**Designing and testing a network of passive seismic surveying and
monitoring in Dehdasht (South Western Iran)**

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ABSTRACT

From August 2016 to July 2017 a passive seismic survey was conducted in South Western Iran as a part of a pilot project aimed to improve the imaging in geologically complex areas. Passive seismic methods have shown to be a useful tool to infer the physical properties of the underground geological structures where traditional hydrocarbon exploration methods are challenging. For this purpose, a dense passive seismic network consisting of 119 three-component borehole seismic stations was deployed over an area of 400 km² around the city of Dehdasht. This paper focuses on the details of the network design, which was devoted to high-resolution seismological applications, including local earthquake tomography and seismic attenuation imaging. In this regard, we describe the instrument types and the station installation procedures used to obtain high quality data that were used to retrieve three-dimensional models of *P*- and *S*-wave velocity and *P*-wave attenuation in the area using tomographic inversion techniques. We also assess the network performance in terms of the seismic ambient noise levels recorded at each station site and we revise the horizontal orientation of the sensors using surface waves from teleseismic earthquakes.

Key words: Passive method, Surveying, Monitoring, Acquisition, Data processing.

INTRODUCTION

Typical seismic exploration practices in onshore oil and gas industry use reflected waves generated by active sources to obtain high-resolution images of the target formations. These techniques allow inferring the physical properties of the underground geological structures. Nevertheless, sometimes, complex structures might yield penetration problems and dispersion effects of seismic waves, making the interpretation of the seismic data very difficult, if not impossible.

Important interpretation uncertainties are found in some areas of the Zagros Mountains (Iran), where the target is under basalt or salt formations, and/or is trapped by the fold thrust-belt configuration (*e.g.*, Sherkati *et al.* 2005). Several fields investigated and explored by the National Iranian Oil Company (NIOC), presented the above issues where the Gachsaran formation (interbedded anhydrite and limestone associated with bituminous shale, subordinate salt and red and gray marl) appears. This Gachsaran formation complicates the investigation of the Asmari target formation because of the salt presence and the thrust configuration.

Exploration, in recent years, has required new solutions to improve the imaging in geologically complex areas. Along with the improvement of the advanced processing of the active data, passive seismic techniques have become a recognized toolbox to investigate when high dispersion, attenuation, or impedance contrasts are present (*e.g.*, Kapotas *et al.* 2003, Martakis *et al.* 2006).

On August 2016, a dense seismological network was established over an area of approximately 70 x 70 km² around the city of Dehdasht (Kohgiluyeh and Boyer-Ahmad province) in South Western Iran (Figure 1). The surveyed area is located within the Zagros folded belt that is one of the most seismically active mountain ranges in the world (*e.g.*, Nissen *et al.* 2011). The aim of the survey was to monitor the local

seismicity and to infer the underground geological structure from the recorded dataset. The Exploration Directorate of NIOC awarded the project, the first of this type in Iran, to Dana Energy. In this framework, Dana Geophysics Kish Company (service provider in Iran) and the consortium Worldsensing-CSIC (equipment and service providers in Spain) established a joint venture to implement the pilot passive seismic project in Dehdasht area.

The main objective of the project was testing the feasibility of local earthquake tomography and attenuation imaging methods to define the depth of topography of the Asmari formation top in Dehdasht area. The Asmari formation is expected to be at depths of approximately 3-4 km in this place, which is deeper than in other surrounding areas where the target is 1-2 km in depth. The high rate of seismicity in the region generates an optimal scenario for the application of the proposed passive techniques, which would complement the existing active source seismic data in the area. Obtaining high-resolution three-dimensional models of *P*- and *S*-wave velocity and *P*-wave attenuation requires accurate earthquake locations and dense ray path coverage. For this purpose, high-quality data were needed. In this study, we present the survey design and describe the technical aspects of the station installation procedures to assure the high-quality standard of the recorded seismic data. We also focus on the instrument performance and analyse the data quality by computing the seismic ambient noise levels recorded at each site using probability density functions (McNamara and Buland, 2004). Finally, we check the horizontal orientation of the seismometers by means of the polarization analysis of Rayleigh waves from teleseismic earthquakes.

SURVEY DESIGN AND INSTRUMENTATION

Network description

The temporary seismic network (internal code DD) consisted of 119 three-component borehole seismic stations that operated from August 2016 to July 2017 and were installed in different stages. In a preliminary phase, 13 stations were sparsely deployed in the area with the objectives of: (1) exploring the seismicity level of the region; (2) assessing the capability of the proposed network configuration to detect and locate the earthquakes; and (3) testing the installation and station maintenance general procedures. This initial phase was carried out during the first half month of the project. During the course of the following month, the rest of the stations were installed. It is worth noting that, for technical and logistic reasons, several stations were uninstalled and new ones were deployed during the project. The causes of the replacement included vandalism, access problems, unexpected transient noise at the sites, or technical failure due to water entering the station. Nevertheless, 90% of the stations operated during the whole time period.

Reasonably regular grids and azimuthal gaps less than 180 degrees are required to obtain accurate earthquake locations. Moreover, the determination of reliable focal depths requires seismic station spacing to be less than twice the minimum depth of interest. In an attempt to balance the successful performance of the system and its cost, we separated the network, geographically, into an inner and an outer ring with the city of Dehdasht at the centre point (Figure 2). The inner ring was composed of 106 seismic stations deployed in a regular grid over a rectangular area of approximately 25 x 20 km², with interstation distances of 2 km. The objective of this high-density zone was to enhance the detectability of the network by lowering the detection earthquake magnitude threshold and to increase the resolution of the data processing methods in the target area, which depends on the epicentre-to-station path coverage. The outer ring

contained 13 stations that were located at distances between 5 and 10 km from the inner grid and had interstation distances from 10 to 20 km. The aim of the outer ring was to decrease the azimuthal gap of the events occurred close to, but outside the inner grid, thus improving the earthquake locations. Stations in the inner grid have the codes: D001, D002 ... D106 whereas the outer ring stations are named: R001, R002 ... R010, RN02, RN08 and RN09.

Seismometers and acquisition devices

All the stations were composed of a triaxial borehole seismometer and a Spidernano seismic recording unit. The seismometers used two different technologies: SARA SS-BHV spring-mass-based sensors, and R-sensors CME-4211 molecular-electronic-based sensors (from now on SS and SR sensors, respectively). The SS sensors are broadband, three-component, shallow borehole seismometers. They have a passive spring locking system and the tolerance tilt is 5 degrees. They offer high sensitivity, wide dynamic range and have a power consumption of 10 mA. The instruments have an anodised aluminium casing and are equipped with electronic controls of the mechanical devices from the surface. The response is flat between 0.2 Hz and 50 Hz for the three components. The SR sensors are broadband, low-noise, three-component, molecular-electronic seismometers. They are equipped with a watertight plastic case and are suitable for posthole installations at depths down to 15 m. The devices have a power consumption of 25 mA and they neither require any maintenance, mass locking nor centring. They do not need levelling and are fully functional with installation tilts up to 15 degrees. The SR sensors are equipped with molecular electronic (electrochemical) transducers and driving electronic circuitry with high stability (Agafonov *et al.* 2015). The seismometers have a homogeneous flat response in the three directions between 0.1

1 Hz and 50 Hz. The instrumentation was chosen to increase the versatility of the seismic
2 network. These sensors are a good option, because their flat response interval in
3 velocity allows the recording of the high frequency body waves from local earthquakes,
4 but they can also be used for imaging methods based on long period body and surface
5 waves from teleseismic events, and seismic ambient noise.

6 Spidernano is a state-of-the-art, low-power seismic data recording unit. It is optimized
7 for permanent setups and offers a robust International Protection Marking enclosure
8 (IP68). One of its main advantages is the low power consumption (0.5 W fully working
9 with GPS on every 5 minutes) that allows more than 50 days of continuous operation
10 with a standard 65Ah 12V battery. The data logger provides three true 24 bits A/D
11 channels with a high dynamic range of 143 dB at 0.002 s. Spidernano applies instant
12 and cumulated drift corrections on the time stamp using the information gathered from
13 each GPS lecture. For the current network we measured less than 2 ppm clock drifts.

14 Some images of the instruments as well as the seismometer-digitizer system responses
15 are plotted in Figure 3.

17 STATION DEPLOYMENT

18 **Borehole construction**

19 Specialized machinery was used to drill approximately 12-meter-depth holes. The
20 boreholes were cased with 10-meter-length PVC tubes with inside diameters depending
21 on the sensor type (SS or SR). Given that the seismometers have internal levelling
22 mechanisms over a limited range of tilt, it was very important to ensure the borehole
23 verticality. After the intubation, the bottom of the pipe and the annular volume between
24 the casing and the rock were filled with concrete. This procedure ensures good

1 mechanical coupling between the casing and the surrounding rocks and prevents water
2 from entering the borehole. At the upper end of the casing, the enclosure box was fixed
3 to the ground with cement and the lid was sealed with a waterproof adhesive. Finally,
4 the structure was surrounded with sand and debris as camouflage. Figure 4 shows some
5 pictures of the installation process.

6 7 **Equipment installation**

8 The sensors were lowered onto the bottom of the borehole using a removable
9 orientation tool with rigid orienting rods. Although the orientation can be adjusted with
10 this tool, the method may be subjected to errors. Therefore, we processed the data
11 recorded by the borehole sensor to check the alignment of the horizontal components
12 with respect to north. As for the verticality of the seismometers, we estimated maximum
13 installation tilts of 1.3 degrees for the SS sensor and 2.2 degrees for the SR sensor. The
14 enclosure box contained the seismic recorder, the battery and the GPS (Figure 4). After
15 the installation, the system required some time to reach stabilization (48 hours for the
16 SR sensors and 24 hours for the SS sensors).

17 18 **Station start-up and data release**

19 We configured the digitizers to sample data at a rate of 250 Hz, which were
20 continuously recorded on-site on the Secure Digital (SD) internal storage card. The
21 sampling rate was chosen to preserve the high frequency components of seismic waves
22 and improve the estimation of source parameters for small earthquakes (*e.g.*, Hiramatsu
23 *et al.* 2002). Spidernano includes Ethernet TCP/IP remote communication capabilities
24 that could be powered using a solar panel. Nevertheless, due to the poor 3G coverage in

parts of the region and for security reasons, we chose to perform a time-based maintenance of the stations. In this regard, the sites were revisited every 12-15 days to change the SD card, check the battery, run the data logger quality control software and reinitialize the acquisition system. We updated the database regularly with the collected data, which were converted from the native Spidernano's SPD format to the standard mini-SEED earthquake data exchange format.

Overall, we obtained three-component data for more than 98% of the total deployment days. In most cases data was only lost during the maintenance operations (less than one hour on each visit). Nevertheless, eventual unexpected station failures could not be identified until the following visit to the station. Thus, issues (such as for instance premature battery discharge) lead to data gaps of up to few days. When feasible, telemetry can solve this kind of issues, even though the cost is not negligible.

DATA QUALITY CONTROLS

Instrument testing

Both the seismometers and the acquisition system are calibrated and certified in the factory before delivery. In addition to the factory tests, we also checked the cable wiring between the sensor and the data logger using the pin and cross talk tests. The pin test ensures that no channel interchange is occurring. "Cross talk test" checks if currents traveling along one channel are generating signals on the other channels, even when they are disconnected (*e.g.*, Havskov and Alguacil 2004).

We tested the stations before the initial start-up using a test suite included in the Spidernano software. These tests check the inner electronics of the acquisition unit as well as the status of the seismometer and facilitate the identification of any malfunction

of the system. We continued checking the stations regularly during the periodic maintenance routines to detect any malfunctioning during the station operation.

Noise performance

The visual inspection of the traces can help identifying instrument malfunctioning, as for instance, the presence of frequent spikes or data gaps. However, a standard test for the quality control of the recorded traces is the evaluation of the data spectral characteristics using Power Spectral Densities (PSD). For this purpose, we used the PQLX open software (McNamara and Boaz 2011) that computes the Probability Density functions (PDF) of PSD's for all the available data using 1-hour length, continuous, 50% overlapping time segments (McNamara and Buland 2004, McNamara *et al.* 2009). The data was corrected for the instrument response to yield ground acceleration, so the computed PSDs could be compared to the reference noise levels defined by the New High Noise Model (NHNM) and New Low Noise Model (NLNM) of Peterson (1993).

This method allowed us to detect station configuration errors or instrument damages, as well as to assess the quality of the stations in terms of the ambient seismic noise baseline levels at each site. Figure 5 shows an example of the PDFs obtained during the whole recording period for the vertical component of station D104. Noise exceeding the limits is identified as traces with data gaps and earthquakes. The instrument bandwidth affects the PSD appearance at the long period range ($T > 10$ s).

Multi-station analysis

1 Apart from the quality control routines carried on for every single station, we assessed
2 the network performance by comparing the data recorded by all the stations of the DD
3 network. The noise conditions at all the station sites are of great importance for the
4 seismic event detection in the area, which is the main objective of this project. In this
5 regard, we note that it was not always possible to select the optimal location for the
6 stations (on bedrock and far from natural and man-made sources) because they had to
7 be confined within the inner grid of the network. Anthropogenic noise sources in the
8 area include industry, road traffic, agricultural machinery, and water pumps. Figure 6
9 compares the noise baselines obtained for all the recorded data during the Dehdasht
10 project. This figure plots the median of the PSDs for all the network stations together
11 with the NLNM and the NHNM. It can be observed that most of the stations perform
12 well (the PSDs are between the NLNM and the NHNM) for frequencies higher than 0.1
13 Hz. The differences observed at long periods ($T > 10$ s) among the stations are due to
14 the different instrument responses of the SS and SR sensors.

15 We also used multi-station representation of the seismic signal applied to local and
16 teleseismic events recorded across the entire network. Figure 7 plots an example of a
17 0.05-0.5 Hz band pass-filtered teleseismic event recorded at several stations of the
18 network. It can be observed that the recorded traces are similar at most of the stations,
19 as expected for an earthquake located at a distance of about 11,800 km; however,
20 stations D075 and R009 present smaller wave amplitudes, probably because of
21 unfavourable installation at these sites.

22 Figure 8 shows band-pass filtered (from 1 to 50 Hz) vertical component recordings at
23 different distances of a typical local seismic event. In spite of the different noise levels
24 observed before the *P*-wave onset, the event is clearly visible at all the stations.

25

HORIZONTAL ORIENTATIONS OF THE BOREHOLE SENSORS

Misorientation of seismometers with respect to the geographic coordinate system is a very important variable for three-component seismological analyses that require the rotation of the seismic records from the original geographic coordinates ZNE (vertical, north-south, east-west) into the ZRT (vertical, radial, transverse) or into the ray-oriented LQT (P -wave direction, SV -wave direction, SH -wave direction) coordinate systems. Some examples include earthquake source investigations, anisotropy studies, receiver function analyses or body- and surface-wave polarization studies (*e.g.*, Ekström and Busby 2008, Wilde-Piórko *et al.* 2017, Lim *et al.* 2018). The orientation is usually determined by indirect methods after the installation of the seismometer, and the azimuths of the horizontal components are reported as auxiliary data (*e.g.*, Ekström and Busby 2008). In the absence of active sources, the orientation of the seismometers can be obtained using passive sources as ambient noise (Zha *et al.* 2013) and P and Rayleigh waves from earthquakes (*e.g.*, Schulte-Pelkum *et al.* 2001, Stachnik *et al.* 2012, Doran and Laske 2017).

In borehole deployments, it is difficult to align the nominal north and east components of the seismometer with geographic north and east in the field. In this survey, the borehole sensors were carefully oriented on site using a standard compass and removable orienting rods; however, there may be unexpected errors. In order to check the orientations of the horizontal components of the seismometers, we used the DLOPy computer code (Doran and Laske 2017). This algorithm takes advantage of the Rayleigh-wave particle motion, which is elliptically polarized in the vertical-radial plane. The Hilbert transform of the vertical component yields a linear relationship with the radial component and, therefore, the direction of maximum cross-correlation between the phase-shifted vertical component and the radial component represents the

source-receiver back azimuth (*e.g.*, Stachnik *et al.* 2012). Long time deployments are preferable, since the accuracy of this method depends on the time period covered by the data series (Vecsey *et al.* 2017). However, DLOPy achieves high accuracy using fewer events than other widely used orientation methods (Doran and Laske 2017).

We used 90 teleseismic earthquakes occurred during the entire deployment period, with moment magnitudes greater than 6.0. We selected events with epicentral distances between 5° and 175° and focal depths less than 150 km. The program uses global dispersion maps to compute the Rayleigh wave time window as a function of frequency.

Then, it makes individual measurements for different wave-packets filtered between 0.01 Hz and 0.04 Hz, at 0.005 Hz intervals, which are then averaged. Figure 9 shows an example of an entire arrival-angle dataset for station D022. This figure plots the orientation angles obtained for all the analysed seismic events at different frequencies as a function of the maximum cross-correlation between the phase-shifted vertical component and the radial component, which is a measure of the data quality. It can be observed that many of the recorded events have low cross-correlation values and that high correlation values cluster around an average angle, which is taken as the misalignment of the north component of the deployed instrument measured clockwise from geographic north. For each station, the clustering of measurements around 0° (or 360°) would indicate no deviation from true north. A cross-correlation threshold value of 0.8 was defined as the minimum-quality measurement used in the final average calculation of the instrument orientation. This threshold can be adjusted as needed to balance between the inclusion of only high-quality measurements and to allow for more data in the final averaging. For the example plotted in Figure 9, the final instrument orientation obtained is $-12^\circ \pm 11^\circ$.

The estimated orientations for all the seismic stations in the network are summarized in Figure 10. Each solid circle represents the estimated angle, in degrees clockwise from north, between the north component of the deployed instrument and the geographic north. The horizontal segments mark the confidence intervals. We were able to estimate stable orientations at 89% of the deployed stations, based on 2 to 28 individual measures. For some stations (plotted in red in Figure 10) the noise conditions did not allow to obtain reliable orientations. Figure 10 shows that the estimated angles are distributed, within the error intervals, around the true north (plotted with a dashed vertical line at 0° in the figure) for most of the stations. However, there are some stations that present larger deviations from the geographic north. We are currently exploring other methods to further validate the orientation estimates.

Misorientation of the horizontal components of motion did not affect the results of the local earthquake tomography performed in this project, which uses *P*- and *S*-wave travel time data from local earthquakes. Horizontal-component waveform changes caused by large misorientation angles neither affected the *P*-wave attenuation models, which were based on vertical-component amplitude measurements.

DISCUSSION AND CONCLUSIONS

This work was aimed to provide a description of the technical issues related to a passive seismic survey conducted in the area of Dehdasht (South Western Iran). The project, which was the first of this type in Iran, had the objective of testing a toolset of high-resolution seismological techniques (including local earthquake tomography and attenuation imaging) to increase the performance of traditional hydrocarbon exploration methods in the area. In particular, the passive seismic methods applied might help delineate the shape and depth of the Asmari formation in Dehdasht area. For this

1 purpose, local seismicity was continuously monitored during 10 months and recorded
2 data was used to retrieve the three-dimensional *P*- and *S*-wave velocity and *P*-wave
3 attenuation structure of the region (data are currently not available for publication).

4 We described the procedures followed for the seismic network deployment and we
5 emphasized the importance of every step to obtain the high-quality waveform data
6 needed to get accurate earthquake locations and dense epicentre-to-station path
7 coverage. The information extracted from probability density functions allowed us
8 identifying instrument malfunctionings and characterizing the sites in terms of the
9 ambient noise levels.

10 The level of local seismic activity recorded by the DD seismic network is high. During
11 the monitoring period, the network detected an average rate of about 1,800 low-
12 magnitude earthquakes per month. Earthquake locations show that seismicity is spread
13 over the region at depths less than about 30 km. Figure 11 shows a selection of the
14 epicentre-to-station paths corresponding to 2,445 high-quality earthquake locations
15 within the surveyed area. Selected earthquakes have a minimum of 10 seismic phase (*P*-
16 and *S*-wave) readings and the root-mean-square of the locations is less than 0.2 s.
17 Homogeneous high-density path coverage is observed, which resulted in final three-
18 dimensional *P*- and *S*-wave velocity models in a $0.5 \times 0.5 \times 0.5 \text{ km}^3$ grid in the surveyed
19 area. Data collected in this experiment and the scientific results of the passive seismic
20 methods applied are not publicly available yet.

21 Although the orientation of the borehole sensors did not affect the results of the
22 tomographic methods applied in this project, this information will be needed in seismic
23 applications that use rotated horizontal seismometer components. In this experiment, the
24 instrument responses at intermediate periods obscured the surface wave arrivals on the
25 horizontal components, thus reducing the number of successful orientation estimates

and increasing the corresponding error bars. Future projects involving the deployment of a local network of three-component borehole seismic stations would benefit from installing a reference three-component seismic station that could be manually handled and accurately oriented. Therefore, several additional techniques could be used to estimate the relative orientation angles between each borehole seismometer and the reference station, using signals with dominant wavelengths greater than the distance between the station pairs (*e.g.*, Diez Zaldívar *et al.* 2016).

This work can be helpful for other groups aiming to perform passive seismic studies for hydrocarbon exploration activities.

ACKNOWLEDGEMENTS

This work would not have been possible without the support of the Exploration Directorate of the National Iranian Oil Company. Several figures were prepared using the Generic Mapping Tools (GMT) software (Wessel *et al.* 2013). Rayleigh wave polarization measurements were determined with the Python code DLOPy (<https://igppweb.ucsd.edu/~adoran/DLOPy.html>, last accessed February 2018). We thank the Associate Editor Peter Hanssen and two anonymous reviewers for their constructive reviews.

FIGURE LEGENDS

Figure 1. Topographic map of Iran. The target area is indicated with a square.

Figure 2. Topographic map of Dehdasht area. The dashed lines enclose the inner and outer network rings. Red triangles are the stations with SS sensors whereas white

triangles correspond to the SR sensors. The solid white square indicates the location of Dehdasht.

Figure 3. Images of the SS and SR borehole sensors and corresponding amplitude instrument responses for the sensor-digitizer systems.

Figure 4. Images of a typical station installation: (a) borehole drilling, (b) wall cementation, (c) enclosure box, and (d) instrumentation.

Figure 5. Probability Density Function of Power Spectral density for the vertical component of station D104 (left). The mode and the 10% and 90% percentile distribution for the whole recording period from 22 September 2016 to 01 July 2017 are plotted. The grey lines represent the NLNM and the NHNM. The traces inside the black rectangle are recordings with data gaps. The traces inside the red rectangle contain local earthquakes (right side of the figure).

Figure 6. Median statistics of the Power Spectral Density (PSD) for all the three-component stations of the DD network in dB referred to $(\text{m/s}^2)^2/\text{Hz}$. The New High Noise model (NHNM) and the New Low Noise model (NLNM) are also plotted.

Figure 7. Vertical-component teleseismic recordings of the M_w 7.9 earthquake occurred on January 22, 2017 at 04:30:22.96 (time 0 in the figure) in Papua, New Guinea region. The traces are instrument corrected and band-pass filtered between 0.05 and 0.5 Hz. The arrival time of *Pdiff*, *PKiKP*, *SKS* and Rayleigh phases is shown.

Figure 8. Record section plot of a local earthquake recorded at the DD network. The vertical-component traces are band-pass filtered between 1 and 50 Hz.

Figure 9. Arrival-angle measurements as a function of cross-correlation for station D022. Different colours indicate the measurements at different frequencies. The

horizontal line marks the average angle of the north component of the seismometer measured clockwise from geographic north (348° at this site).

Figure 10. Instrument orientations at all the stations of the DD network in degrees clockwise from geographic north. Reliable orientations could not be estimated for the stations plotted in red.

Figure 11. Plot of selected epicentre-to-station paths in the surveyed region in the period September 2016 to May 2017. Red triangles are the stations with SS sensors whereas white triangles correspond to the SR seismometers. Earthquake epicentres are plotted with open black circles.

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1   FIGURE 1

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FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11