Integrated Passive Seismic Methodologies: Application in Hydrocarbon Exploration in India.

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Abstract

Passive Seismic methodologies appeared in the hydrocarbon sector at the end of the 90s, as a potential tool with applications in Exploration and Production. Since that time, many applications used the term “passive seismic” (hydraulic fracturing monitoring, direct hydrocarbon indicators, structural and lithological imaging using earthquake or noise-based methods, etc.). For about a decade, Passive Seismic was trying to find its place in the industry and Oil companies to investigate which of all those methods have the potential to be used as valuable tools.

During the last ten years and due to important R&D efforts, some of the Passive Seismic methods improved a lot and relevant projects proved which of the methods can be useful, either during exploration or at the production stage. Additionally, new areas like mining or geothermal started applying these methods, providing even higher potential to Passive Seismic.

Our research is focused in developing efficient and innovative ways of exploiting Passive Seismic data, for exploration purposes. The integration of different passive seismic methodologies, the advanced software development for automatic detection and P&S-waves phase picking, the novel development and application of new methods like Reflected-Wave Passive Seismic Interferometry along with the most recent Passive Seismic surveys in India are going to be presented in this publication.

Introduction: Integrated Passive Seismic Overview

Integrated Passive Seismic technology for exploration applications utilizes natural seismic signals (pure ambient noise and/or local/regional and teleseismic events), which are recorded by a dense seismological network installed at the surface (consisting of 3C seismic sensors), aiming to provide 3D structural, lithological and geotectonic information. The 3D P-wave velocity distribution can be attributed to structural imaging of the subsurface, while Vp/Vs variations are related to porosity characteristics of geological formations. Moreover, 2D/3D virtual reflection seismic imaging of an area of interest, can be obtained without the use of any artificial seismic source.

The basic concept is to exploit the totality of the useful signal, in the band of 30-40 sec up to 30-40 Hz, using a well-designed, single acquisition scheme. The integration of the different results that can be obtained by application of each Passive Seismic methodology can lead to very important and helpful information, not only for the upper part of the crust, where the E&P activities are taking place, but also for the deeper crustal structures and the relevant tectonic characteristics.

The main passive seismic methods that are commonly used in hydrocarbon, mining and geothermal exploration are separated in earthquake-based and noise-based methods. In the following paragraphs a brief description of these methods, along with their main deliverables, are presented (Fig. 2).

Earthquake-Based Methods

Earthquake-based methods are separated in 3 different techniques according to the exploited earthquake signal: local, regional or teleseismic events.

1. *Local Earthquake Tomography (LET)*

For this method, which is the first that has been applied in hydrocarbon exploration since the late 90s, the exploited part of the passive seismic signal consists of the P- & S-wave travel times from the seismic source (local earthquakes) to the receivers installed at the surface. The travel times are used both for the initial hypocentral locations of the recorded earthquakes and for tomographic inversion. The major scope is to obtain 3D Vp, Vs and Vp/Vs models for an area of interest, as well as optimized hypocentral locations, based on the calculated 3D velocity models (Evans et al, 1994).

Additionally, the accurately estimated earthquake locations provide the possibility to obtain information on the presence of active faults, as their characteristics can be determined by the calculation of the fault plane solutions for each event. Stress variations can also be estimated, both spatially and in depth, providing additional information about the geotectonic regime prevailing the investigated area.

2. *Surface-Wave Tomography* from regional or teleseismic events (SWT)

The low-frequency surface-wave signals that are generated by strong teleseismic events (Love and Rayleigh) are recorded by a seismic network installed over an area of interest and exploited, as they carry significant information, especially for the deeper parts of the crust (even down to Moho depth). The surface-wave dispersion from regional or teleseismic events is processed to generate 2D phase velocity maps which are used as input for inversion on ordait to calculate a pseudo-3D S-wave velocity model (Jin and Gaherty, 2015).

This method is very useful during the early stages of an integrated Passive Seismic survey, as the estimated deep Vs distribution may serve as initial model for the Local Earthquake Tomography procedure.

3. *Reflected-wave Passive Seismic Interferometry (RWPSI)*

The output of the autocorrelation of the P- & S-wave coda of local earthquakes that arrive nearly vertically at a recording station corresponds to the zero offset virtual reflection response of the earth below this station. The RWPSI imaging is similar to conventional active seismic imaging, but can be applied both for P and S waves, while its resolution is controlled by the passive seismic network's interstation distances and the recording sampling rate (Polychronopoulou et al, 2020).

Noise-Based Methods

1. *Ambient Noise Tomography*

Seismic noise can be processed using the Ambient Noise Tomography technique, providing a Vs model for the first few km of the subsurface. By processing the cross-correlation of long time series of pure ambient noise, group and phase dispersion curves are calculated and the next step is the generation of 2D group and phase velocity maps. These maps are the input for an inversion procedure, which finally provides a pseudo-3D Vs model (Bensen et al,2008).

The resulting Vs model is more detailed than the one derived by application of SWT due to the higher frequency content of the signal, but it is limited to the first few km of the upper crust.

Integrated Passive Seismic – Processing Workflow

The above-mentioned earthquake-based and noise-based methods can be applied separately or combined, targeting to maximize the information that can be acquired from a single passive seismic dataset. The innovative integration of passive seismic methodologies has been applied in Mauleon Basin in South France, in Gerolekas Bauxite mine in central Greece and in Tripura and in Assam in India. The implementation of the methodology, and the results from the Mauleon and Gerolekas integrated passive seismic surveys have been recently published by Polychronopoulou et al. (2018, 2019). The contribution of LET, ANT and SWT methods in hydrocarbon exploration and the new knowledge in terms of deep imaging and geotectonic characteristics of the West Tripura area presented in this study.

The Ambient Noise and Surface-wave Tomography can be combined, in order to generate a pseudo-3D Vs model imaging the subsurface volume from the surface down to the Moho. In the case of existence of local earthquake activity, this model can be used as initial velocity model both for calculating the hypocentral parameters of the recorded earthquakes (x, y, z, t_o) and for the 3D joined hypocentral-velocity inversion procedure (Local Earthquake Tomography). This procedure will result in the estimation of the optimum 3D Vp, Vs and Vp/Vs models, as well as the optimized hypocentral locations. The above-mentioned procedure is depicted in Figure 1.

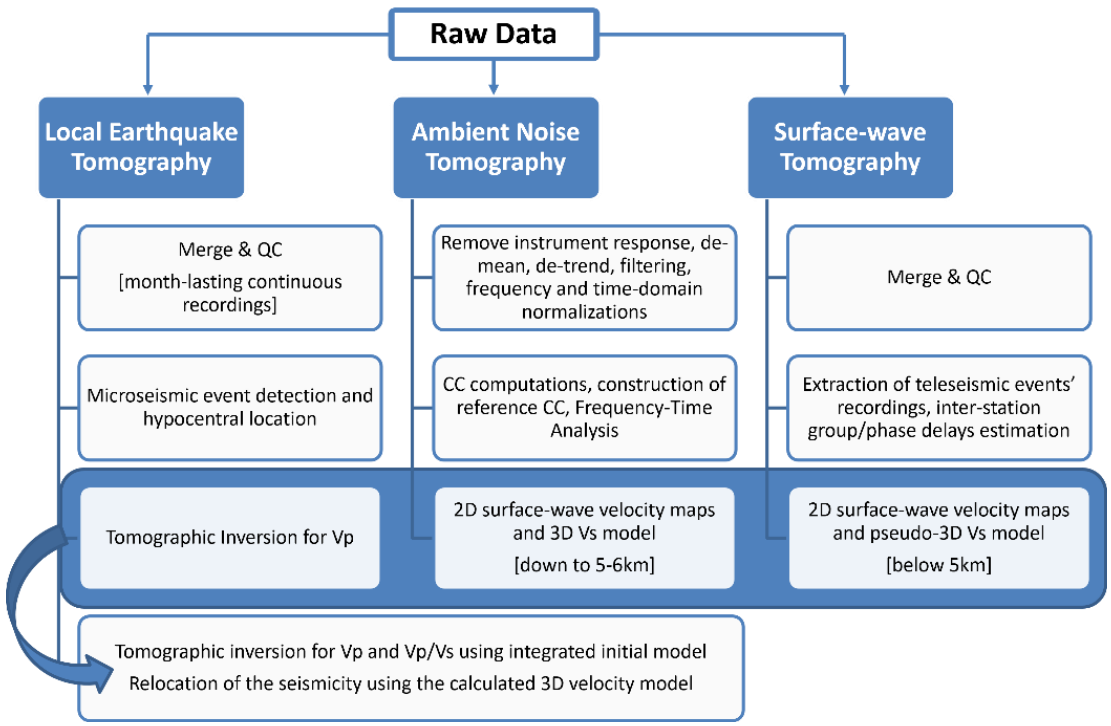

Figure 1. Processing workflow for integration of LET, ANT and SWT methods.

Moreover, in the case of absence or limited occurrence of local seismic events, the ANT and SWT methods can provide a reliable, even though coarser, 3D Vs model for the area of interest.

The next step of the integration of passive seismic techniques is the combination of LET and RWPSI. Based on the optimized velocity models and hypocentral locations of the seismic events (LET), the autocorrelated P & S-wave coda from the local events that arrive nearly vertically below each station provides a 2D/3D virtual reflection imaging of the study area, without using any artificial seismic source.

The RWPSI method is the latest development of passive seismic and its applications and its first results have been published very recently. (Polychronopoulou et al., 2020).

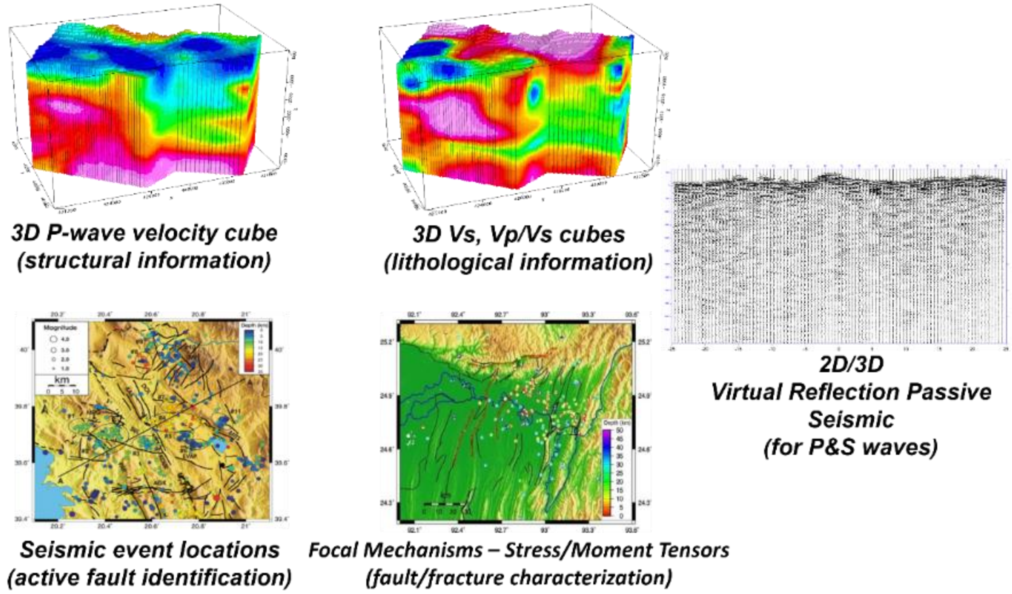

Figure 2. Passive Seismic main deliverables.

Passive Seismic applications in India

During the last three years, two major passive seismic surveys took place in India. The first one was launched in December 2019 by ONGC and the area of interest was located in West Tripura. In December 2020, OIL the second passive seismic survey commenced, for OIL, concerning an area in Assam-Arunanchal Pradesh.

West Tripura PST survey (ONGC)

The PST survey in West Tripura has been completed in June 2022. It was carried out in two phases, with monitoring periods of 3 and 8 months, respectively. The area of interest was approximately 4,500 km^2, with difficult accessibility, hilly terrain and complicated geotectonic regime.

During Phase-I, the target was an initial seismicity assessment of the study area, as well as a coarse modeling, in the case of occurrence of adequate seismicity. The PST network consisted of 108 seismic stations (100 Short Period and 8 Broadband). After the encouraging results of Phase-I, a second phase was decided and a denser network of 348 stations was installed in the same area, with interstation distances of 2.5Km.

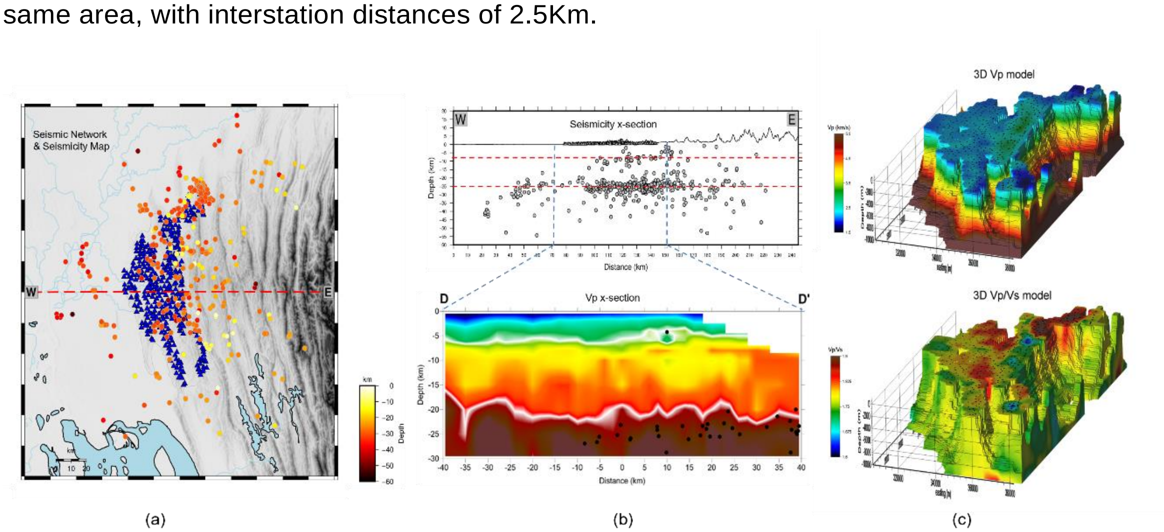

Figure 3. (a) The seismic network (blue triangles) and the seismicity distribution (colored circles) in the broader Tripura area (b) the WE seismicity x-section (top) and a WE P-wave velocity x-section (bottom) and (c) the 3D Vp (top) and Vp/Vs models (bottom).

During the 11 months of data acquisition, 619 earthquakes were detected and located within or close to the network area (Fig.3a) and for the Local Earthquake Tomography procedure 70941 P-& S-wave travel times were used. Additionally, Ambient and Surface-Wave Tomography were applied. The delivered Vp, Vs and Vp/Vs models provided structural and lithological information from the surface down to a depth of 30km (Fig.3b, c). Moreover, 215 focal mechanisms were calculated and the relevant geotectonic characteristics and stress variations were estimated.

The PST results were evaluated using existing well and geological data. Apart from the excellent matching with the aforementioned data for the first 4-5 km, where the existing information was reliable, the 3D PST models also provided information on the existence and form of two major unconformities in the area: the neogene-paleogene and the paleogene-crystalline basement unconformities (white lines, Fig.3b-bottom). Moreover, based on the seismicity distribution, the existence of two decollement zones was proposed and evaluated (dashed red lines Fig.3b-top), which is in total agreement with recent scientific estimations for the West Tripura area (Das et al., 2022).

It is also very important to mention that the information that can be obtained by combination of the estimated 3D Vp and Vp/Vs models may contribute to identifying new high potential prospects in poorly explored or deeper structures within the study area. This is very helpful for the hydrocarbon exploration in West Tripura, taking into account the limitations of the application of 2D/3D seismic in the area, because of accessibility, environmental and social issues, as well as its geological complexity.

Conclusions

The scope of this study is to demonstrate the recent advances in Passive Seismic technology, the importance of integration of its various techniques and the applicability and effectiveness of the method in hydrocarbon, mining or geothermal industry. Moreover, the results of the Passive Seismic surveys in India and the newly derived knowledge for the area of West Tripura and Pradesh are presented.

The improvement of existing processing algorithms and the development of new ones (i.e the automatic event detection and phase picking algorithm by Lois et al. 2013, 2019) in order to handle a very large amount of continuous recording from dense seismic networks, increased the capability of Passive Seismic to provide reliable and accurate imaging and fulfill the requirements of the industry.

Passive Seismic method utilizes P, S and surface waves which naturally occur in earthquake or ambient noise signals. Because of their low frequency content, they can provide deep structural and lithological information (in terms of Vp and Vp/Vs models) that may complement a seismic reflection campaign and/or add new knowledge in terms of subsurface imaging and tectonic characteristics of an exploration area, especially in case of difficult accessibility and complicated geotectonic regimes. Moreover, the method is insensitive in velocity inversions, which are common in thrust-belts and severely affect the seismic reflection surveys, because of the position of the naturally occurring seismic signals below or within the target volume.

Considering the aforementioned advantages and the fact that the method is totally environmentally friendly and cost effective, Passive Seismic methodology has been evaluated by the hydrocarbon exploration sector in India, as well as other countries worldwide, and has recently attracted the interest of the mining and geothermal industry.

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