

Tailoring Reflection Seismic Experiments to Geothermal Exploration Targets in Indonesia - Wayang Windu Geothermal Field Case Study

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ABSTRACT

Reflection seismic exploration in volcanic areas is still a scientific challenge and requires major efforts to develop imaging workflows capable of an economic utilization, e.g., for geothermal exploration. The SESaR (Seismic Exploration and Safety Risk study for decentral geothermal plants in Indonesia) project therefore used both active P-wave and S-wave seismic to test site-specific exploration procedures in different tectonic and lithological regimes to compare imaging conditions.

Based on the results of a small-scale, active seismic pre-site survey in the area of the Wayang Windu geothermal field in November 2012, an additional medium-scale active seismic experiment using P-waves was carried out in August 2013. Thus, for the first time in the area, a powerful, hydraulically driven seismic mini-vibrator device (LIAG's mini-vibrator MHV2.7) was used as seismic source instead of hammer blow applied in former field surveys. Aiming at acquiring parameter test and production data southwest of the Wayang Windu geothermal power plant, 48-channels were used in a high-resolution configuration, with receiver group intervals of 5 m and source intervals of 10 m. Thereby, we acquired a 630 m long profile.

In general, we observe the successful applicability of the vibroseis method for such a difficult seismic acquisition environment. Taking into account the local conditions at Wayang Windu, the method is superior to the common seismic explosive source techniques, both with respect to production rate as well as resolution and data quality. Source offset was the key strategy to prevent surface wave noise. Further, source signal frequencies of 20-80 Hz are most efficient for the attempted depth penetration, even though influenced by the dry subsurface conditions during the experiment. Depth penetration ranges between 0.5-1 km, and a supposed fault could be located and traced to depth. Based on these new experimental data, processing workflows can be tested the first time for adapted imaging strategies. This will not only allow to focus on larger exploration depths covering the geothermal reservoir at the Wayang Windu power plant site itself, but also opens the possibility to transfer the gained knowledge to other sites.

1. INTRODUCTION

Seismic reflection surveying is one of the proven geophysical methods to investigate subsurface structures and conditions. However, there are still specific methodical challenges in geothermal exploration because seismic energy attenuation and especially signal scattering occur to a large degree (Smith et al. 2011, Wiyono et al. 2013). While mostly seismological methods are applied to determine magma chambers and calderas working with tomographic modeling and Vp/Vs analyses (e.g., Yellowstone: Husen et al. 2005; Campi Flegrei: Vanorio et al. 2005; Japan: Nakagome et al. 1996; Merapi: Lühr et al. 2013 and references therein) active seismic measurements and structural imaging are hampered in areas covered by pyroclastics, such as most of the geothermal exploration sites in Indonesia. In contrast to efforts in submarine areas (e.g., Planke et al. 2005) still not well resolved issues on land concern wave propagation or energy absorption in areas covered by pyroclastic sediments, scattering in presence of sills and dykes, or the adaptation of active P-wave surveying (Krawczyk and Polom 2013) or S-wave seismics for shallow sites (Wiyono et al. 2014).

In the SESaR (Seismic Exploration and Safety Risk Study for Decentral Geothermal Power Plants in Indonesia) project we carried out both small and medium scale active seismic experiments between November 2012 and August 2013 in the Wayang Windu geothermal area. Different configurations utilizing a sledgehammer and LIAG's mini-vibrator MHV2.7 as small- and medium-sized sources were used to investigate shallow and deeper targets. The aims of these investigations are to identify site-specific parameters towards large-scale seismic exploration methods, and to determine the subsurface structure regarding the development of adapted methodical procedures for seismic exploration of geothermal targets in Indonesia.

2. INVESTIGATION AREA

Indonesia is located at the contact of three tectonic plates (**Fig. 1a**), which makes it as one of the most active seismic regions. It is also the country with the largest geothermal potential worldwide, estimated to 27.000 MW (Surya Darma et al. 2010). On West Java, in the centre of the volcanic zone, the most powerful geothermal power plant (200 MW) of Indonesia is installed at the Wayang Windu geothermal field (**Fig. 1b**). This field lies in the Pangalengan plain with elevations between 1400 m and 2343 m above sea level. East of the seismic survey area three mountain peaks line up from north to south: Gunungs Sambung, Wayang and Windu (**Fig. 2**). Most of the geothermal concession area is covered by tea plantations.

The surface geology in the Wayang Windu region consists of four main lithologies based on volcanic products (Alzwar et al. 1992). Malabar-Tilu volcanites with tuff and laharic breccias dominate the northern half of the concession area, and large parts of undifferentiated efflata deposits of old volcanites with fine to coarse dacitic crystalline tuff and tuffaceous breccias are found the southern half (Fig. 2). Waringin-Bedil andesite with alterations of lava breccia and tuff alternate with young volcanites with efflata and andesitic-basaltic lava flows in the reservoir region. The area is also influenced by fault structures that mainly trend NE-SW.

The seismic surveys are located at the western flank of the Wayang and Windu volcanoes (Fig. 2) to test signal answers at different locations surrounding the power plant.

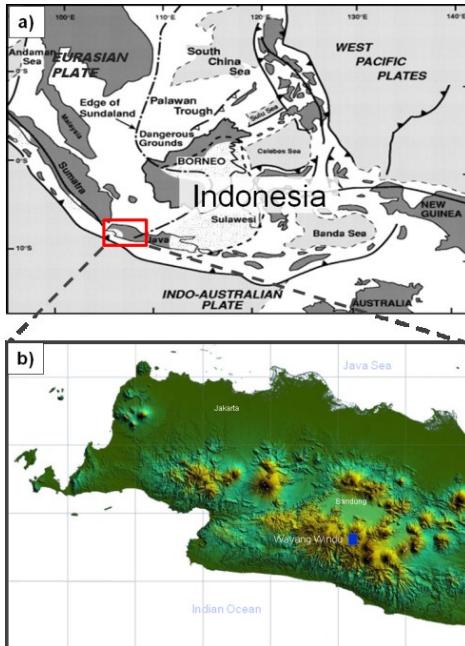


Figure 1: Location map of the survey area with a) tectonic situation of Indonesia (after McClay et al., 2000), and b) the Wayang Windu site in the southwestern volcanic province on Java island (blue square).

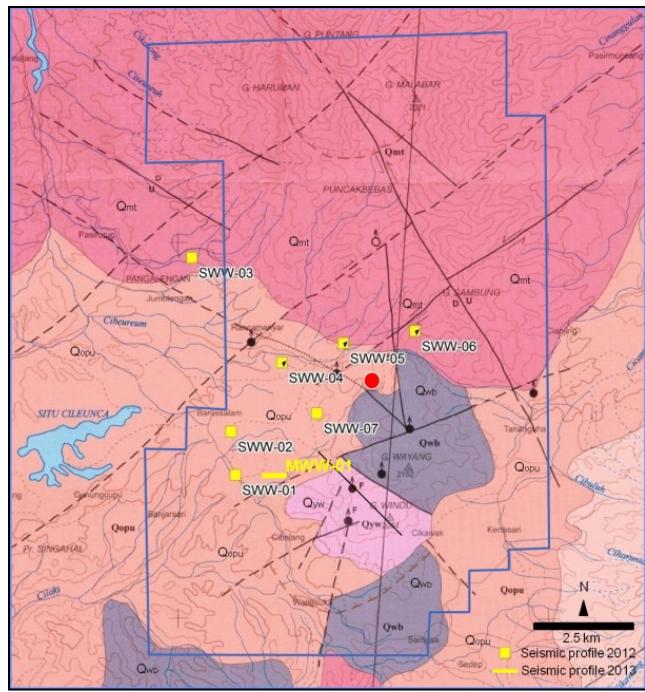


Figure 2: Geological map of the survey area in Wayang Windu (after Alzwar et al. 1992) with locations of the seismic profiles (yellow, labeled M/SWW-0x) acquired in the concession area (blue outline) around the power plant (red dot). Qopu: old volcanic undifferentiated eflata; Qwb: Waringin-Bedil andesite; Qyw: young volcanic eflata; Qmt: volcanites with tuff and laharic breccia. Fault structures mainly trend NE-SW (black dashed lines).

2. REFLECTION SEISMIC SURVEYING

Different reflection seismic configurations utilizing small- and medium-sized sources were used to investigate shallow and deeper targets to identify site-specific parameters towards large-scale seismic exploration methods, and to determine the subsurface structure in the Wayang Windu geothermal area.

2.1 Small-scale seismic survey in 2012

A high-resolution P-wave reflection seismic acquisition design was chosen for the pre-site survey in 2012. For the small-scale setup, a 3-kg sledgehammer hitting on a 0.3x0.3 m aluminium plate was taken as source every 10 m. 48 vertical geophones (14-Hz) in 5-m intervals were used for all profiles, and thereby seven seismic profiles of 235 m spread length each were gained (Fig. 2: profiles SWW-0x). Recording time was 1 s, sampled at 1 ms.

The data quality gained at the different locations was surprisingly variable. The direct comparison of examples from profiles SWW-01 and SWW-02 reveals the immense quality difference (Fig. 3). Slow surface waves of nearly 100 m/s propagation velocity and strong, incoherent amplitudes are present in all shot gathers that are imaged down to 600 ms two-way traveltime (TWT). A high noise level caused by surrounding human activities on nearby roads, in the plantation area, and by wind was generally present. This resulted mainly in the surface wave propagation characteristics imaged, that preferentially spread the disturbing surface wave energy in the uppermost layer. In the data from profile SWW-02 not even a first break is observed. This is in strong contrast to profile SWW-01, where reflections at both shallow (100 ms TWT) and larger depths (300 ms TWT) are observed (Fig. 3).

In summary, a good signal quality was observed on profile SWW-01 only. Almost no significant P-wave signal was recorded on profiles SWW-02 to SWW-07, which all show similar poor subsurface responses like SWW-02. Therefore, this profile location represents an anomaly status in the whole investigation area.. To investigate the significant difference in P-wave signal propagation in more detail, and to observe the expected quality decrease by increasing the distance from the location of profile SWW-01, we therefore decided to place the start of the intended medium-scale profile as close as possible to small-scale profile SWW-01.

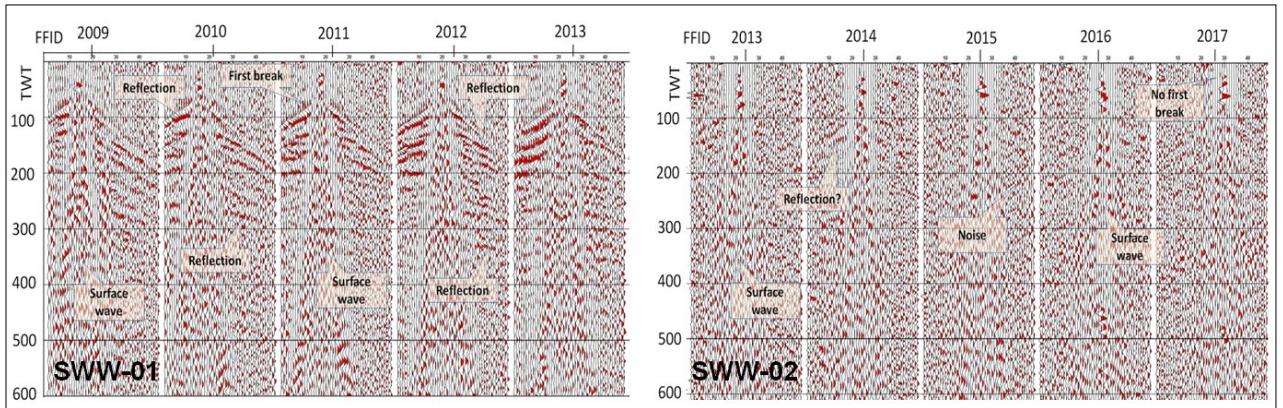


Figure 3: Preprocessed shot gathers (200 ms AGC and 20-22-145-155 Hz bandpass filter applied) from profiles SWW-01 (left) and SWW-02 (right). Down to 600 ms two-way traveltime (TWT) the gathers exhibit extremely contrasting data quality for the field files (FFID) exemplified.

To these data a processing sequence consisting of bad trace editing, geometry installation, amplitude scaling, bandpass filtering, top muting, interactive dynamic corrections, CMP-stacking, FD-migration, and a raw time-to-depth conversion using smoothed stacking velocities was applied. The resulting depth section of profile SWW-01 reveals strong and continuous reflectors (Fig. 4), whereas all other profiles did not allow subsurface structural imaging due to the poor signal content in the raw data. Between 50-110 m depth in section SWW-01, the strongest amplitudes occur and image along the entire section two continuous reflectors (Fig. 4). Below, rather faint reflections can be interpreted in the central part of the profile with the deepest reflector at ca. 170 m depth. The uppermost 50 m of the section show weak but coherent signal as well indicating a slightly bowl-shaped structure. Here, the western part of the section presents an east-dipping reflector that smears out in the central part of the profile and gains back stronger amplitudes towards the eastern end of the line (Fig. 4, 30-60 m depth). The loss of image quality may be caused by less compacted material present in the region. The bowl-shaped structure together with the outstanding reflection response is interpreted as a small local basin, probably filled by young volcanic material from the surrounding area.

2.2 Medium-scale seismic survey in 2013

The medium-scale P-wave reflection seismic setup in 2013 was designed to combine several targets: to investigate local changes of seismic subsurface response in more detail, to explore the capability of the vibroseis method for typical pyroclastic regions in the West-Java geothermal province, and to achieve higher depth penetration to investigate reflection responses up to 1000 m, to approach closer to the reservoir depth of 1500-2500 m. The survey design in the WW area was strongly supported by the local infrastructure resulting from tea plantation management, so that a wide area access due to a mostly rectangular network of well maintained dirt roads was enabled. This also helped minimizing difficulties caused by topographic variations in the region. LIAG's hydraulically-driven seismic mini-vibrator MHV2.7 (27 kN peak force, 20-450 Hz maximum bandwidth, 3 t total weight) served as seismic source for this experiment. It meets not only the requirements to use an environmental save seismic source within the protected tea plantation area, but also fills the gap that no seismic vibrator source was available in Indonesia. Due to its small dimensions of only 1.8 m width and 4 m length, the vibrator device fits well to all local road conditions, which are mostly not suited for heavy equipment. Again, 48 vertical geophones (14-Hz) in 5-m intervals and vibrator points at 10 m distance were used so that one profile of 630 m length was acquired with receiver spreads of 235 m length (Fig. 2: profile MWW-01). After initial parameter tests regarding sweep duration, frequency bandwidth, and profiling productivity, a sweep of 10 s duration ranging from

20-80 Hz was chosen. This represents the lowest two octaves of the source system, since a strong decrease of higher frequencies was detected during field analysis. Two excitations at each source location were carried out to enable investigation of the local source signal repeatability. Uncorrelated signal recording of 12 s duration was sampled at 1 ms.

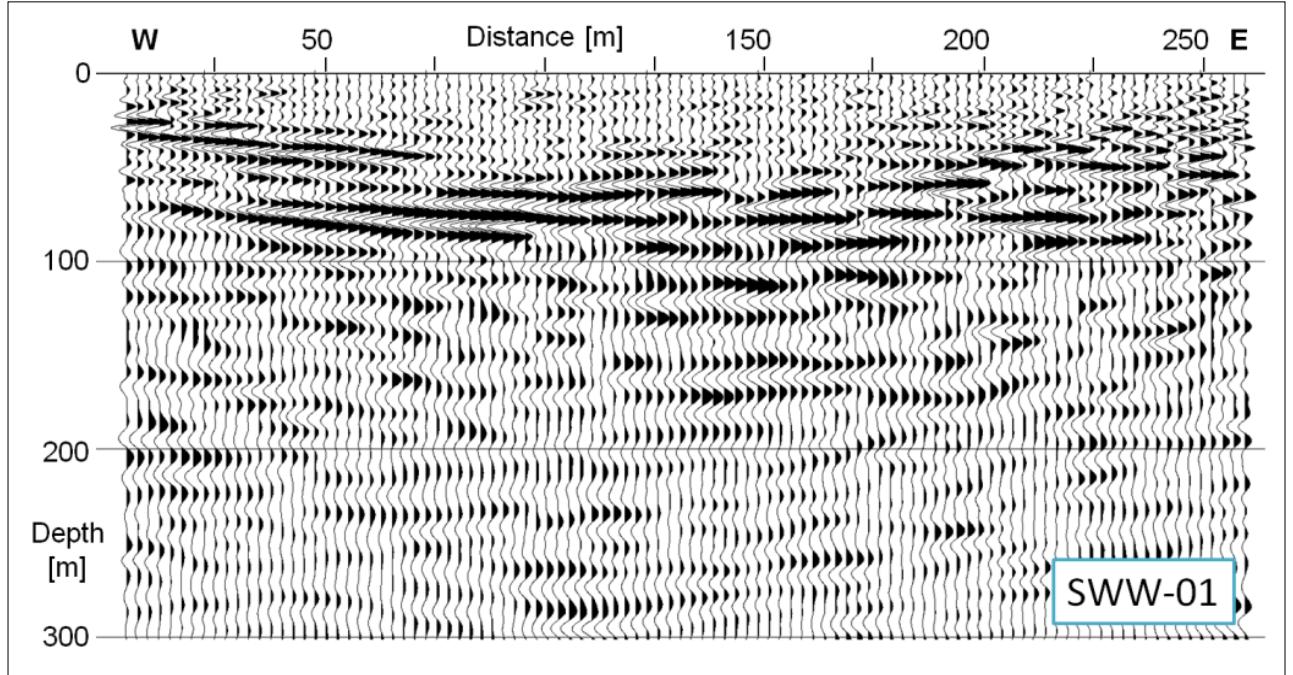


Figure 4: FD-migrated reflection seismic profile SWW-01 after depth conversion using smoothed stacking velocities (horizontal to vertical $\sim 1:2$).

Compared to the shallow experiment in 2012 using a hammer source, the higher energy and deeper penetration of the vibroseismic signal is evident immediately in the raw data (Fig. 5). The seismic records were only slightly processed using a 300 ms AGC and a bandpass filter with 40-50-150-180 Hz corner frequencies. Thereby, most of the noise is reduced especially at low frequencies on profile SWW-01, if compared to raw data, and the reflection images are improved. The seismic records of profile MWW-01 were equally treated which mainly reduced the air blast energy. While reflections gained with the hammer source are observed down to ca. 300 ms depth, the vibroseis data clearly show reflections down to ca. 800 ms depth in the shot records (Fig. 5).

The processing of profile MWW-01 comprised similar steps as for SWW-01, only expanded by vibroseis correlation and air-blast attenuation processing. The 630-m-long depth section of profile MWW-01 has good and interpretable signal quality down to at least 1 km depth (Fig. 6). The strong events further below may rather be attributed to migration smearing effects because no reflections can be depicted in the shot data. Mainly horizontal layering is observed, marked by very continuous and strong-amplitude reflectors between 100 to at least 300 m depth. Further below the section looks more transparent, but still exhibits continuous reflectors, for instance at ca. 800 m depth (Fig. 6, 150-250 m distance) with some dipping events immediately above. Since the profile was acquired in the region where old volcanic undifferentiated efflata are mapped at surface, the layering and the variable transparency may be attributed to different volcanic activities or products.

The most interesting structures in terms of reservoir exploration and pathways close to surface are found in the eastern half of profile MWW-01. Here, two strong fault indications are evident (Fig. 6, 450-500 m distance) between 80-230 m depth. There is no clear image of the fault itself, but consistent reflector offsets over a depth range of ca. 100 metres suggest this interpretation. By visual correlation with the geological map the location of this fault trace would correlate with a fault structure mapped at surface (c.f., Fig. 2). This fault trace is clearly defined east of the profile, and only interpreted in the area closer to line MWW-01. A second fault may be supposed in the western half of the line (Fig. 6, 200-300 m distance) where a disturbed area occurs between 200-350 m depth. Thus, with this new profile at hand, we can also determine with more confidence the westward continuation of supposed faults mapped at surface as well as presumably blind faults at depth.

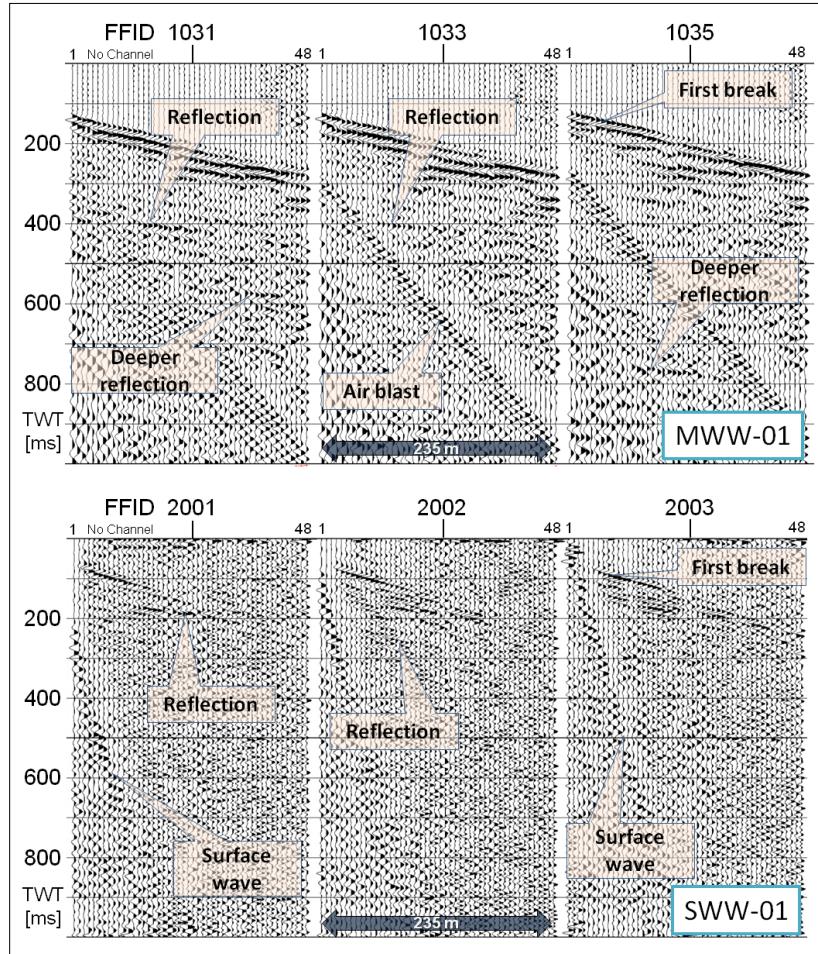


Figure 5: Comparison of shot gathers from the medium-scale (top) and small-scale (bottom) reflection seismic experiments, demonstrating the higher energy input of the vibroseis data (FFID - field file identity).

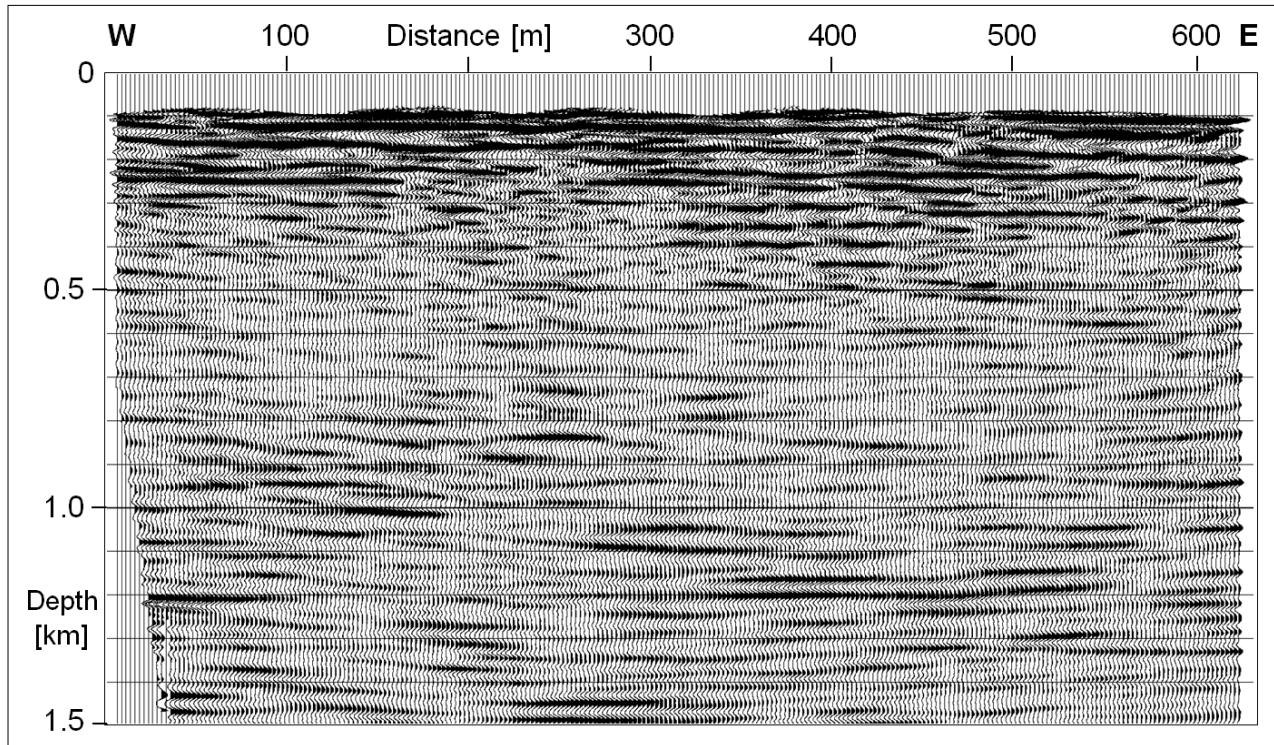


Figure 6: FD-migrated reflection seismic profile MWW-01 (for better interpretation the section is stretched 3-fold). The mean CMP coverage is 12-fold, with 30-fold maximum value in the western third of the line.

4. DISCUSSION OF IMAGING QUALITY AND FIELD SETUP

Not many active seismic experiments exist that show successful imaging in geothermal areas governed by pyroclastics (e.g., Nakagome et al. 1996). While many authors use rather refraction seismic and ray tracing methods to detect magma chambers at km depths (e.g., Gudmundsson et al. 1994, Zollo et al. 2008), others warn of interpreting coherent noise or seismic waves guided by sills or volcanic layers (Melosh et al. 2010, Smith et al. 2011). Wiyono et al. (2013, 2014) state for the volcanic provinces in Tarutung (North Sumatra) and Lembang (West Java) that P-wave data reveal not even first breaks due to strong attenuation, and that only S-wave data have the potential of imaging structures in pyroclastic sediments. This is not the case here, because both surveys presented show clear reflection seismic images using only P-wave acquisition tools. Furthermore, by combining both surveys the different scales of resolution and depth penetration provided by the use of the different sources are complemented into an image from surface down to more than one km of depth.

In this study, the offset between source and first receiver is presented to be of critical importance for the seismic imaging of pyroclastic deposits. Different acquisition geometries to find the best experiment design possible that is furthermore adapted to the local conditions were experienced in the 2013 reflection seismic survey. During this survey variable distances between source and first receiver were tested which finally provided the key in this study for the high-resolution imaging at the Wayang Windu geothermal field in Indonesia (see seismic section in Fig. 6). This is in line with a case study in the Basin and Range Province where wide-aperture data were used (Smith et al. 2011). Seismic 2-D profiling using undershooting techniques (Gudmundsson et al. 1994) rather results in travel-time modeling than structural imaging.

Usually strong-amplitude surface waves (ground roll) hamper the data quality in P-wave acquisition and disturb near-offset parts of the seismic image. This is also seen in our study in all shot gathers where strong noise from surface waves, propagating with a low velocity of approximately 100 m/s in a chaotic high-amplitude pattern, is observed to different degrees (Fig. 7). This unfortunately prevents a successful field design that counteracts surface wave generation by application of source and receiver patterns. Other noise sources are air waves and environmental noise that are usually tackled by processing tools like muting and filtering. Additionally, the mean P-wave velocity for the reflector events is less than 1500 m/s, indicating unsaturated or dry near surface layers. This requires a relatively small total receiver spread distance and dense receiver intervals for a sufficient move-out detection and velocity filter processing. We interpret the low surface wave and P-wave velocity as result of a dry zone of pyroclastic material in the shallow subsurface, which is also an explanation for the strong P-wave signal attenuation observed.

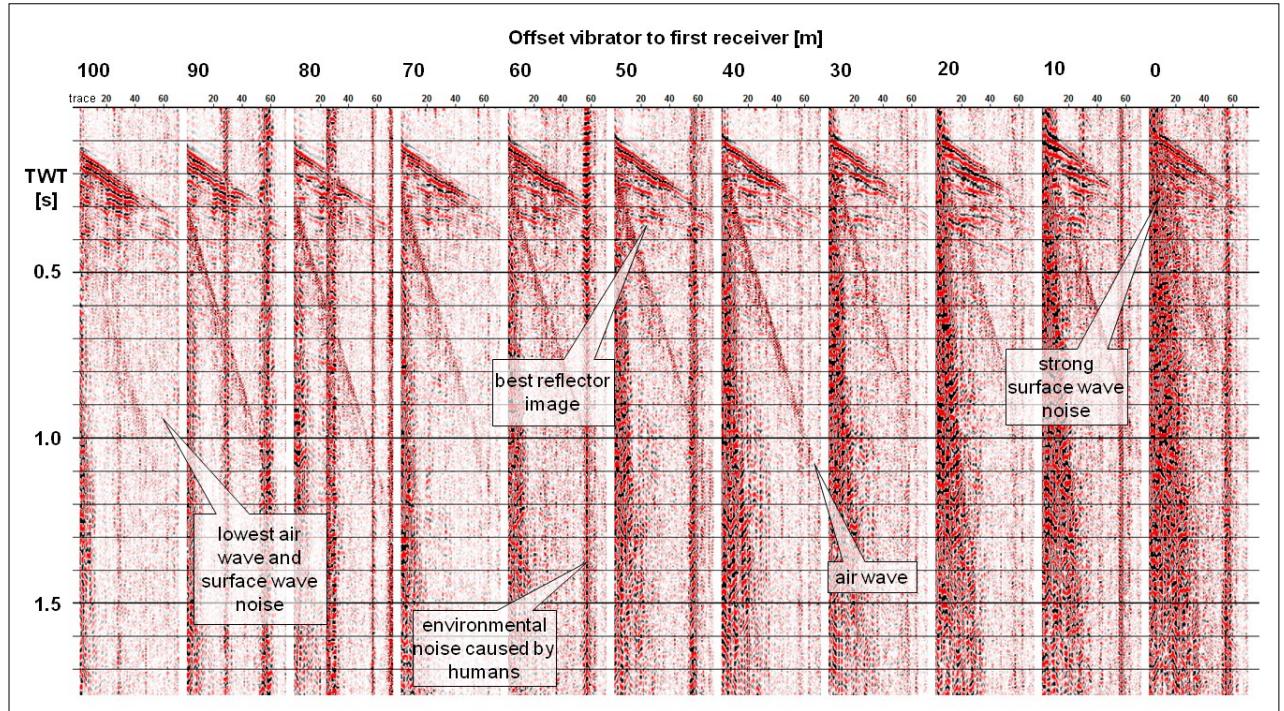


Figure 7: Shot gathers of profile MWW-01 that are subject to different offsets between vibrator source and first receiver.

To bring out reflections from the raw data not only by processing but by adapted field design is of great value. In the volcanic area of Wayang Windu we varied the distance between source and first receiver (Fig. 7, middle panel). The analysis of the reflector found at ca. 330 ms depth reveals that its imaging quality is very variable, and that this is a function of source-receiver distance. The 330-ms reflection is best identified and strongest, when vibrator and first receiver are 50 m apart (Fig. 7), resulting in a total spread length of 295 m. At distances up to 80 m or only 20 m, this reflection is also observed, but with less signal strength and thus less confidence. It is also not observed at smaller or larger distance. Using a zero-offset configuration hampers imaging because the signal is hidden by the strong surface waves (Fig. 7, right panel). The largest test offset chosen was 100 m. Even though surface wave and air wave have lowest energies at this distance, a reflection is not gained (Fig. 7, left panel). This emphasizes that acquiring reflection seismic data should be tested for offset shots.

Such type of phenomenon was reported in the Rye Patch geothermal area on a larger scale where Gritto et al. (2002) gained signals from far-offset shots that vanished across a prominent fault structure. In contrast, we imaged here a supposed fault structure at depth without such an extreme signal loss (see Fig. 6, CMP 200). However, more specific processing could be applied to gain the fault's characteristics in detail. This would also open the opportunity to test if amplitude variations with source distance provide a possibility to distinguish areas of different volcanic sediments or bright spots (c.f., Zollo et al. 2008). This could also be enhanced by the use of small- and medium-scale shear-wave seismic vibrators (c.f., Polom et al. 2013, 2010, Krawczyk et al. 2013). An interesting study would also be the extension of the medium-scale profile to detect and analyse where the signal turns to worse. The extension of line MWW-01 further westwards would stay in the same lithology but shows significant differences as exemplified in the small-scale survey (c.f., Fig. 3), an extension to the east would meet a different lithology (c.f., Fig. 2).

4. SUMMARY AND CONCLUSION

Both seismic experiment designs used in 2012 and 2013 in the Wayang Windu geothermal field using small- and medium-scale setups resulted in successful imaging of the subsurface structure. The seismic sections show a good signal-to-noise ratio with clear reflection events and the evidence for a formerly supposed fault. Due to the low energy of the hammer source its penetration depth is rather limited (max. 170 m depth at Wayang Windu), while the mini-vibrator provided enough power to image structures down to 1 km and more.

The 2014 medium-scale experiment confirmed the advantages of the high-resolution vibroseis method in a typical volcanic area on Java covered by pyroclastic material. Taking into account the local conditions at Wayang Windu, the vibroseis method is superior to impact or explosive source techniques, regarding production rate, structural resolution, data quality, and environmental safety in a densely populated and cultivated area.

Thus, our recommendation for a seismic exploration strategy in volcanic areas is the following: (1) perform *shallow* surveying with high-resolution seismics (P-wave, S-wave), (2) shape *medium* exploration setup accordingly and perform parameter tests, (3) identify potential areas for exploration optimisation, and (4) image reservoir structure at depth by *large-scale* survey. This will require an iterative surveying procedure, but will reduce imaging failure and thus drilling costs drastically.

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