thermal conductivities from the core samples and temperature logs for well BH-4, which reached down to 2,383 km in 2006. Temperature log is depicted in the left figure of Figure 2 and it was recorded right after the drilling and shows a thermal gradient of 31 °C /km. But, it was surely disturbed by the circulation of drilling mud. Right hand side figure in Figure 2 shows temperature profiles recorded in the year 2010 from long-term temperature monitoring using optical fiber, where one can observe temperature of 91 ^{o}C at 2 km depth, which, in turn, indicates an average geothermal gradient of 38 ^{o}C /km within the shallower 2 km depth assuming a temperature of 15 ^{o}C at the surface.

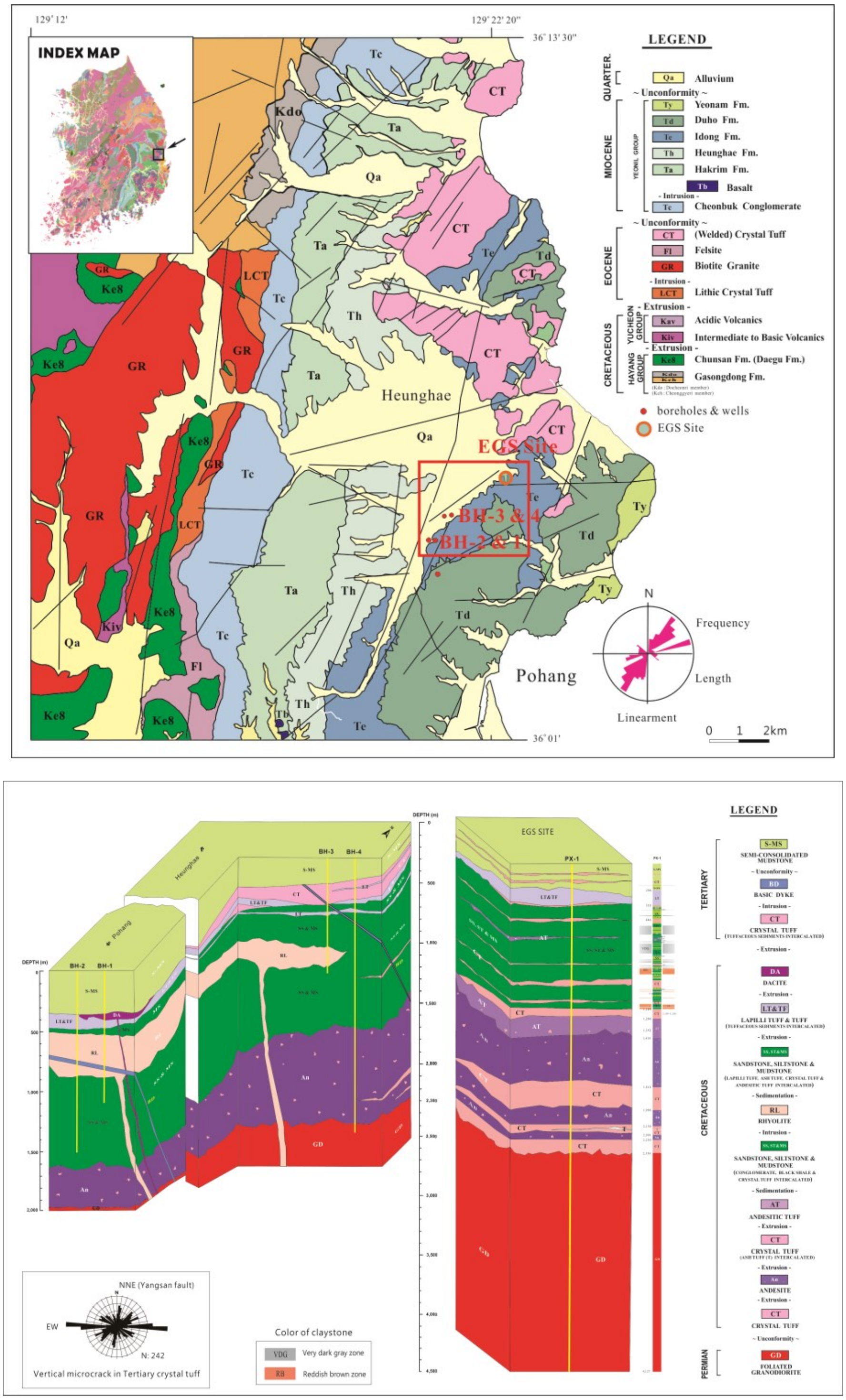

Figure 1: Geologic map with lineament distribution deduced from Landsat TM image analysis (upper), and a 3-D view of the geological model of the Heunghae Basin (lower) deduced from core and well logs for 4 wells drilled from the Pohang project and PX-1 well drilled in the EGS project.

Figure 3 summarizes stratigraphic data from neighbor wells, most of which were drilled for petroleum exploration in 1960s. All of these boreholes are located to the west/south-west of the EGS site. The right figure of Figure 3 depicts depth to the granite in a northwest to southeast cross section. Granite depth varies from 110 m at the shallowest zones to about 900 m at the deepest part. Borehole PY-3 did not found the granite unit. Borehole #201, located to the west of the EGS site, showed the shallowest granite depth (110 m) and from there getting deeper to the west and south. As we go further to the East from the petroleum exploration transect shown in the left figure of Figure 3, towards the Heunghae Basin where wells BH-4 and PX-1 locates, the granite shows a flat roof to depths of about 2.2 km, as can be seen in both wells (Figure 2).

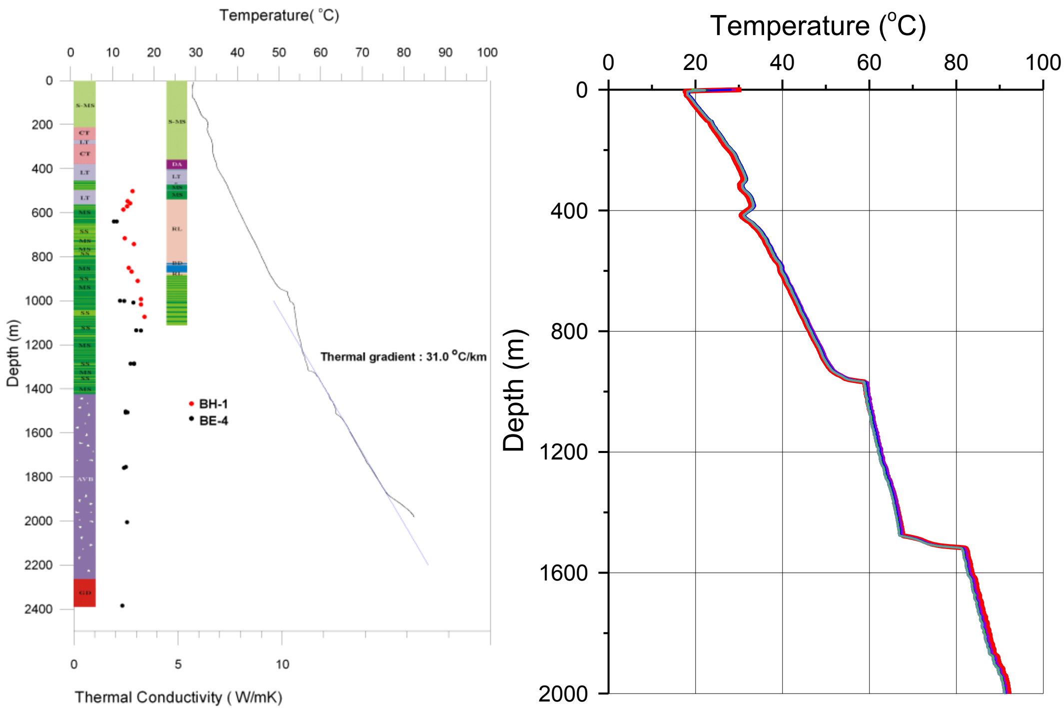

Figure 2: Stratigraphic column, thermal conductivity, and temperature logs for two wells (YR 2006) and temperature monitoring for well BH-4 (YR 2010). For symbology in left plot please refer to Figure 1. Note the temperature at 2 km depth of BH-4 of about 91 °C in 2010 (right plot).

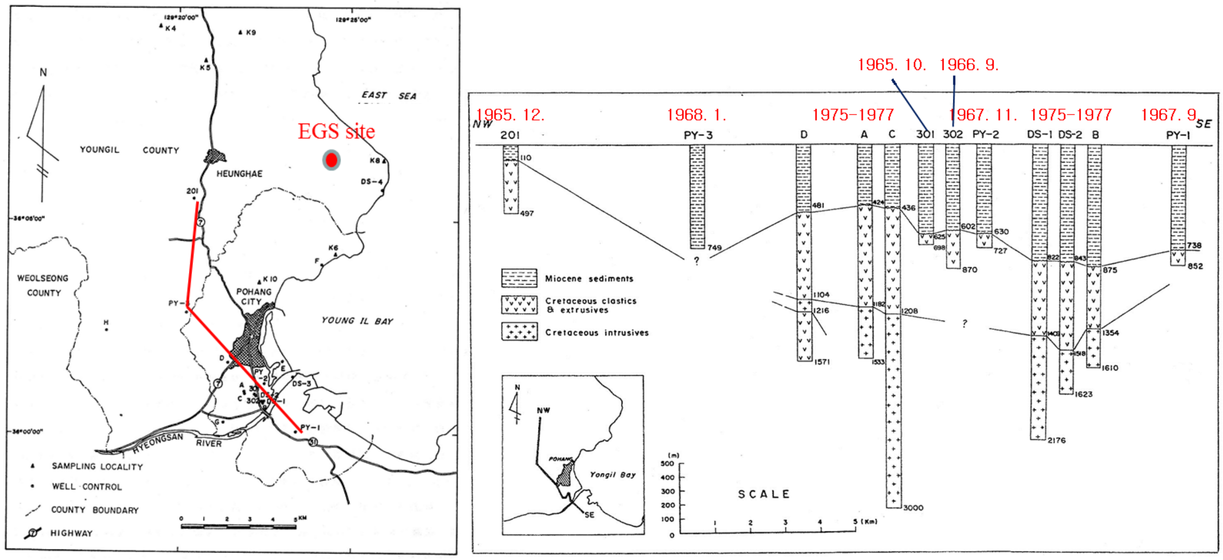

Figure 3: EGS site location and variation of depth to the granite formation from northwest to southeast. Drilling was performed for petroleum exploration in 1960s. Note that depth to the granite is between 400 m and 900 m at the southwestern part from the EGS site (Han et al., 1986).

3. GEOPHYSICAL DATA

Additionally to the drilling and geological studies, various geophysical and petro-physical studies have been also performed around the pilot site. We performed gravity surveys and analyzed air-borne magnetic data compiled by KIGAM. The purpose of these surveys was to get an idea of the thickness of the sediment units as these rocks could work as the cap rock of a hypothetical geothermal reservoir and to identify the regional structures, if any. The covered area with the gravity survey using LaCoste-Romberg G-type gravimeter was 20 km by 20 km with 392 measuring stations, each of them was roughly spaced by 1 km. Figure 4 shows the residual Bouguer anomaly map with the measuring stations as dots. As we can see in this figure, the thick Tertiary sediments appear as a central low anomaly bowl. The spectral analysis of the data says that the thickness of this sedimentary basin is about 500 m. A three dimensional (3-D) inversion of gravity data incorporating topography also shows the shape of this basin and a thickness of about 500 m in the central part is suggested. The yellow rectangle in the right section shows the pilot area and it is located on the eastern margin of the thick sedimentary basin.

Geothermal waters or potential reservoirs in Korea are closely related with deeply extended fractures. This means that a geothermal anomaly should be analyzed in terms of the lineaments distribution. Thus, a main target of geophysical surveys was to delineate deeply connected fracture zones. We concentrated our survey on the southern part of Heunghae Basin where several lineaments cross each other (Figure 1). Various geophysical campaigns were conducted in this zone such as self-potential (SP), 3D magnetotelluric (MT) and controlled source audio frequency magnetotelluric (CSAMT) surveys.

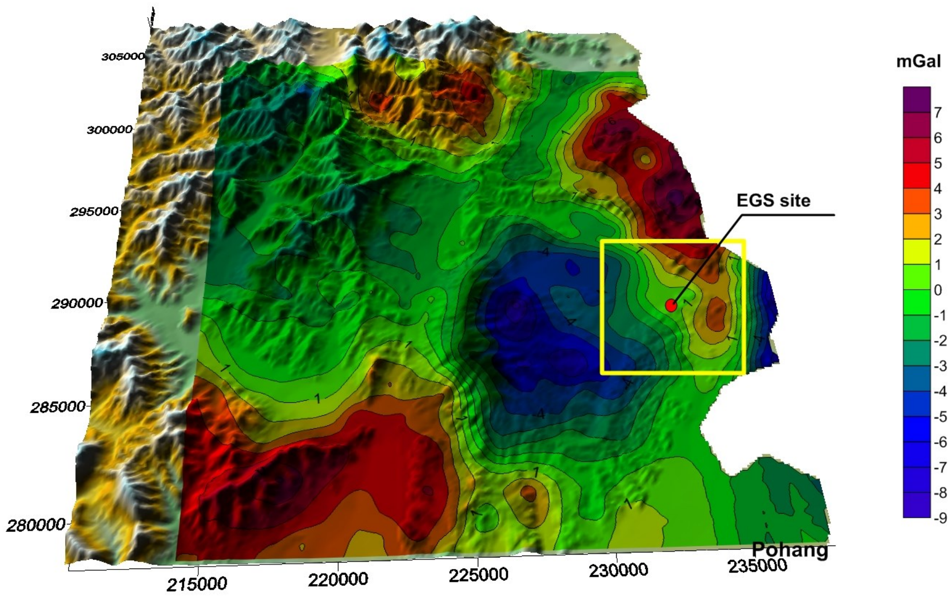

Figure 4: Residual Bouguer anomaly map superimposed on the topographic map. A total of 392 measuring stations are denoted by dots, which are roughly spaced by 1 km (Song et al., 2006b).

Figure 5 shows, as an example, the location map of the magnetotelluric (MT) survey stations over the target area on Heunghae Basin and the 3D interpretation results. We locate the remote reference station very far away from the study area (about 480 km apart) at Kyushu Island, Japan, because Korea suffers extremely strong EM noises due to old rock formations that show high resistivity and the presence of power lines covering almost entirely the country. Using this remote reference station, we could get high quality MT data for 70 sites as shown in Figure 5. A 3D interpretation, including the sea-water on the east of the site, has been performed using the 44 stations included inside the green rectangle in Figure 5, which is the first attempt to include the sea water effect in the 3D inversion (Lee et al., 2007). The 3D inversion shows a very clear image of the electrical structures beneath the area of study and is consistent with the drilling results (Figure 6). The inverted images clearly shows deeply extended conductive structures which are interpreted as two fractures intersecting at the position of the test well (BH-2). Note that the shallow conductive layer presents a thickness of 400 m in the southern part and 200 m in the northern part, which is consistent with the 3D geological model shown in Figure 1.

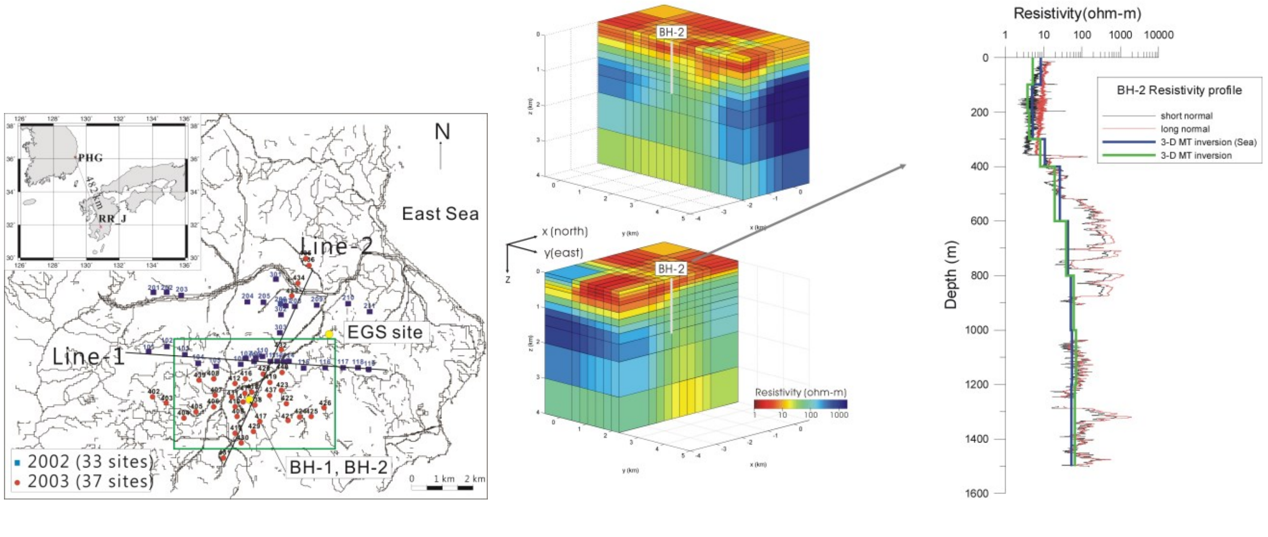

Figure 5: Location map with MT stations and the remote reference site (small insert upper left corner). Green rectangle surrounds the 3D inversion region. Resistivity models from 3D inversions considering the sea as a constraint and a comparison of the resistivity profiles between the resistivity log and the resistivity model by the 3-D inversion at the location of BH-2. The location of test borehole (BH-2) is overlain on the figure (Song et al., 2006b).

In addition to the geophysical data already discussed (gravity, magnetic and MT) geophysical well logging data was recorded for the existing and newly developed boreholes. Thermal and physical properties of rock and core samples from the site or nearby areas were also measured. Figure 6 shows an example of measured mechanical properties of core samples from BH-1 according to the depth and petrology. Physical properties include density, porosity, absorption ratio, wave velocities, electrical resistivity, and so on. Using the data described above, a common geological model can be setup and continuously updated by new information.

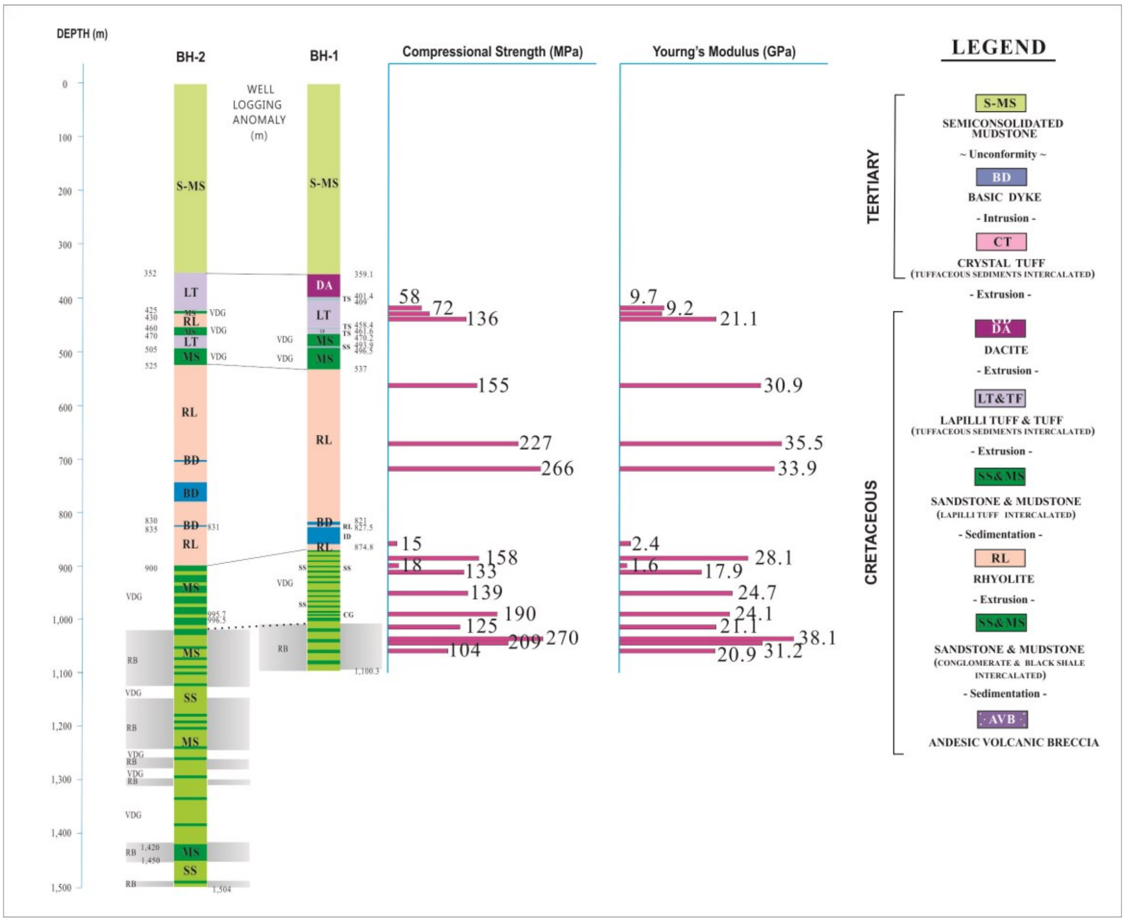

Figure 6: Example of recorded mechanical properties in core samples: Geological column, compressional strength and Young's modulus of core samples from borehole BH-1.

4. CONCLUSSIONS

We have gathered a big data base collected from the EGS pilot site and its surroundings. Next step was to integrate all this data and set up a common three dimensional geological model. GoCAD™ is a useful tool for this purpose. Once this model was developed, a common geological model can be continuously and easily updated whenever new data or evidences are acquired from drilling new wells, additional geological/geophysical surveys, and so on. It in turn can also be used for updating interpretations of existing geophysical models. Seismic velocities at each layer in the 3D model can help to interpret reflection seismic data, and this new interpretation can be used to update the 3D model.

The common 3D geological model can also play a very important role for planning the drilling of new wells as well as its design. During the stimulation stage, three dimensional velocity structures and stress regimes from the 3D model will give great help to design the stimulation procedure and consequently give insights to the microseismic interpretations as well.

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