2D Seismic Imaging at the Orita Geothermal Area, Imperial Valley, California

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Keywords

Orita geothermal area, 2D seismic data, fault visualization and interpretation, seismic-to-simulation software

ABSTRACT

The Orita geothermal area (OGA) is presently being explored and developed by Ram Power Incorporated (RPI) for electricity generation. It is located in the east-central portion of the fault-bounded Imperial Valley, southern California. Like in most known and producing geothermal resource areas located within this deep sedimentary basin, the surface expressions of faults are buried under thick deposits of Holocene lacustrine and deltaic sediments.

Thirty-six (36) line-kilometers of two-dimensional (2D) seismic data were acquired in April 2010 primarily to image these faults as well as the gross bedding patterns of the sediments. The faults were interpreted from the final post-stack migrated sections using conventional techniques. Seismic sections in SEG-2 format were later uploaded into a seismic-to-simulation software package for clearer fault visualization, greater accuracy, and faster interpretation.

Several NW-SE trending, west to southwest-dipping high-angle gravity faults were delineated. This preferred fault orientation generally follows the structural trend in the Imperial Valley region. Well to fault intersection analysis and correlation showed that some of these faults were intersected by the wells drilled from 1981 to 82 and those drilled recently. These faults were found to have contributed to the higher bulk permeability of the wells, especially when they are intersected at greater depths where the sediments are slightly metamorphosed and brittle due to elevated temperature and pressure conditions.

1. Introduction

During the last quarter of 2009, Ram Power Inc. (RPI) started the geophysical exploration of its Orita geothermal leases within the East Brawley Known Geothermal Area at Imperial Valley County, California (Fig.1). The geophysical methods used were detailed gravity (Fox and Hulen, 2009), magnetotelluric sounding

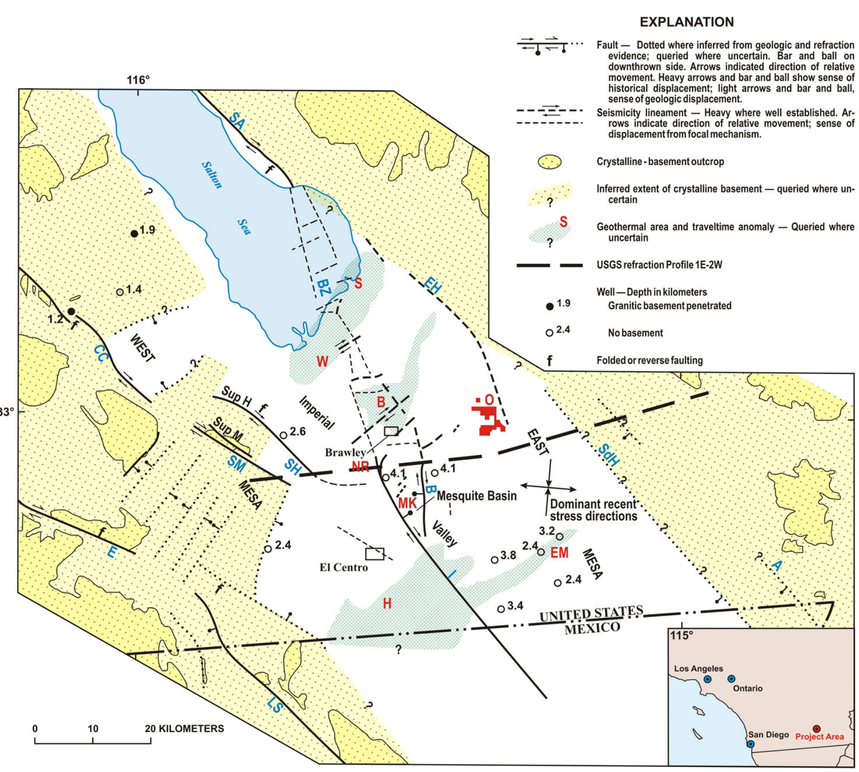

Figure 1. Structure and tectonics of Imperial Valley region and location of the Orita Geothermal Area (OGA), modified from Fuis et al., 1982. The faults shown are abbreviated as: A, Algodones fault; B, Brawley fault zone; BZ, Brawley seismic zone; CC, Coyote Creek fault; E, Elsinore fault; EH, East Highline Canal Seismicity lineament; I, Imperial fault; LS, Laguna Salada fault; SA, San Andreas fault; SdH, Sand Hills fault; SH, Superstition Hills fault; SM, Superstition Mountain fault. The geothermal areas are: B, Brawley; EM, East Mesa; H, Heber; MK, Mesquite-Keystone; NR, New River; O, Orita; S, Salton Sea; and W, Westmoreland.

(Quantec Geoscience, 2010), and high-resolution 2D seismic reflection surveys (Zapata Inc., 2010).

The seismic survey was carried out in April 2010 primarily to image the subsurface, especially the gross bedding patterns of the sediments and the faults that cut these rock formations. Like in most known geothermal areas in the Imperial Valley region, there are no surface expressions of faults at the Orita geothermal area since these are mostly covered by 60-100 m thick Holocene sedimentary deposits (Van de Kamp, 1973) and it was assumed that these structures can be best imaged by seismic reflection survey.

The information on the spatial locations, geometry, and the direction and magnitude of motion of these faults are valuable in understanding the deep plumbing system that controls the circulation and flow of hydrothermal fluids. These faults and their associated fracture zones are excellent targets for drilling of production and injection wells.

Aside from structural imaging, the seismic data will be used in future research, such as seismic amplitude interpretation and pore-fluid substitution analysis as applied to geothermal exploration. These studies require that the true amplitudes of the reflections are preserved during data collection and processing.

To attain these objectives, thirty-six (36) kilometers of high-quality seismic data were acquired along two north-south strike lines and three east-west dip lines (Fig.2). The factors considered in planning these survey lines include the shape and orientation of the basin based on the seismic refraction studies of the U.S. Geological Survey, published litho-stratigraphy of early East Brawley deep exploration wells, logistical factors (e.g., the area is within the highly-agricultural part of Imperial Valley, presence of concrete irrigation structures and the need to use relatively low-impact vibrators), technical factors especially the relatively high ambient noise primarily due to vehicular traffic, and to a lesser extent the budgetary constraint.

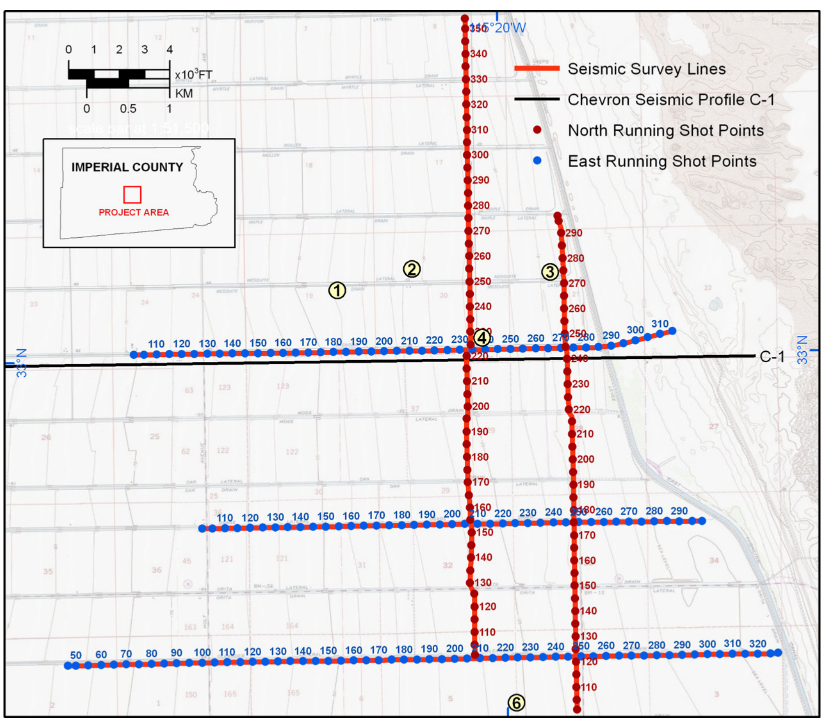

Figure 2. Plan map of 2D seismic reflection lines at Orita Geothermal Field. Also shown is the 1973 Chevron seismic profile C-1 (Severson, 1987) and the approximate locations of old- and newly-drilled deep exploration wells: (1), Rutherford-1; (2), Emanuelli-1/Orita-2; (3), Orita-3; (4), Emanuelli-2/Orita-4; and (6), Borchard-A1.

The seismic data were acquired using the common-midpoint (CMP) method of seismic surveying. The acquisition geometry and parameters and the data processing flow used were designed to attenuate noise and increase signal-to-noise ratio. Several enhancements were applied to the CMP stack due to specific site conditions.

The final migrated sections were considered of good quality and structurally revealing. These sections showed sharp and unambiguous reflector-package discontinuities, down to about 1.8 km, that correspond unmistakably to major faults (Hulen, 2010). Below this depth, the reflectors appear more vague, blurry, or 'choppy". Several NW-SE trending and W-SW dipping high-angle major faults were identified and traced with varying degree of confidence down to a depth of 4.3 km (Zapata Inc., 2010; Hulen, 2010).

The same seismic data in SEG-2 format were uploaded into the recently-acquired oil-industry-based seismic-to-simulation software for clearer fault visualization and higher accuracy interpretation. The results from both conventional and automated seismic interpretation and visualization techniques were combined together to come up with the unified structural framework of the Orita geothermal area. Some of these faults, especially the deeper-penetrating ones, were targets of recently-drilled deep exploration wells.

2. Velocity and Geologic Structure of Survey Area

The Orita geothermal area lies on the eastern central part of the fault-bounded Imperial Valley. The valley is the northern half of the Salton Trough, the northwest landward extension of the Gulf of California rift system (Elders et al., 1972). Mexicali Valley, where the Cerro Prieto geothermal field is situated, is the southern half of the trough to the south of the U.S.-Mexico border. The Salton Trough was filled as it subsided with 4-6 km-thick continental sediments deposited mainly by the prograding delta of the Colorado River since the Pliocene time (Muffler and Doe, 1968; van de Kamp, 1973). The rest of the sediments were derived from the bounding mountain ranges to the west and east of the valley.

Figure 3 shows the interpreted geologic and seismic velocity (V_p) structure along seismic refraction profile 1E-2W acquired by the U.S. Geological Survey (Fuis, et al., 1982). This profile, that passes south of Orita, shows the sediments thinning gradually to the east towards the Chocolate Mountains, while to the west, they are truncated by buried scarps coinciding with the Superstition Hills and Superstition Mountain faults (Figs. 1 and 3).

This profile also shows that Orita is underlain by about 4 km-thick sedimentary rocks with velocities ranging from 2 to 5 km/sec. This layer is underlain by almost 2 km-thick transition zone with velocity ranging from 5 to 5.6 km/sec. The transition zone consists of similar sedimentary sequence, albeit relatively metamorphosed. This highly silicified and chloritized zone lies at depths between 4 km and 4.5 km.

Two deep exploration wells drilled recently by RPI confirmed the two upper shallow-crustal layers. The 4,366 meter-deep Orita-4, penetrated poorly- to highly-consolidated sedimentary pile consisting of mudstones, claystones, siltstones, and fine-grained sandstones, and was completed within the slightly metamorphosed sedimentary rocks of the transition zone. A borehole compensated sonic log from 0.38 to 3.58 km depth of Orita-3 obtained average sonic velocities ranging from 1.8 to 4.8 km/sec. This is comparable to the 2 to 5 km/sec sedimentary rock velocity obtained by the USGS seismic refraction survey.

into a common-depth point (CDP) stack section at the Lawrence Berkeley Laboratory. This 64-km long E-W section runs along latitude 33º and passes right at the center of OGA.

At Orita, Severson (1987) identified one major fault which she inferred to be the East Highline Canal Seismicity Lineament (EHCSL). This southeast-trending lineament crossed the eastern edge of OGA. Just like the rest of the seismicity lineaments in Imperial Valley region, the EHCSL was drawn on the basis of the earthquake epicenters compiled by Johnson in 1979 (in Fuis et al., 1982). Two other steeply-dipping to vertical faults were

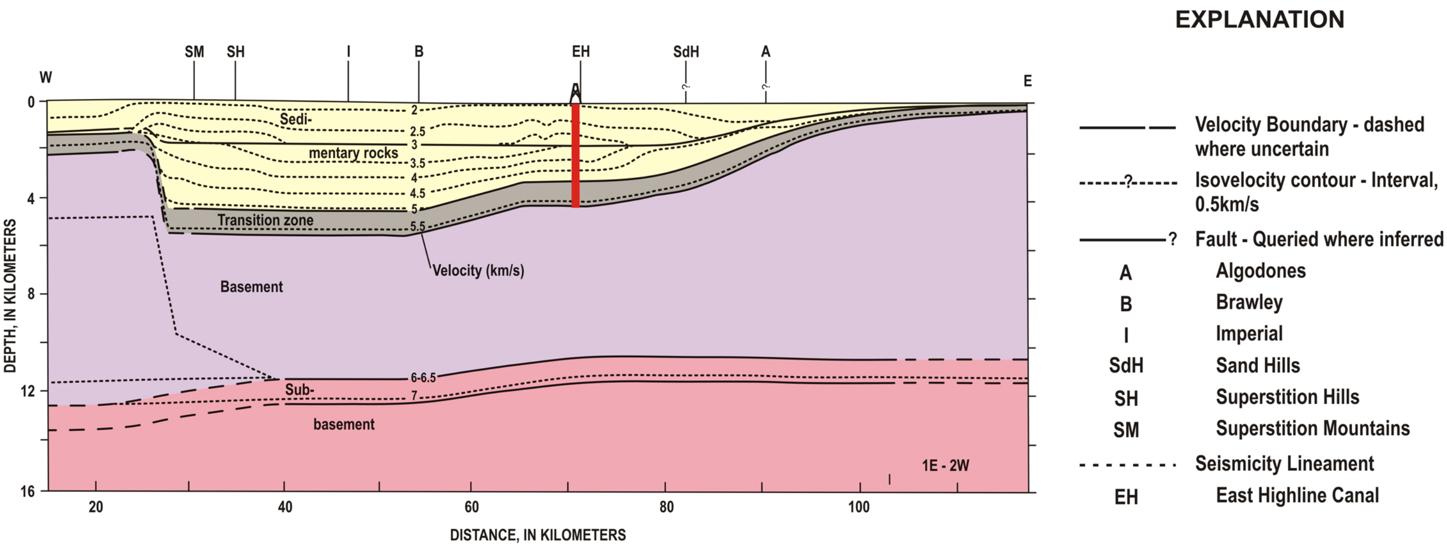

Figure 3. Seismic refraction profile 1E-2W, modified from Fuis et al., (1982), with interpreted velocity and geologic structure of the Imperial Valley. Well A (red vertical line) is the recently-completed 4.3-km deep well of RPI. See Figure 1 for location of seismic profile.

Igneous intrusives were encountered in two RPI wells. Cuttings of diabase dikes were sampled together with the silicified and chloritized sedimentary rocks at depth intervals between 3,687 m and 3,932 m. These depths are within the interpreted depth range of the transition zone. Some early East Brawley wells also encountered igneous dikes and sills, with thickness ranging from 3 to 35 m (Keskinen and Sternfeld, 1982). Detailed petrologic and geochemical analysis revealed that these are of basaltic to dioritic composition and similar in affinities to the diabasic sills found in the Salton Sea and Heber geothermal fields.

Below the transition zone, at about 5 km below surface, are the basement and subbasement layers with velocities ranging from 5.6 to 6 km/sec and 6.5 to 7.2 km/sec, respectively. The basement in this part of Imperial Valley is inferred to be mostly metasedimentary rocks of the lower greenschist facies. Metamorphism is brought about by elevated temperature and pressure conditions at these depths (Muffler and White, 1969). For instance, the RPI well has a 12-day maximum warm-up temperature of 288ºC at 3,756 m depth. The top of the gabbroic subbasement crust is inferred to be at about 10.5 km deep.

3. Previous Seismic Reflection Data

During the early 1970s, Chevron and Exxon acquired 285 kilometers of seismic reflection lines within the Imperial Valley region (Severson, 1987). One of these lines, C-1, was reprocessed

delineated. Strike-slip is their principal mode of displacement as deduced from the association of flower or palm structures with faults. Another criterion cited for a strike-slip motion is the abrupt change in dip across the fault.

Line C-1 also provided a good picture of the shallow structure below the Orita area that complements the model proposed by Fuis et al., (1982). The westerly-dipping reflections confirm the predicted tapering of the sedimentary section to the east. The recently-acquired seismic reflection data obtained generally similar reflection patterns.

4. Recent Seismic Data Acquisition, Processing, and Interpretation

The new seismic data were acquired using the common-midpoint (CMP) shooting technique with symmetric split-spread and shot on/shot off the spread. The source and receiver array geometry were designed to attenuate both coherent and random noise and obtain high signal-to-noise ratio. Some of the important acquisition and processing parameters are briefly described.

Three 15,000-lb vibrators (iVi Envirovibes) centered on half-station and at a source interval of 200 ft were used as seismic energy sources. They were synchronized and controlled by a Seismic Source Inc. Force2 Encoder/Decoder. At each shot point the vibroseis put in unison 12 sweeps of 8-100 Hz linear upsweeps of energy into the subsurface. Each sweep length is

10 secs and 4 secs listening time for a total uncorrelated record length of 14 seconds.

The receiver array consisted of 6 GSC geophones, with resonant frequencies of 8 Hz, over 100 ft and receiver group interval of 100 ft. A Seistronix EX-6 System, which is capable of recording up to 432 channels per shot, collected the reflected data. The maximum far offset was set to 17,000 ft in order to meet the desired imaging depth. The nominal maximum fold was 75.

The shot record data were processed using the standard CMP processing sequence with several enhancements added. The general processes involved in creating the CMP stack are vibroseis correlation, gain, sorting, deconvolution, normal moveout (NMO)/Mute analysis, and refraction statics. The CMP stack was subjected to final pass of datum statics, spectral whitening, F-X deconvolution, and migration to reposition the reflectors to their proper spatial positions.

The resulting post-stack migrated sections in SEG-2 format were then uploaded into an oil industry-based seismic-to-simulation software package for much clearer fault visualization and more accurate delineation. Most of these tasks are performed in the interpretation window. The vertical and horizontal scales of the seismic section can be adjusted or exaggerated to emphasize reflection variations and discontinuities for fast and superior delineation of fault planes (Fig. 4). One of the software's capabilities is to develop the structural framework of the area, while faults are being picked using the modeling-while-interpreting functionality. The direction and magnitude of displacement were determined by horizon tracking and matching technique.

Aside from interpreting faults and horizons using automated processes, the software can, as applied to geothermal exploration, also generate synthetic seismograms, perform time-to-depth conversions, create maps, and gather all the information required to support a well drilling project proposal. The well track of a vertical or directional well can be designed so that it will intersect a particular fault plane/s at any desired depth.

5. Results

Figure 4 shows part of an E-W line with the interpreted major faults. The delineated major faults are striking roughly N 13º W subparallel to the regional tectonic trend. They dip to the west-southwest at angles ranging from 45º to 80º (Hulen, 2010). Horizon tracking and matching shows dip-slip movement along the fault planes and downdropped to the west, generally towards the basin's main axis. Measured dip slip range from 80 up to about 900 ft.

Most of the major faults are also inferred to have strike-slip components in response to the regional compressive stress. Subordinate antithetic faults were also recognized. They occur as short segments of disrupted bedding slanting down to the east. These faults terminate into the larger west dipping faults.

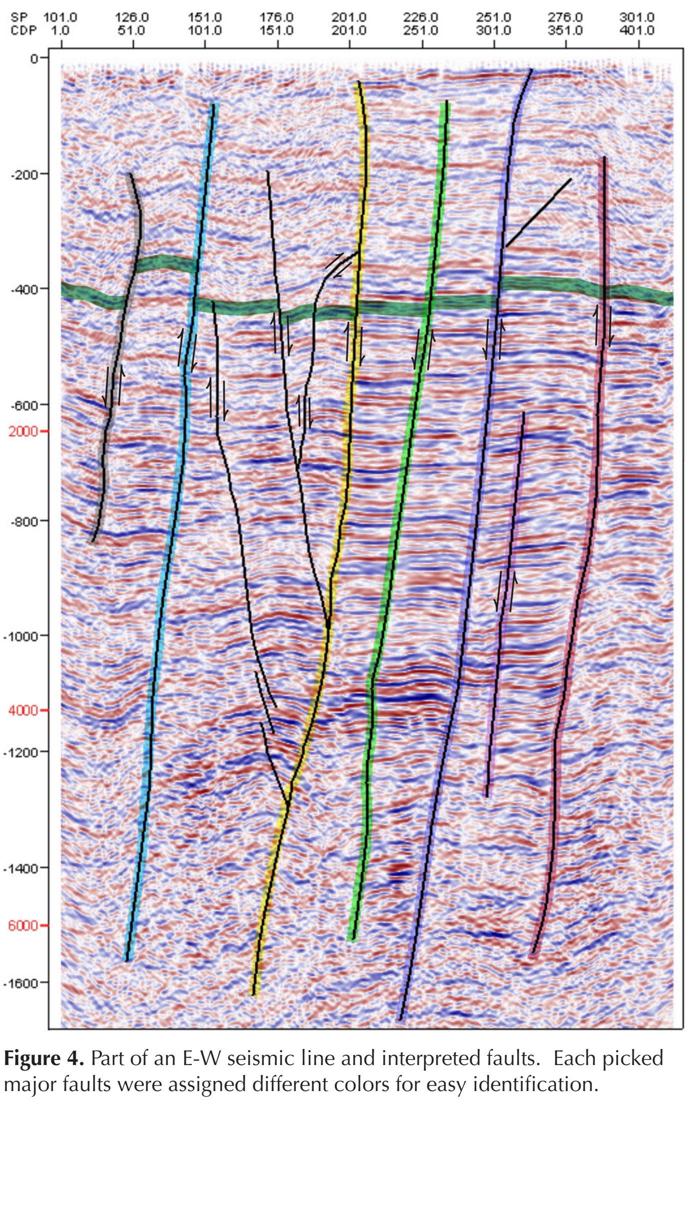

Figure 4. Part of an E-W seismic line and interpreted faults. Each picked major faults were assigned different colors for easy identification.

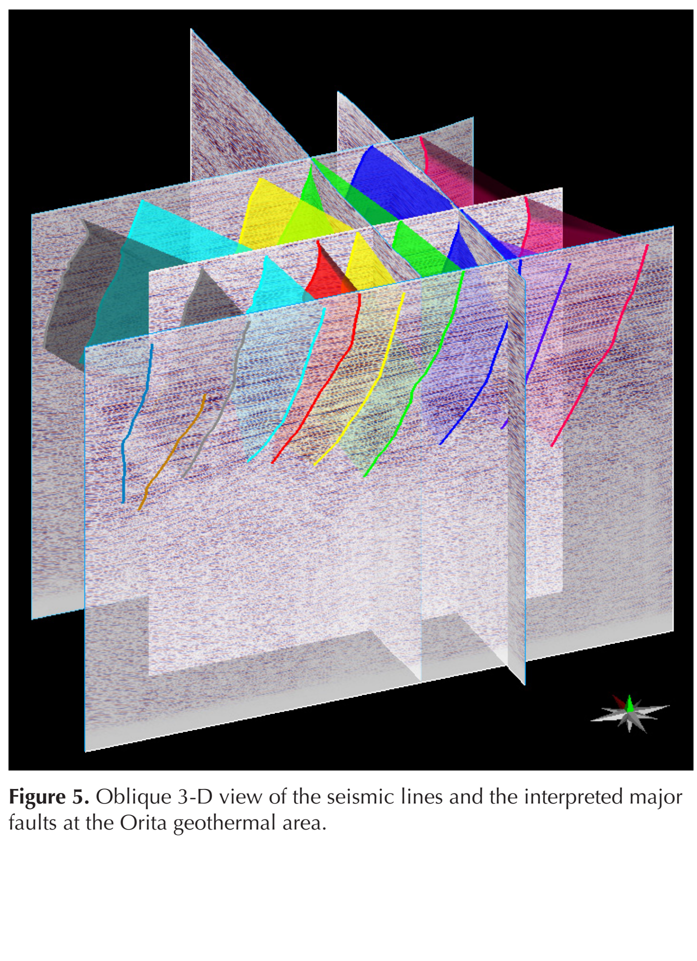

Figure 5. Oblique 3-D view of the seismic lines and the interpreted major faults at the Orita geothermal area.

Well-fault intersection analysis indicates that one of the major faults was intersected by well Emanuelli-2 at approximately 2.8 km depth. The permeable zone associated with this fault was found during the long-term flow test, to be contributing about 70% of the well's total mass flow. At greater depths, below 3.6 km, where the sediments are relatively silicified and chloritized, the fluid entries are mostly associated with diabase dikes. Drilling and geological evidences indicate that these zones of weakness within the relatively brittle formation, along which the igneous rocks have intruded, were ground-prepared by faults and their associated fracture zones.

6. Conclusions

The seismic data has successfully imaged the overall structural features of the subsurface in the Orita geothermal area and allowed a detailed delineation of the faults. These faults were interpreted using both conventional and automated techniques. The results were combined to come up with a unified structural framework of the geothermal area. The imaged buried faults were used in developing the conceptual model of the geothermal system and as specific targets for the drilling of production and injection wells.

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