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The use of passive seismic methods for Geothermal exploration and monitoring

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Introduction

Geothermal energy harvesting is gaining momentum as the need for less-carbonated sources of energy arises. Along with this increase of interest comes the need for multiplication of exploration campaigns, dedicated to the localization, the characterization, and the selection of suitable prospective areas for geothermal systems exploitation. In parallel, the perspective of large-scale deployment of Geothermal assets also underlines the need for enhanced surveillance strategies and monitoring tools.

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From a geophysical perspective, the characterization and surveillance of geothermal targets usually focuses on the electrical and electromagnetic properties of the subsurface (e.g. Muñoz, 2014). However, as in any geophysical study, multi-physics approaches facilitate interpretation. Thus, both objectives, exploration and surveillance, can benefit from geophysical seismic methods which help to better understand the geological configuration of the subsurface, locating fractured zones and interfaces, identify hydrothermal fluids presence and circulation pathways. Seismic methods are usually a good complementary to electrical and electromagnetic information to understand the distribution and evolution of petro-physical parameters that are key indicators in geothermal contexts.

However, the present state of the geothermal energy market prevents investing as much financial efforts in geophysical exploration strategies as for the hydrocarbons market for instance, hence typically discarding the use of technologies such as 3D active seismic (for exploration) or 4D active seismic (for surveillance). As a consequence, cost-effective strategies must be deployed to accompany this movement.

Passive seismic methods are part of the solution. By opposition to active seismic methods, passive approaches do not require the costly deployment of logistics associated with the use of an active seismic source. Instead, they are based on the analysis of the ambient seismic signal, which can be cost-effectively recorded using seismic sensors in passive mode, and which, if properly processed and interpreted, can provide useful information about the spatial distribution and temporal evolution of the subsurface seismic properties.

Passive seismic methods emergence – The progression of seismic acquisition technologies

In the 1880s, modern earthquake detection began with the invention of the seismograph, an instrument capable of capturing ground motion produced by seismic waves. British scientist John Milne, often regarded as the founder of modern seismology, created a horizontal-pendulum seismograph sensitive enough to record distant earthquakes. The technical principle was straightforward: as the ground moved, the seismograph's heavy mass remained stationary due to its inertia, allowing the relative motion of the ground and the mass to be traced. These early seismographs gave scientists a new way to measure the strength and duration of seismic waves, leading to the classification of different wave types and laying the foundation for the Richter scale in the 1930s, a scale that quantifies earthquake magnitude based on wave amplitude.

Initially, earthquake recordings were analog, relying on ink pens to trace waveforms onto paper rolls. This method had limitations: recordings had to be reset after each event, and the analog traces could be difficult to interpret, especially for large, overlapping seismic events. In the 1960s, seismology began a significant shift as stations worldwide established standardized networks like the World-Wide Standardized Seismograph Network (WWSSN), which allowed comparison and cross-validation of seismic data from different locations. Yet, analog technology still limited the extent of what could be captured, often requiring events to “trigger” the recording mechanism. Triggered recordings meant that only seismic events exceeding a certain threshold were captured, resulting in the loss of data from smaller earthquakes and seismic tremors.

The digital revolution in the 1970s transformed earthquake detection. Digital seismometers replaced analog systems, offering higher resolution and accuracy, as well as the capacity to store continuous, high-quality data. The introduction of continuous recording was a breakthrough: it enabled the capture of all seismic activity, from minor tremors to major earthquakes. Continuous digital recording removed the need for triggered mechanisms and allowed real-time monitoring, essential for identifying seismic events before larger quakes. Additionally, with the digital storage of data, seismologists could archive vast amounts of seismic information, facilitating data analysis and pattern recognition across regions and over time.

Through these technological advancements, seismology has evolved from occasional triggered recordings to continuous, high-resolution digital monitoring, culminating in a networked, data-rich approach that enhances our ability to monitor, understand, and respond to earthquakes.

The ambient seismic signal – One person’s trash is another person’s treasure

Entering the age of continuous seismic recording, the field of seismology has expanded its scope beyond the study of large earthquakes to include the rest of the ambient seismic signal, which was until then often referred to as seismic “noise” and was usually disregarded as irrelevant or undesirable. This negative vision is due to the inherent difficulties of conducting active seismic surveys in such environments where this seismic “noise” shows high amplitude, in which case the picking of body waves arrival time becomes less accurate or impossible.

Rather than filtering out this background motion, scientists now treat seismic noise as a valuable signal, one that can reveal critical details about the Earth’s structure and dynamics. Passive seismic methods designate all the methodologies and tools that have been developed to infer subsurface information from the analysis of those seismic recordings. Figure 6.1 shows a 250 seconds duration recording of the ambient seismic signal, represented in the temporal domain. This signal typically illustrates the dual structure of the ambient seismic signal, which can simplistically be described as two main components, coherent seismic events on one hand, and incoherent seismic signals on the other hand. Different passive seismic approaches exist to extract information from the coherent or incoherent components of the ambient seismic signal.

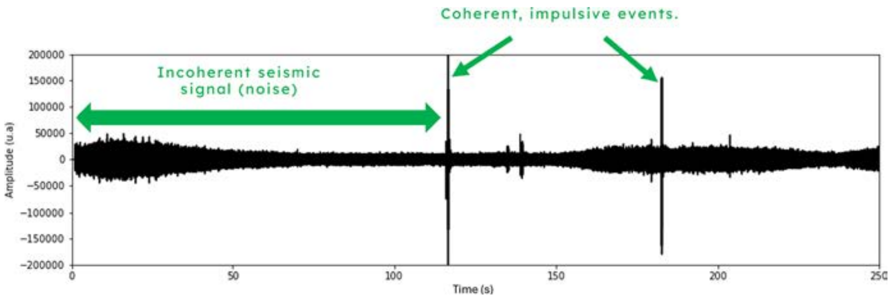

Figure 6.1 *Ambient seismic signal recording of 250 second duration. The seismic sensor used is a 5 Hz geophone.*

Coherent seismic events designate impulsive signal such as produced by earthquakes, microseismicity, or other impulsive, high energy seismic sources. The study of how those events propagate within the subsurface (body wave picking, location, focal mechanism, etc.) to infer either seismic properties or characterize their source mechanism is a family of approaches to which we will refer to in the following as **Seismological analysis**.

Incoherent seismic signals designate the large majority of the ambient seismic signal which cannot be directly identified as a single seismic event and isolated to be analyzed as such, but rather the sum of numerous contributions of uncontrolled sources such as ocean waves, atmospheric disturbances, and human activities. Yet even this part of the signal holds valuable information. For instance, Horizontal to Vertical Spectral Ratio (HVSR) analysis is a well-known, robust method to infer the thickness of the sedimentary layer overlying the bedrock, which has seen much use in geotechnical applications. For geothermal characterization and monitoring though, the most relevant family of methods able to take advantage of incoherent seismic signal recordings is the so-called Ambient Noise Seismic Interferometry (ANSI) analysis.

This relatively new approach (Shapiro and Campillo, 2004) has been a major development in the field of passive seismic methods, for seismologists have extended their capacity to retrieve Green's functions, which describe the response of an elastic medium between two points as waves propagate through it. Traditionally, Green's functions were obtained through earthquake-generated waves, providing data only after significant seismic events. However, ANSI achieves similar insights through the cross-correlation of ambient noise recorded at different seismic stations. By continuously recording these incoherent background vibrations and examining the data between paired stations, scientists can derive Green's functions, revealing the Earth's structure without relying on earthquakes. Putting it another way, ANSI tools manage to extract coherent seismic waves components from the incoherent seismic signal, hence making seismic analysis possible. In the rest of the paper, we will refer to this family of methods such as **Ambient Noise Seismic Interferometry (ANSI) analysis**.

Hence, the shift from traditional earthquake seismology to ambient seismic noise seismology relies on the precision of digital technology and the ability to record data continuously and at high resolution. This approach allows seismologists to capture even faint shifts in wave properties, which would be missed with a triggered or intermittent recording system. These subtle changes in the Earth's wave velocities provide crucial data for understanding not just earthquake-prone areas but also regions experiencing slower processes, like crustal deformation or fluid shifts in fault zones. Through these advances, passive seismic methods now serve as a powerful lens into the Earth's structure and its subtle movements and transformations, further bridging seismology with physics to deepen our understanding of the dynamic planet we inhabit.

A cost-effective, high-value tool in the geothermal geophysical toolbox

Passive seismic methods present two main interests in the context of geothermal industry development. First, their cost-effectiveness makes it an economically competitive tool for exploring geothermal subsurface context, at different scales, in complementarity to electrical, electromagnetic and other geophysical methods. Second, their input data – the ambient seismic signal – being continuous, free of charge, those methods can also be implemented as a continuous measurement allowing for quasi-real time monitoring of the subsurface.

The problematics surrounding geothermal exploration and the associated geophysical targets are as diverse as the variety of existing geothermal contexts. In this paper we will first present the practical and theoretical basis of the passive seismic approaches that are being used for geothermal exploration and monitoring purposes. Then we will focus on exposing how the diversity of geothermal geological contexts calls for different seismic responses and hence different geophysical objectives and how the global exploration and monitoring strategies can be improved thanks to the integration of passive seismic measurements.

6.1 Methods

6.1.1 *Seismological analysis*

The analysis of seismic events and microseismic events can provide significant amount of information about the subsurface, either by better identifying and locating the structural mechanisms that induce the seismicity, or by analyzing the seismic wavefield properties associated with those events, i.e. seismic waves velocity and attenuation properties in the vicinity of the seismic array. The following paragraph proposes a summary of the most used and emerging techniques to achieve both objectives.

Detection of earthquakes

Earthquake detection has undergone substantial development over the past decades, integrating traditional techniques with advanced computational tools to improve accuracy and reliability. The Short-Time Average/Long-Time Average (STA/LTA) method, introduced in the mid-20th century, remains a widely used and foundational approach for seismic monitoring. This method calculates the ratio of short-term signal energy to long-term background noise to identify sudden energy surges indicative of seismic events. STA/LTA gained prominence in the 1970s with the advent of automated seismic networks, enabling real-time earthquake detection. However, while effective for detecting moderate to large earthquakes, STA/LTA is prone to false positives in environments with high cultural or natural noise, such as urban areas or regions affected by storms.

To address these limitations, template matching emerged in the 1990s and has since become a critical tool for detecting smaller or repeating earthquakes. This technique involves comparing incoming seismic waveforms with a database of previously recorded seismic signals. When a match is identified, it confirms the occurrence of a similar event. Template matching is particularly effective in regions with dense seismic networks, such as California or Japan, where high-quality waveform libraries are available. Its ability to identify microseismic events and repeating patterns, such as slow-slip events or earthquake swarms, has proven invaluable for understanding seismicity in complex tectonic settings.

In the 2010s, machine learning revolutionized earthquake detection by introducing powerful algorithms capable of analyzing vast amounts of seismic data with minimal human intervention. Neural networks are trained on labeled datasets to learn the features that distinguish seismic events from noise. These systems can process continuous seismic streams, detecting small-magnitude earthquakes and events buried within background noise (Mousavi et al., 2020).

Hybrid approaches, combining STA/LTA, template matching, and machine learning, represent the cutting edge of earthquake detection. These integrated systems leverage the strengths of each method, ensuring high sensitivity to small and large earthquakes while reducing false alarms (Yue et al., 2021). Today's detection frameworks reflect decades of innovation, enabling precise monitoring of seismic activity across diverse tectonic environments and laying the groundwork for improved earthquake response and mitigation efforts.

Localization

Earthquake localization, the process of determining the origin of an earthquake in time and space, has advanced dramatically over the past century. The foundational approach relies on analyzing the arrival times of seismic waves, particularly P-waves (primary waves) and S-waves (secondary waves), which travel at different speeds through the Earth. By measuring the time differences in their arrivals at multiple seismic stations, the distance to the earthquake's epicenter can be estimated. This method, developed in the early 20th century, became a standard tool in global seismology with the establishment of seismic networks such as the Worldwide Standardized Seismograph Network (WWSSN) in the mid-1900s. However, traditional approaches often struggle with events in regions of sparse station coverage or complex crustal structures, where seismic wave propagation deviates from standard models.

To overcome these challenges, the introduction of seismic tomography and 3D velocity models in the late 20th century represented a major breakthrough. These methods account for variations in the Earth's subsurface, significantly improving the accuracy of earthquake localization, particularly in tectonically complex regions like subduction zones. Template matching has also been instrumental in localization. By comparing real-time waveforms with those of well-located events, the locations of new earthquakes can be inferred with remarkable precision. This method excels at identifying and locating small, repeating earthquakes that may not generate strong signals across broad networks. The rise of machine learning in the 2010s has further transformed earthquake localization by automating seismic waveform analysis and improving accuracy. Neural networks trained on synthetic and real seismic datasets can estimate earthquake hypocenters (the points of origin beneath the Earth's surface) with impressive speed and precision (Zhu et al., 2019). Probabilistic methods, such as Bayesian inference combined with machine learning, allow robust localization even in areas with limited station coverage or high noise levels. These innovations highlight the remarkable progress in earthquake localization, offering critical insights into seismic processes and ensuring effective monitoring of tectonic activity worldwide.

Magnitude

The estimation of earthquake magnitude has evolved significantly since its inception, transitioning from simple empirical scales to sophisticated, physics-based calculations that leverage global seismic networks and advanced computational tools. The concept of quantifying an earthquake's size was first formalized by Charles F. Richter in 1935 with the introduction of the Richter scale, or the local magnitude (ML) scale. This method measured the amplitude of seismic waves recorded by a specific type of seismograph (the Wood-Anderson torsion seismometer) at a standardized distance of 100 kilometers from the epicenter. The Richter scale was revolutionary because it provided a logarithmic measure of earthquake size, allowing a single number to represent the energy released during an event. While the Richter scale worked well for moderate earthquakes in Southern California, it had limitations for very large earthquakes and those occurring outside the region for which it was calibrated. This led to the development of additional magnitude scales, such as the surface-wave magnitude (Ms) suitable for large, shallow events or body-wave magnitude (Mb) focusing on compressional body waves useful for deep-focus earthquakes. Despite their broader applicability, these scales also had shortcomings, such as underestimating the size of very large earthquakes (known as saturation).

To address these issues, the moment magnitude scale (Mw) was introduced in the late 1970s by Hiroo Kanamori and Thomas Hanks. This scale is based on seismic moment, a physical quantity directly related to the energy released during fault rupture. Mw considers the area of the fault that slipped, the average slip displacement, and the rigidity of the rocks involved. Unlike earlier scales, Mw does not saturate for large earthquakes, making it the preferred standard for global seismology. Modern earthquake magnitude estimation has benefited from advancements in seismic instrumentation and computational methods. Broadband seismometers, capable of capturing a wide range of frequencies, allow for detailed analysis of seismic waveforms across the globe. These instruments provide the data necessary for calculating magnitudes using regional and global network observations.

Machine learning has recently entered the field of magnitude estimation, offering tools to analyze complex seismic datasets and refine magnitude calculations. Algorithms trained on historical seismic data can predict magnitudes with high accuracy, even for events with unconventional waveforms or sparse station coverage. These advancements underscore the ongoing progress in seismology, ensuring that magnitude estimates remain a critical tool for understanding earthquake dynamics and microseismicity.

Focal Mechanism Determination

The focal mechanism of an earthquake describes the orientation and type of faulting that occurs during the rupture, providing insights into the forces driving tectonic processes (Byerly, 1955). This information is typically represented by a "beachball diagram", which visually depicts the fault's geometry and slip direction based on seismic wave patterns. The analysis of focal mechanisms has been integral to seismology since the mid-20th century, offering valuable clues about earthquake dynamics and regional stress fields. Early methods for determining focal mechanisms relied on the first-motion polarity of seismic waves. When an earthquake occurs, compressional P-waves radiate outward, creating zones of compression (upward motion) and dilation (downward motion) recorded at seismic stations. By mapping these first-motion polarities, seismologists can infer the orientation of the fault plane and the direction of slip. While effective, first-motion polarity analysis required a dense distribution of seismic stations for reliable results, limiting its application in remote regions or areas with sparse networks.

The advent of waveform modeling in the 1970s marked a major advance in focal mechanism determination. By analyzing the amplitude and shape of seismic waves, particularly the long-period components, scientists could model the faulting process more precisely. Waveform modeling also enabled the estimation of moment tensors, mathematical representations of the forces involved in an earthquake. Moment tensor inversion, introduced in the 1980s, uses seismic waveforms to solve for the fault plane orientation, slip direction, and seismic moment, providing a comprehensive description of the earthquake source. Modern techniques for determining focal mechanisms combine data from dense regional networks, broadband seismic stations, and advanced computational models.

Automated systems, such as the Global Centroid Moment Tensor (GCMT) catalog, continuously process seismic data to generate focal mechanisms for significant earthquakes worldwide. These systems rely on inversion algorithms that use broadband waveform data to produce accurate and reliable solutions, offering insights into the faulting style and regional stress regime Machine Learning has recently been applied to focal mechanism analysis, offering tools to process vast amounts of seismic data efficiently. Neural networks trained on synthetic and real earthquake datasets can rapidly classify faulting styles and estimate moment tensors with high accuracy. The study of focal mechanisms provides critical information for understanding tectonic processes and seismic hazard. For instance, the analysis of focal mechanisms during aftershock sequences can reveal how stress is redistributed on faults after a major event. Additionally, comparisons of focal mechanisms across different earthquakes help map the orientations of active faults and infer the directions of regional tectonic stress. Modern focal mechanism analyses, with their increasing precision and automation, remain a cornerstone of seismology, linking the physics of faulting with broader geodynamic processes.

6.1.2 *Ambient noise seismic interferometry (ANSI)*

At the heart of ANSI is the concept of a “diffuse field”, where energy from seismic waves is dispersed evenly in all directions through a medium like the Earth’s crust. This concept has its roots in statistical physics, where wave energy behaves in random but statistically predictable ways. By understanding how this energy propagates, researchers can use noise as a sort of “natural tomography”, revealing the Earth’s properties, such as wave speed and material composition, down to fine scales.

More practically, the ANSI method designates a signal processing approach that allows to extract coherent seismic waves from the incoherent ambient seismic signal recordings. This reconstruction process is achieved through cross-correlation operations between the diffuse noise signals recorded at two different locations on the earth’s surface (Figure 6.2), yielding empirical Green’s functions (EGFs) that are estimates of the impulse response of the subsurface medium in between the two

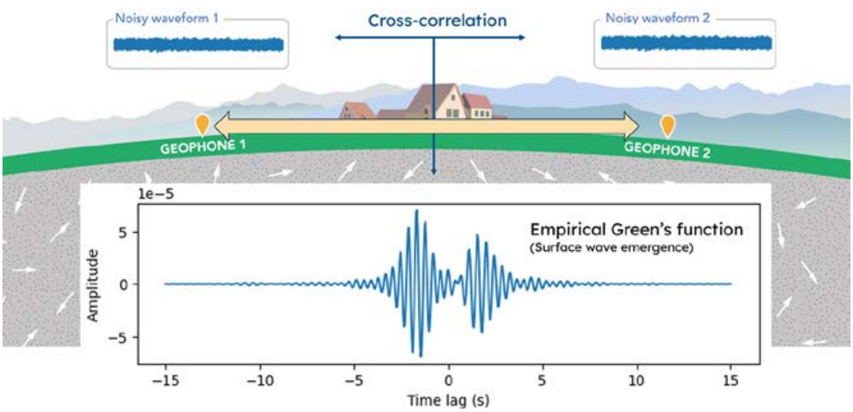

Figure 6.2 *Illustration of the Empirical Green’s function emergence process. Two incoherent noise signals recorded at two different locations are cross-correlated, to extract the EGF of the subsurface in between the two sensors. (White frame) In this example, the reconstructed EGF is highly dominated by surface wave (real data).*

sensors. The coherent components of those EGFs, which can then be submitted to a seismic analysis to infer information about the subsurface, depend on the ambient seismic signal composition, that is, its spatial and temporal characteristics. The reconstructed wavefield is usually dominated by interface waves (Rayleigh or Love waves in onshore context, Scholte waves in offshore context, see Mordret et al., 2020), but can also provide coherent body waves if the ambient seismic signal characteristics allows to (Brenguier et al., 2020).

The interferometric process itself is a sequence of signal processing operations (Bensen et al., 2007), which must be carefully parametrized to maximize the signal-to-noise ratio (SNR) of the reconstructed coherent waves. After pre-processing two signals of equal durations recorded at two different locations, cross-correlations operations lead to the final EGF. Finally, the SNR of the reconstructed wavefield can be significantly increased by stacking multiple EGFs that have been reconstructed sequentially in time.

This operation allowing the extraction of coherent seismic waves form the ambient seismic signal then opens the way to two types of seismic analyses, that can be applied to geothermal context studies (or to other geoscience contexts). The first is **Tomography**, where seismic properties (usually shear wave velocity, Vs) of the interface waves are analyzed over an array of sensors, to provide as an output 3D models of Vs spatial distribution within the subsurface. The second is **Monitoring,** where the changes in Vs value are measured in between EGFs reconstructed at different times. The following paragraphs provide a few elements about how the methods are implemented, what inputs are required and what outputs are expected.

6.1.3 *Tomography*

Ambient noise tomography (ANT) aims to resolve a 3D shear wave velocity (Vs) distribution of the investigated area using the dispersion properties of surface wave reconstructed throughout the cross-correlation operation described above. Traditionally, a two-step inversion approach is conducted to map dispersion properties and then define a pseudo-3D Vs velocity model by stitching local 1D velocity models.

First, group velocity dispersion curves of surface waves (usually the fundamental mode, but higher modes can also be included) are determined using a Frequency-Time Analysis (FTAN) over a frequency ranges (Levshin et al., 1972). This operation is performed by picking the dispersion curve within the FTAN diagram, as illustrated in Figure 6.3.

Recovered dispersion curves are estimated from cross-correlated waveforms, hence averaging the dispersion properties of the medium along the ray between pairs of stations. To resolve spatial seismic velocity variation, inter-station dispersion curves are inverted into group velocity maps (fundamental and higher modes if available) defined over the selected frequency range using a straight ray seismic wave tomography approach (Barmin et al., 2001; Mordret et al., 2013) or Eikonal equation (Lin et al., 2009).

Local dispersion curves sampled from each point of the maps at every available frequency are inverted independently into 1D shear wave velocity models constrained with depth. The final pseudo-3D shear wave velocity model is built by stitching 1D models side by side. Note that recent advances in seismic ambient noise tomography lead to a 1 step full 3D imaging procedure (Zhang et al., 2018) where 3D Vs model is resolved using a probabilistic inverse approach.

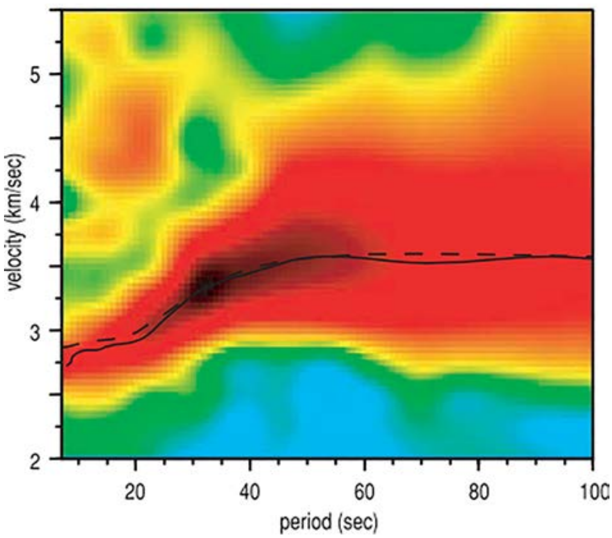

Figure 6.3 *Illustration of a raw FTAN diagram, measured group speed curve as the solid line, from Bensen et al. (2007).*

Note also that recent advances have started to pave the way for ambient noise tomography of attenuation properties, which can bring valuable insights for geothermal characterization and surveillance (Pérez and Cuellar, 2018), as will be discussed in the following paragraphs. Attenuation analyses through ANSI methods is still in relatively early developments, hence in this paper we do not provide an overview of the technical description of the process or different possible approaches, but we refer the reader to the work of Boschi et al. (2019), Magrini and Boschi (2021) for – non exhaustive – examples of how the seismic attenuation properties of the subsurface can be derived from the ambient seismic signal using ANSI processes.

6.1.4 *Monitoring*

The cross-correlation operation described in the previous section, which leads to an estimate of the EGF and the emergence of coherent seismic waves can be done sequentially, using any temporal resolution (minutes, hours, days, month, year), depending on observation purpose and on the characteristics of the noise distribution. If the seismic noise sources are globally stable in both time and space, it is possible to extract the waveform evolution over time and perform a velocity variation analysis. Several strategies can be considered, such as studying velocity variation measured on the ballistic part of the wavefield, often corresponding to surface waves, or on the so-called coda waves, which correspond to late arrival time and represents the multiple contribution of highly diffracted waves within the medium. The choice between the two strategies can depend on the noise stability characteristics, the coda waves often being favored in case of unstable ballistic wave reconstruction.

Various methods exist for extracting velocity variations (for a review, see Yuan et al., 2021). The doublet method (Poupinet et al., 1984) is preferred for working with the coda, as it is more effective in cases of strong decoherence across seismic signals and small velocity variations (~10^{-1}%) (Olivier et al., 2017). Windowed cross-correlation (Snieder, 2006) and stretching methods (Sens-Schönfelder and Wegler, 2006), on the other hand, can be more easily applied to ballistic waves, as they tend to have a high signal-to-noise ratio and show strong velocity variations (Voisin et al., 2016). An illustration of the stretching method is shown in Figure 6.4. The correlogram is a collection of EGFs reconstructed at different times. A reference waveform is selected or computed (e.g. average waveform) which is then stretched and compressed applying multiple coefficients. A semblance analysis is then performed with each waveform of the correlogram. The stretching coefficient that shows the highest semblance with a given waveform yields the corresponding velocity variation, also often referred to as the dv/v value.

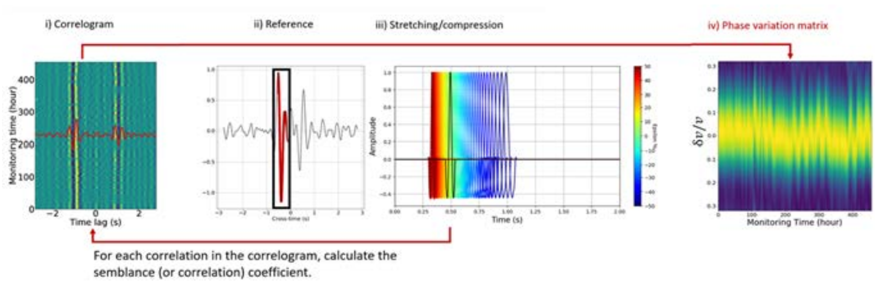

Figure 6.4 *Illustration of the stretching process. (i) Raw correlogram, (ii) chosen stack and time windows to perform the stretching process (red waveform), (iii) sketch of the application of the stretching/compression on a waveform by an epsilon factor (shift to red, compression, shift to blue, stretch), (iv) coherency matrix of the resulting stretching process, where the yellow show the best correlation coefficient between each stretched/compressed seismic trace and each line of the correlogram. The dv/v value is extracted from this matrix.*

The velocity of seismic waves can vary depending on several physical parameters and hence provide capacity for monitoring different phenomenon within the subsurface. As a non-exhaustive summary, Wada et al. (2017) demonstrate that variations in seismic velocity within the Earth's crust can be influenced by environmental disturbances, such as precipitation (Sens-Schönfelder and Wegler, 2006; Tsai, 2011), atmospheric pressure loading (Olivier and Brenguier, 2016), thermoelastic stresses (Hillers et al., 2015; Meier et al., 2010), ground water change (Voisin et al., 2016; Gaubert-Bastide et al., 2022). Noise-based velocity monitoring has also improved understanding of tectonic and volcanic processes, allowing for the detection of long-term post-seismic relaxation in fault zones (Brenguier et al., 2008; Hobiger et al., 2012), velocity decreases as precursors to volcanic eruptions (Brenguier et al., 2011; Wegler and Sens-Schönfelder, 2007), and interactions between seismic and volcanic systems (Brenguier et al., 2014). Application to geothermal monitoring contexts is addressed in the following paragraphs.

6.2 Passive seismic methods for geothermal exploration

Geothermal exploration aims at detecting subsurface areas that hold favorable conditions for geothermal exploitation. Depending on the geological context, and particularly on the type of geothermal field being considered, the targeted geological configuration can vary, as will the associated geophysical signature. Moeck et al. (2014) propose a classification of geothermal contexts in two main categories:

Convective systems: which are characterized by the presence of fluid in a reservoir that is set in motion within a convective loop induced by the presence of a heat source. The heat is transported to the surface by the fluid as a function of the permeability of the medium. Convective systems can take place in various geological contexts:

- <u>Volcanic reservoirs</u>: where the convection is controlled by the magma chamber. The productive zone of the reservoir is the up-flow zone, which concentrates the hottest fluids and the top of the reservoir is enclosed by conductive clay-caps.
- <u>Magmatic reservoirs</u>: where fluids circulate in a network of permeable faults near a recent hot magmatic body acting as the heat source.
- <u>Non-magmatic reservoirs</u>: where fluids are circulating in a permeable fault network set up during extensive crustal dynamics. As the crust gets thinner, the upwelling of the Moho increases heat flow, creating local thermal anomalies.

Conductive systems: In these geothermal systems, the heat comes from the natural thermal gradient, to which may be added heat flows from granites. As the heat sources are too weak to allow convection, the temperature field is distributed by conduction through the material. Again, one can distinguish different geological contexts leading to conductive geothermal systems:

- <u>Igneous reservoirs</u>: which are not reservoirs per se, but thermal anomalies linked to radioactive disintegration. Exploiting the geothermal type of resource implies fracturing the rock and stimulating fluid circulation within the formation to extract energy.

- Sedimentary reservoirs are typical contexts where geothermal energy extraction is based on the exploitation of the natural thermal gradient, which can be locally accentuated by thermal conductivity contrasts, such as in a deep porous and permeable sedimentary layer.
- “Mountain” reservoir: where the heat from the natural thermal gradient is advected upwards through fluid circulation in deep crustal faults linked to the formation of mountain ranges.

6.2.1 *Seismological analysis*

The analysis of seismic events, whether they occur locally or have a more regional origin, can provide a range of information to characterize a geothermal area, understand the global geological configuration and locate the most suitable prospection zones. Several seismic attributes can be derived during those analysis, depending on the data available and the geophysical context. Overall, those methods have been used for the location and characterization of multiple geothermal targets such as heat sources, hydrothermal activity, faulted and permeable zones, of fluid migration pathways and to characterize reservoir properties. Pérez and Cuellar (2018) provide a synthetic summary of the different kinds of analysis that can be performed within a seismological analysis dedicated to geothermal exploration. The following paragraphs transcribe some of this summary, while adding more recent references and analysis.

The most direct approach is to analyze the seismic activity itself. Locating events, evaluating magnitudes, identifying focal mechanisms and statistical distributions are different and complementary ways to relate the temporal and spatial distribution of seismic activity with geothermal key parameters.

Another set of methods aims to understand and map the seismic properties of the subsurface by analyzing how the seismic events propagate within it. The aim is to evaluate seismic velocity models or seismic attenuation models and track the specific signature of geothermal targets.

Seismic activity characteristics analysis

Location and magnitude of events

The intensity of seismic activity can be associated with tectonic processes but also with fluid dynamics related to geothermal heat sources. Overall, the characteristics of seismic activity provide a direct signature of the energy contained within the magmatic and hydrothermal system, i.e. the geothermal target potential (Pérez and Cuellar, 2018).

Hence, a seismological array can be set-up in the exploration area for a given period to try and record multiple seismic or microseismic events for which specific information such as location, magnitude and focal mechanisms can be inferred and compiled into a catalog. Such an approach will typically provide information about active fault zone geometry, location of fractured zones that facilitate hydrothermal fluid flow (Simiyu, 2009; Faulds and Hinz, 2015).

Figure 6.5 shows an example of microseismic analysis carried out at the Menengai geothermal prospect in Kenya (Simiyu, 2009). The location of microseismic event epicenters underlines the existence of two different trends that could be associated with fault zones, which intersect at the Menengai crater. Such observation suggests that these faults are likely still active, and at their intersection magma and thermal-fluid flow are occurring.

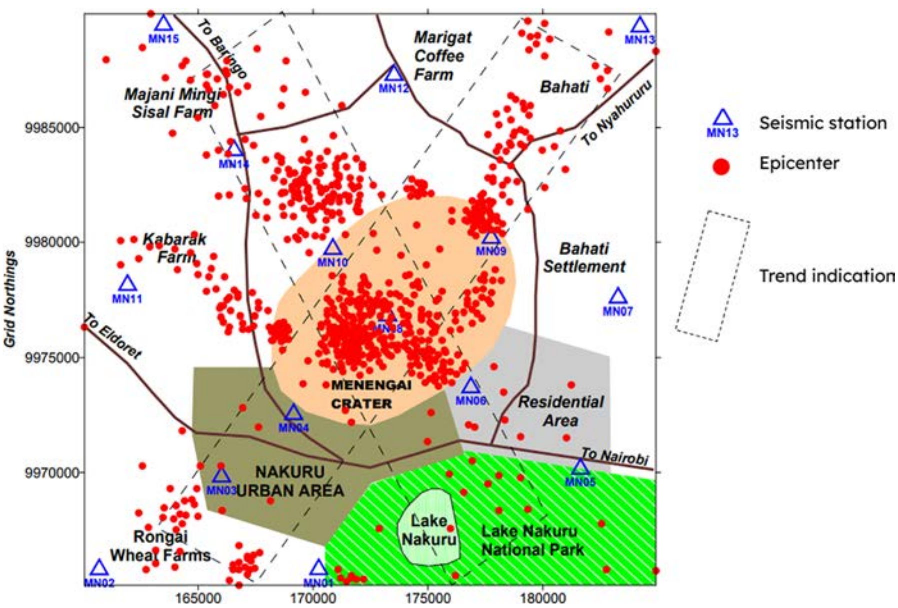

Figure 6.5 *Map indicating a passive seismic network (blue triangles) and the location of microseismic events epicenters (red dots) in the area of the Menengai Crater. Modified after Simiyu (2009).*

Another potential insight from seismic catalogs relates to the detection and location of zones where the brittle/ductile boundary is characterized by a relatively high elevation. Close to the surface, the rocks of the crust tend to have a brittle behavior which can relate to significant seismic activity. But progressing in depth, the increase of temperature induces a transition from brittle to ductile behavior (e.g. Tanaka, 2004; Suzuki et al., 2014), which leads to a drastic decrease in seismic events activity and occurrence. Figure 6.6 shows an illustration of such an observation at the Olkaria geothermal field in Kenya. The main production fields (OWF and NEF-DOMES) are associated with a highly elevated brittle/ductile transition, indicating highly elevated heat sources.

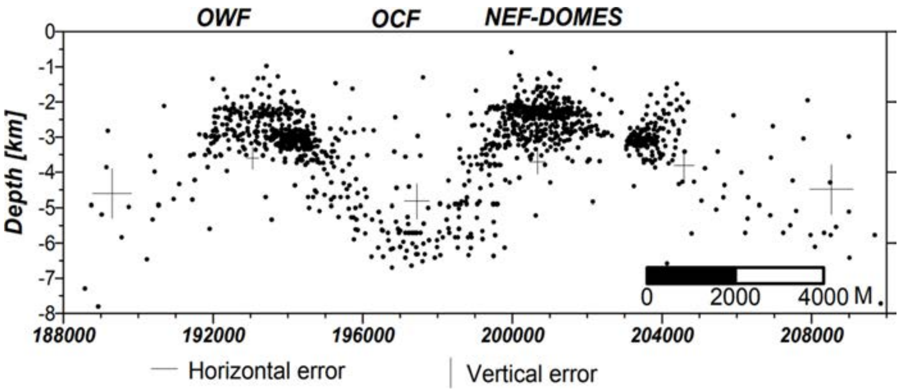

Figure 6.6 *Illustration of highly elevated brittle/ductile transition zone which correlate with geothermal production fields (OWF and NEF-DOMES). Modified after Georgsson (2009).*

Focal mechanisms

In addition to locating microseismic events, understanding their focal mechanism provides additional understanding about the tectonic processes that drive the geothermal context of an area. It helps understanding the regional and/or local stress field and provides information about the type of faults in the exploration area and the orientation of the fault planes and/or fractured zones. Analyzing jointly the stress field and the faults and fracture configuration is useful to understand the local thermal fluid flow process (i.e. identifying the most permeable zones and their potential to serve as thermal fluids pathways).

Figure 6.7 illustrates the kind of results that can be obtained through focal mechanisms analysis. Antayhua-Vera (2017) produced this map after a microseismic analysis conducted at the geothermal prospect of Las Tres Virgenes, in Mexico. Their findings demonstrated the correlation of the stress field at that site with the regional tectonic regime of the Gulf of California, and provided local understanding of fault location, orientation and type, and hence of how hydrothermal fluids are expected to flow within the geothermal system.

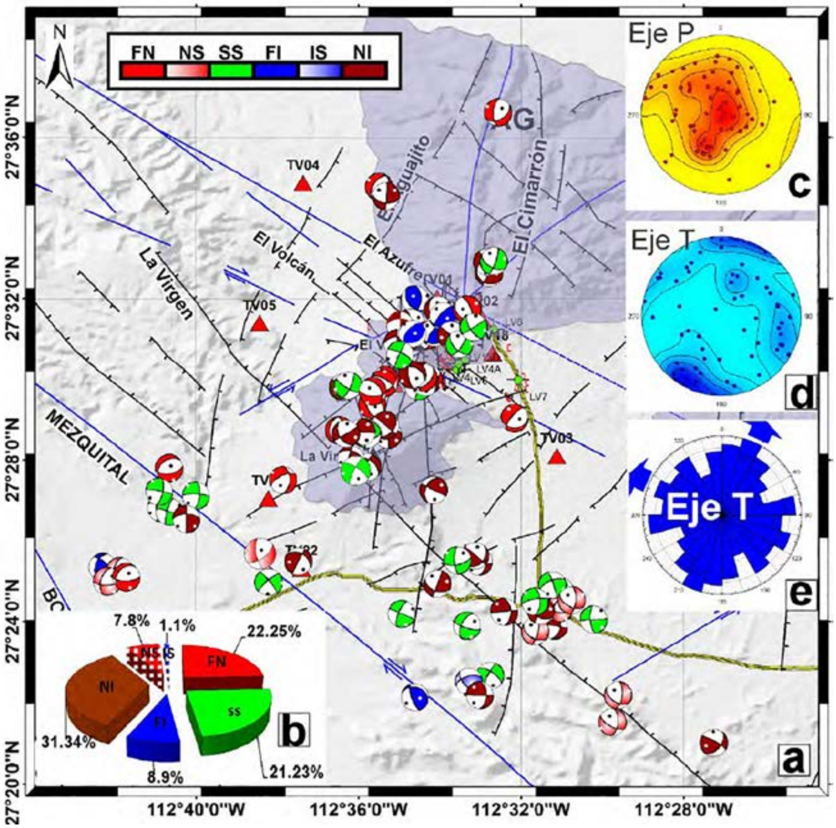

Figure 6.7 *Modified after Antayhua-Vera (2017). (a) The map shows focal mechanisms obtained from 91 seismic events. (b) Classification of events. (c) Spherical projection of pressure. (d) Spherical projection of tension axis (e) is the Rose diagram of the tension axis, with arrows indicating the preferential directions of all focal mechanisms.*

Statistical seismology

In this context, statistical seismology refers to a method dedicated to analyzing the statistical relationship that exists between the number of seismic events and the magnitude of the events. Gutenberg and Richter (1944) identified an exponential relationship between the number of earthquakes and their magnitude, and express the frequency of occurrences of seismic events as:

$$\log N = a - bM \tag{6.1}$$

where N represents the cumulative number of earthquakes whose magnitude exceeds M, and a and b are fitting parameters that describe the relationship at a given location for a given observation period.

Among those two parameters, the so-called b-value is critical and defines the slope of the straight line that characterize the relationship (Pérez and Cuellar, 2018). The b-value is considered an indication of the type of process that drives the seismic mechanisms, with values close to 1 associated with tectonic process, considering a homogeneous crust submitted to high stress field, whereas b-values greater than 1, sometimes close to 2, are representative of geothermal and volcanic environments. Multiple reasons are invoked to explain this difference, such as heterogeneity, low effective stress, fracturing, high thermal gradient, change of fluid composition and distribution, we refer the reader to Pérez and Cuellar (2018) to access multiple references on that topic.

As an illustration of the method, shows the results of a pseudo 3D tomography of b-values conducted by Benton et al. (2011) at the geothermal field of Tres Virgenes in Mexico. Several high b-values anomalies are identified that seem correlated to different known faults in the area that exhibit high fracturing degree and intense hydrothermal fluid circulation (Antayhua-Vera et al., 2022).

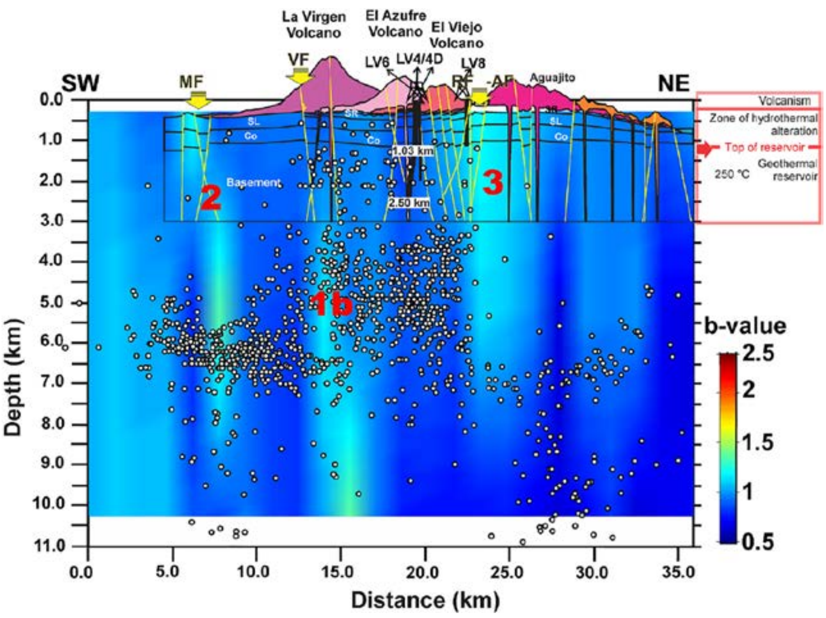

Figure 6.8 *Modified after Antayhua-Vera et al. (2022). Results of a pseudo-3D tomography of b-values conducted at the Tres Virgenes geothermal field.*

Waveform analysis

Following a similar logic as for *b*-values analysis, geothermal or volcanic contexts tend to induce seismic events whose waveform might differ from events produced in "pure" tectonic context. Waveform analysis, in the temporal of frequency domain can be a way to distinguish both environments, hence better characterizing the geothermal sites of interest. Examples of typical seismic signals produced in volcanic environments can be found in the work of Wassermann (2012), Zobin (2011) and Inza-Callupe (2014).

Subsurface seismic properties analysis – The interest of joint velocity/attenuation analysis

Beyond the study of the intrinsic properties of seismic events such as location, focal mechanism, statistical characteristics or waveform, the recording of the events over an array of seismic sensors also opens the way for characterizing directly an estimate of the subsurface seismic properties' distribution in the area. Using the earthquake as an uncontrolled, yet coherent source of energy, and tracking how the seismic waves propagate within the explored area can help derive 3D models of seismic properties and infer geothermal assets characteristics. The following paragraphs propose some examples of such analysis, distinguishing between attempts to retrieve a **seismic velocity** model of the area from studies focused upon **seismic attenuation** analysis.

In many seismic analysis, seismic velocity is the "favored" studied parameter and velocity-focused work usually treat seismic attenuation as an "undesirable" effect (Vardy and Pinson, 2018), because strong attenuation contexts tend to decrease the accuracy of velocity estimation. However, attenuation properties are also very relevant to be investigated if one seeks to infer complementary types of information. Indeed, the intrinsic seismic attenuation properties characterizing the anelastic behavior of subsurface rocks are sensitive to different parameters of the rock nature, type and composition than seismic velocity, which makes the joint study of those properties relevant in an exploration context.

Velocity models

If a sufficient number of seismic events are recorded through a seismic sensor array, it is possible to pick body wave time arrivals and process the travel times to infer a 3D seismic velocity model of the subsurface. Such an approach, sometimes called "Earthquake tomography", requires specific processing methodologies such as joint inversion of the seismic events hypocenters and of the subsurface velocity model, for in that case the location of the seismic source (the earthquake) is also an unknown parameter.

Muksin et al. (2013) performed such an earthquake tomography to characterize the seismic properties of the Tarutung geothermal area, in Indonesia. Their method included simultaneous inversion of micro-earthquake locations and 1D velocity models, followed by a 3D tomographic inversion. The resulting 3D Vp model helped them to accurately delineate the structure of the Tarutung and Sarulla basin, identifying complex zones, and orientation of fault areas, as illustrated in Figure 6.9a). They also derived a Vp/Vs ratio 3D model in which high Vp/Vs values anomalies are potentially related to a configuration of fluid bearing sediments associated with fracturing, such context suggesting favorable conditions for geothermal exploitation (Figure 6.9b).

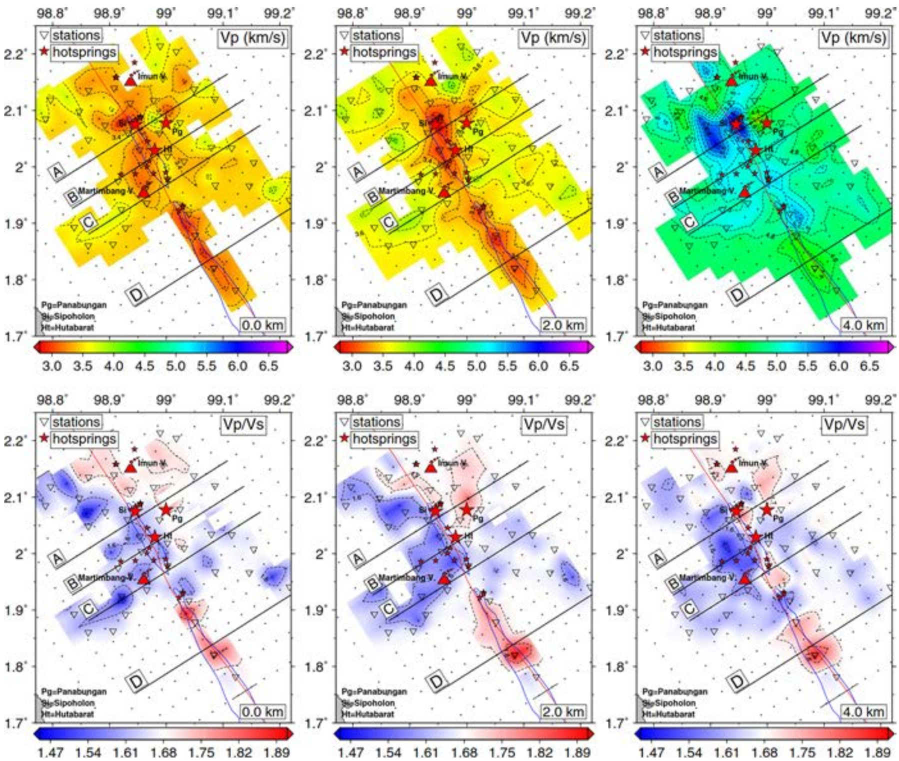

Figure 6.9 *Modified after Muksin et al. (2013). Horizontal slices of the Vp and Vp/Vs 3D models at depth of 0, 2, and 6 km for Vp in (a), (b), and (c), and for Vp/Vs in (d), (e), and (f).*

Vp/Vs ratio measurements designate the analysis of the velocity ratio of the P (compression) and S (shear) body waves. It allows a qualitative interpretation of the subsurface elastic properties, and has proven a useful approach in seismic geothermal exploration as Vp/Vs anomalic values have been able to identify different geothermal favorable contexts. For instance, as discussed, Muksin et al. (2013) identified fluid-bearing sediments through high Vp/Vs anomalies, whereas Simiyu (2009) identify and delineate the heat source of the Menengai caldeira in Kenya as a low Vp/Vs anomaly (Figure 6.10). In geothermal context, low Vp/Vs values are usually associated with a local decrease of P-wave velocity due to low pore pressure, high heat flow, fracture systems and vapor/gas saturation presence in the surveyed area (Pérez and Cuellar, 2018).

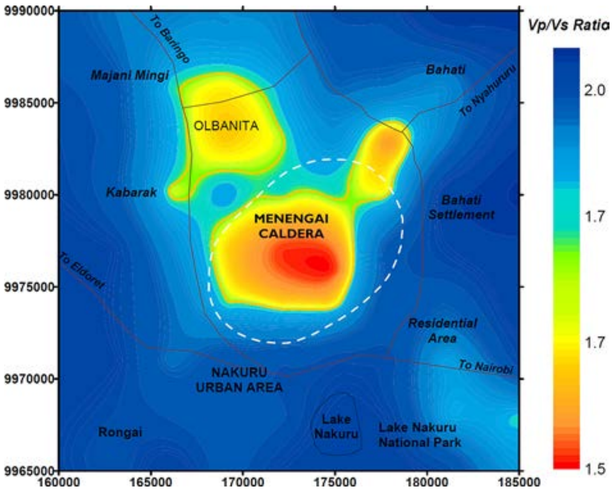

Figure 6.10 *Modified after Simiyu (2009). Vp/Vs ratio map extracted from a 3D tomography at the Menengai geothermal area. The low value anomaly correlated with the expected location of the heat source at this geothermal site.*

Attenuation models

In the context of geothermal exploration, the two key resources to identify are heat and fluid. Attenuation anomalies have been shown to highlight such favorable targets. Sato et al. (1989) and Mavko (1980) propose that an increase of seismic attenuation properties can be related to an increasing temperature. Hough et al. (1999) interpret a pseudo mapping of the thermal distribution by imaging the variability of attenuation structure in Coso geothermal reservoir. This behavior of dependence between attenuation and temperature of geothermal rocks at reservoir conditions as been highlighted by Jaya et al. (2010) and Poletto et al. (2018) with a petrophysical approach using Biot-Gassmann relation.

On the other hand, Haberland et al. (2009) associate attenuation increasing to an augmentation of the fluid content. For Grab et al. (2017) velocity structures reflect lithology while attenuation is a better indicator for reservoir permeability and fluid saturation in magmatic geothermal reservoir. Hudson et al. (2023) use attenuation tomography to map crustal fluid pathways and hydrothermal/geothermal systems in volcanic context. Attenuation imaging method can also provide complementary information to the traditional approaches used in geothermal exploration. In volcanic context, Muskin et al. (2013) demonstrate that regions of high attenuation and high conductivity are related to high fluid content.

Multiple studies have also proven anelastic properties to be a good indicator of the presence of magma or melting materials, which tend to significantly dissipate seismic energy during wave propagation. This correlation has typically been documented in studies investigating mantle properties and characteristics (e.g. Karato, 2004; Nakajima, et al. 2013).

However, as mentioned previously, evaluating intrinsic attenuation properties of the subsurface through seismic events analysis is not an easy task, for it requires to discard or correct for other seismic attenuation mechanisms which are rather related to the propagation path of the seismic waves such as geometrical spreading and multipathing (Ko et al., 2012).

Lin et al. (2024) present a recent study of attenuation structures in the northern Taïwan volcanic zone where they explore the attenuation features of the area and their relation to the local magmatic and tectonic mechanisms.

The authors collected seismic waveforms from 43 earthquakes using a seismic array of 118 stations, for a period of about 1 year, and isolated the P-waves and S-waves arrivals. Their data analysis process begins with a 1D inversion to establish a baseline attenuation model, corrected using a frequency-dependent power law that adjusts for changes in attenuation across frequencies. This model initializes a 3D inversion, where amplitude data is standardized to a reference frequency (5 Hz) to ensure consistency across frequencies and Fréchet kernels were computed by 3D ray tracing through the tomographic velocity model. The inversion estimates differential inverse quality factors (Q^{-1}) perturbations, with prior covariances and smoothing ensuring model stability and resolution robustness. Ultimately, the authors manage to estimate 3D models of Qp and Qs (quality factors) in the area.

The results of this analysis for geothermal exploration are the potential identification of hydrothermal activities and magma reservoirs at varying depth, which are characterized by high attenuation values (low Q factors), as illustrated in Figure 6.11.

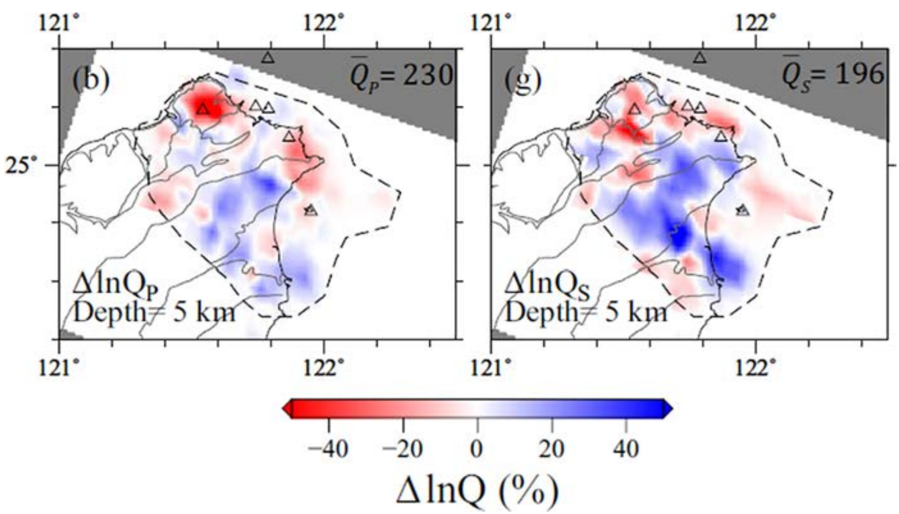

Figure 6.11 *Illustration of subsurface attenuation characterization based on seismological analysis (modified after Lin et al., 2024). The maps show lateral variation of attenuation values extracted from the global attenuation 3D model, focusing on a specific depth of 5 km.*

Another example of geothermal areas characterization through attenuation assessment can be found in the work by Antayhua-Vera (2017). Quality factors were computed using the coda of a collection of seismic events to derive coda attenuation (Qc) maps, at multiple frequencies (i.e. probing different depth of the medium). In their interpretation, the authors relate high Qc values (low attenuation) with area of high permeability (Figure 6.12).

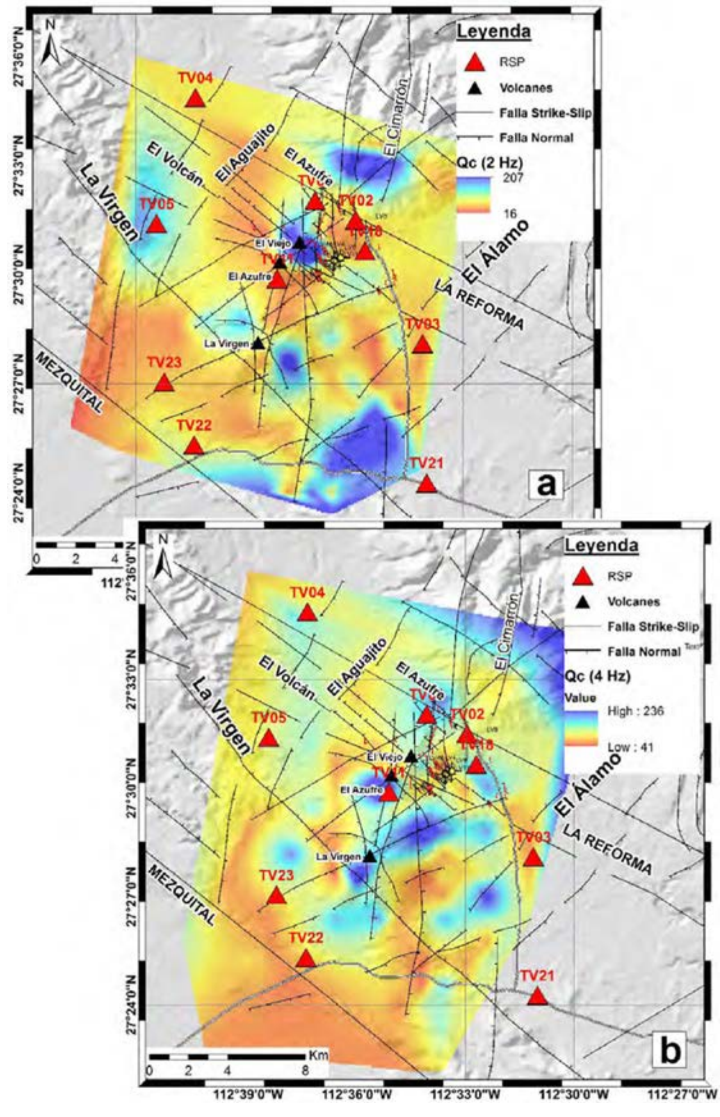

Figure 6.12 *Modified after Antayhua-Vera (2017). Iso-maps of coda quality factor (Qc) values at the geothermal field of Tres Virgenes, Mexico.*

As for Vp/Vs analysis, examining the quality factor ratio of P and S waves (Qp/Qs Ratio) can also inform on the specific features of the geothermal field. For instance, low Qp/Qs ratio (P-waves more attenuated than S-waves may indicate a medium partially saturated with fluids (Pérez and Cuellar, 2018). The presence magmatic bodies, on the contrary, would result in almost complete attenuation of the S-wave, hence high Qp/Qs ratio (Georgsson, 2009). Another interesting example is found in the work by Yeh et al. (2021), who used Qp/Qs analysis to investigate the subsurface context of the Taipei area in Taiwan. They observe low Qp/Qs values that they interpret a due to a dominance of scattering attenuation due to a highly fractured medium but denying the existence of a magmatic chamber, as was pointed out by an earlier study based on velocity analysis only (Lin, 2016), hence illustrating the interest of analyzing jointly both velocity and attenuation features to obtain a geological and geothermal assessment as complete as possible.

6.2.2 *Ambient noise seismic interferometry (ANSI)*

ANSI methods are another possibility to derive 3D models of the subsurface seismic properties. By opposition to earthquake-based velocity tomography, ANSI tools present the advantage of allowing data acquisition and producing results even in areas where earthquake activity is low, where tomography analysis based solely on detection of seismic events would not be possible. The geophysical value brought by ANSI studies (3D models of seismic properties), their flexibility for implementation in various contexts (passive sensors deployment over a few days or weeks), along with the economic advantage inherent to passive seismic studies has brought ANSI methods and particularly 3D Vs tomography technology as a nearly common geophysical tool in today's geothermal exploration strategies. Hence a several applications of ANSI-based tomography models are presented in the literature, addressing various geothermal contexts.

Toledo et al. (2022) investigated the potential of the method in the volcanic context. The authors derived a 3D Vs model at the Theistareykir geothermal field in Iceland, where a clear separation between a high Vs anomaly and a low Vs anomaly is observed, which follows a N/NW orientation (Figure 6.13). Such observation agrees with the trend and pattern observed through a Magnetotelluric investigation of the site, hence confirming the interest of ANSI based Vs models for geothermal characterization. Overall, low velocity anomalies coincide with bodies of low electrical resistivity, which would consistently suggest the presence of rocks saturated with hydrothermal fluids (Toledo et al., 2022)

Also in the volcanic context, Sánchez-Pastor et al. (2021) also observe a consistent correspondence between low electrical resistivity anomalies and low Vs anomalies at the Hengill geothermal field in Iceland. The authors also pushed their interpretation to identify iso-velocity curves as transition zones within the geothermal system, proposing the 2 km/s iso-velocity curve as being a proxy to the bottom of the steam cap and the 3 km/s iso-velocity curve as being the base of the stratification composing the Hengill volcanic system. Another illustration of 3D Vs tomography application for geothermal characterization of volcanic contexts can be found in Martins et al. (2020), where the authors identify a low-velocity cavity which is interpreted as an area of up-flowing fluids where temperature and permeability are enhanced.

Cheng et al. (2021) propose an ANSI tomographic application in a crustal fault context where hydrothermal fluids are known to reach the surface. They use relative spatial velocity variations observed in the area to infer the presence of faults (Figure 6.14) where hydrothermal fluids are expected to circulate. Their seismic analysis also shows good correspondence with resistivity models obtained with controlled sources audio-magnetotellurics (CSAMT) measurements, where low velocity anomalies correspond to low resistivity anomalies.

In a sedimentary context, Planès et al. (2020) used a 3D Vs tomography to improve their understanding of the geological context at the Greater Geneva basin. They manage to identify geological and topographical relationship and also interpret iso-velocity curves depth variation as a mean to identify the thickness of the sedimentary cover.

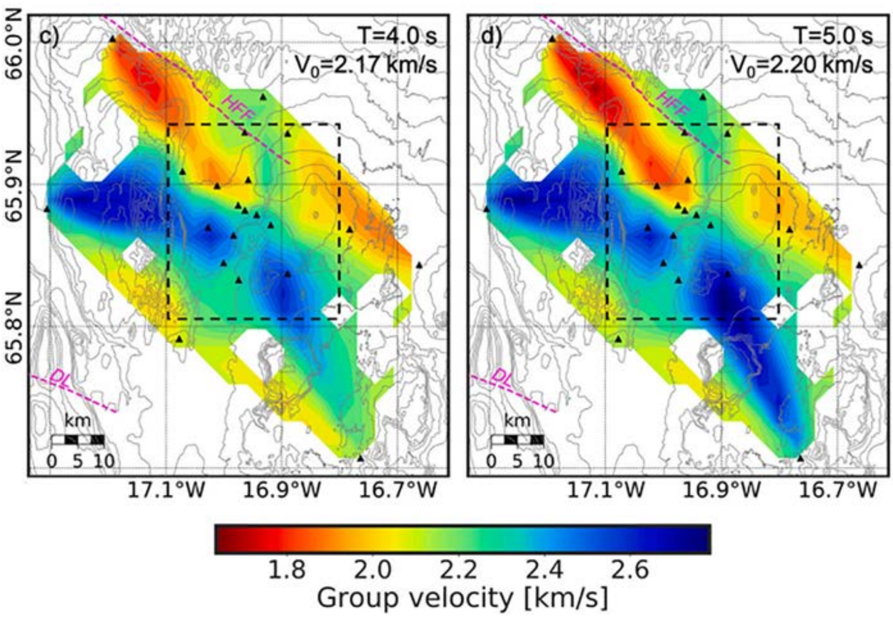

Figure 6.13 *Modified after Toledo et al. (2022). Rayleigh wave group velocity maps at two different frequencies.*

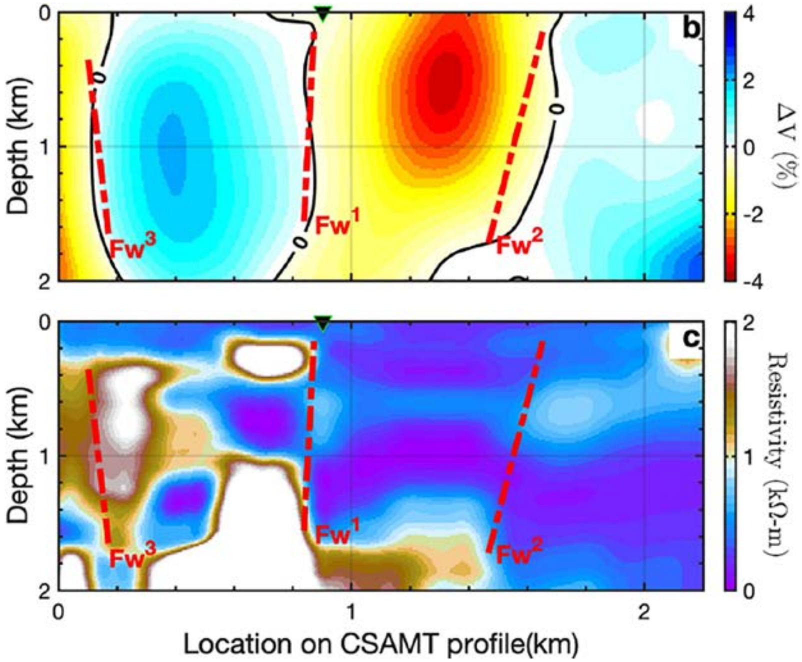

Figure 6.14 *Modified after Cheng et al. (2021). (Up) Spatial relative velocity variations section. (Down) Resistivity cross-section derived from CSAMT acquisition.*

Many other examples of ANSI based tomography application to geothermal systems characterization can be found in the literature. Overall ANSI-based 3D Vs tomography allows a better understanding of the geological context and features, identifying faults, delineating geological layers limits and highlighting geothermal systems key characteristics. Many authors point out that seismic information provided by ANSI tomography tools is consistent with information obtained through electrical or electromagnetic surveys, hence introducing the complementary role of passive seismic methods within geothermal exploration workflows, as discussed in the following paragraph.

6.2.3 *Integration into the geothermal exploration workflow*

Within geological exploration workflows, the role of geophysical methods is to provide data or models that inform on the subsurface response to the solicitation by a given physical field (e.g. electromagnetic, electrical, seismic, magnetic, gravimetric). Energy is propagated within the medium and the propagation modes and characteristics inform on the physical properties of the rocks associated with those physical fields (e.g. resistivity, velocity, attenuation).

As in many geophysical exploration strategies, it is rarely one method that brings in the open useful information, but rather a multi-physics approach where complementary data and models are compared or even inferred simultaneously, so that different information converge toward the most logical interpretation.

From that perspective, passive seismic methods are a relevant tool within the geothermal exploration toolbox. In general, the most utilized strategies to detect and characterize geothermal targets are based on electromagnetic methods (Muñoz, 2014) as geothermal reservoirs display clear conductive signature. Nevertheless, seismic properties can also highlight similar geological features (Toledo et al., 2022) driven by the presence of water- filled fractures which tend to decrease seismic velocity and increase seismic attenuation. Joint interpretation of passive seismic with other geophysical methods is usually highly valuable. Several approaches can be adopted, we provide below a non-exhaustive list of those methodologies along with a few literature examples:

- <u>Workflow integration</u>: Exploration workflows can benefit from dedicated multi-physics workflow such as "Play and Fairway analysis" (Craig et al., 2021) where ANSI-based Vs tomography brings insight on the elastic structures of the investigated area allowing to characterize complex geothermal context.
- <u>Statistical integration</u>: Models obtained from multiphysics imaging methods are always the resulting complex combination of geophysical responses of the heterogeneous subsurface (e.g. faults, layers, fluids, petrophysics, lithology etc.). Statistical integration approaches aim to highlight and isolate specific geological targets that can affect differently the geophysical responses of various geophysical methods (e.g. Ars et al., 2024; Muñoz et al., 2010; Bauer et al., 2012).
- <u>Constrained inversion</u>: Going beyond the "simple" co-interpretation of Vs velocity models in parallel to other geophysical models, one can also use a constrained inversion approach where ambient noise tomography is proceeded under the constrain of a 3D resolved pre-obtained model describing the distribution of other physical parameters such as resistivity (Ars et al., 2024).
- <u>Joint inversion</u>: In this case, the geophysical inversion process itself is parametrized to find the best fitting models under the constraint of a given relationship coupling the physical model properties. A typical example in geothermal exploration context of such an approach is the joint inversion of ANSI-based surface wave dataset with gravimetric dataset. Both physical fields are sensitive to elastic properties of the underground, and the joint inversion process results in an improved resolution of both geophysical models (e.g. Carillo et al., 2024; Ars et al. 2024).
- <u>Perspectives</u>: So far, ANSI based tomography methods have been focused on deriving Vs models of the subsurface. However, recent developments have highlighted to possibility to also derive 3D seismic attenuation models from the ambient seismic signal (e.g. Soergel et al., 2020; Cabrera-Perez et al., 2024). Such evolution may lead to future co-processing of seismic and resistivity datasets for better imaging of attenuation and conductive structures, since they both exhibit high sensitivity to the presence of fluids.

6.3 Geothermal monitoring

Another crucial aspect of Geothermal energy large-scale deployment is the surveillance of the subsurface environment during operations to ensure performance and conformance. 4D active seismic survey cannot fulfill this objective, again due to their prohibitive deployment cost, in addition to complex logistics for repeated onshore deployment. Yet again, passive seismic methods can be deployed to enhance our capacities for monitoring the evolution of Geothermal assets and their seismic properties, continuously and cost-effectively. Just like for exploration purposes, in this paper we distinguish two "families" of passive seismic methods that can be used for enhanced surveillance of geothermal fields. First, all the methods based on the analysis of impulsive seismic events, independently of their magnitude (from large earthquakes to micro-tremors), which we refer to as **Seismological analysis**. Second, the methods and analysis tools based on **Ambient Noise Seismic Interferometry (ANSI)**, where incoherent parts of the ambient seismic signal are analyzed and processed to extract coherent seismic wavefields, which can then be analyzed to infer the seismic properties (velocity, attenuation) of the subsurface.

6.3.1 *Seismological analysis monitoring*

Seismological analysis methods have been used to fulfill a variable number of objectives in the geothermal monitoring context. Possibly one of the most known functions of passive seismic monitoring is the detection and analysis of microseismic events to track for potential operation-induced seismicity and ensure that such seismicity remains in the range of expected epicenter locations and events magnitude. This constitutes a typical objective of passive seismic monitoring of Enhanced Geothermal Systems (EGS). This denomination designates geothermal contexts where fluid circulation is artificially stimulated through enhancement of the rock formation permeability by means of hydraulic stimulation technics. Locating and analyzing the microseismic events that are induced by the stimulation operations allows for operators to assess the effectiveness of the process in time, by following the extent of the resulting fracture network, analyze the effect and relationship of the operations with the local stress field, and ultimately avoid the triggering of undesired, large magnitude seismic events.

Statistical seismological analysis tools, such as b-value computation, can also be used as a monitoring tool, to fulfill various objectives. The possibility of monitoring water injection processes through b-value analysis within the reservoir has been illustrated by multiple authors, many of which can be found in the review from Pérez and Cuellar (2018). As an illustration for this chapter, we refer to the study of Antayhua-Vera et al. (2022) where the authors studied the spatio-temporal distribution of b-values at the geothermal field of Tres Virgenes in Mexico (Figure 6.15). Their observations report that increases of *b-value* are generally coincident sudden increases in water injection dynamics.

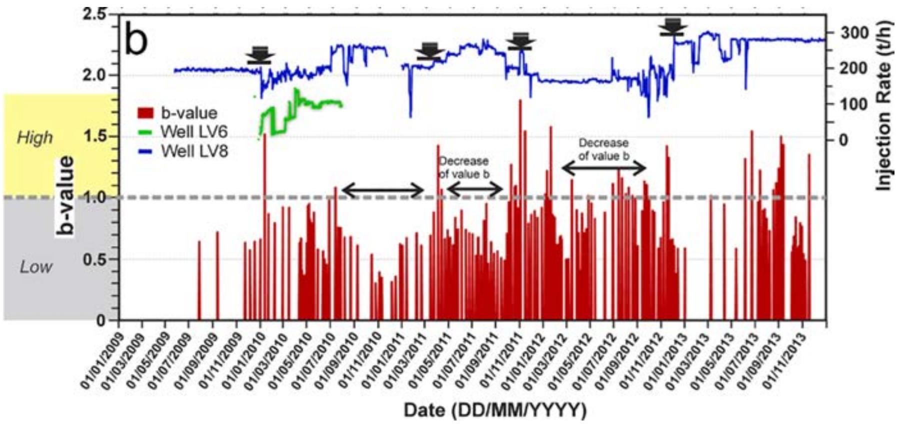

Figure 6.15 *Modified after Antayhua-Vera et al. (2022). Water injection rates comparison with b-values for a period of about 4 years at the Tres Virgenes geothermal field (vertical black arrows indicate sudden water injections).*

Another interesting report describing microseismic monitoring applications on geothermal sites can be found in Cruz-Noé et al. (2018). The authors report key observations following the 30 years duration monitoring of microseismicity of three Mexican geothermal fields, namely Los Azufres, Los Humeros and La Tres Virgenes. Multiple analysis are presented which relate to various interpretation and links to the geothermal field production activity itself, including fault reactivation due to modification of the local stress field, but also induced seismicity related to geothermal water injection and geothermal fluid extraction. They also report on the effects of drilling, hydraulic stimulations, and well testing on the micro seismic activity itself.

Beyond the analysis of microseismicity activity characteristics such as statistical distributions or source mechanism, information about geothermal assets evolution in time can also be obtained through the analysis of seismic properties, typically seismic velocity and seismic attenuation. A sound illustration of such analysis can be found in the work by Guo and Thurber (2022). The authors applied a time-lapse tomographic approach based on a double-difference workflow. They analyze a catalog of earthquakes and apply two different tomographic analysis to evaluate both the changes in P-wave velocity (DDV tomography) and P-wave attenuation (DDQ tomography), during a relatively long monitoring period (>5 years). Their work allows them to produce 4D models of velocity and attenuation parameters and to relate the observed variations to injection processes within the geothermal reservoir. An interesting diagram is available in the “Supporting information” document associated with their work (Figure 6.16), which depicts how P-wave attenuation (Qp) and velocity (Vp) are expected to vary depending on the on-going process induced by fluid injection within the geothermal system.

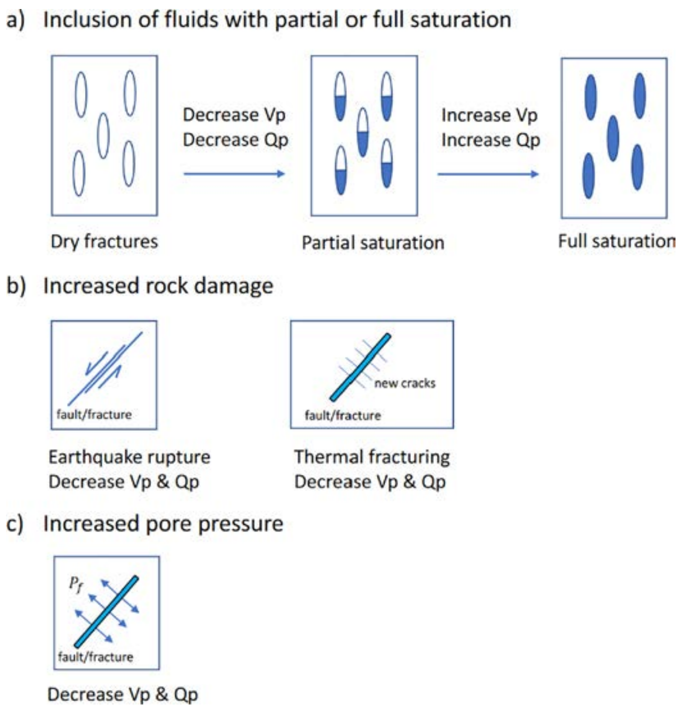

Figure 6.16 *Schematic illustration of different injection-induced processes occurring in geothermal reservoir and their associated seismic response in terms of P-wave seismic velocity and attenuation. Modified after Guo and Thurber (2022) – Supporting information.*

6.3.2 *Ambient noise seismic interferometry monitoring*

ANSI-based methods have been gaining momentum during the last two decades as relevant tools for seismic monitoring of the subsurface. ANSI-based monitoring approaches are often referred to as the dv/v method, since it consists of tracking velocity changes by comparing ANSI-based reconstruction waveforms in time through phase-shifts measurements. Such an approach has the potential to detect very subtle shear wave velocity changes (when dealing with surface wave), possibly on the order of 0.1% and lower depending on the site conditions. Geophysicists have demonstrated the sensitivity of the method to various phenomena such as precipitation, atmospheric pressure loading, thermoelastic stresses, ground water change, stress relaxation and others. Applications to geothermal monitoring have not yet been very numerous, but edifying studies yet exist that highlight the strong potential of ANSI for geothermal operations surveillance.

For instance, Muñoz-Burbano et al. (2024) have been monitoring seismic velocities using ANSI approaches at the Domo de San Pedro Geothermal field, in Mexico, using a seismic array of 20 broadband stations. The authors have been able to reconstruct velocity relative variations maps sequentially in time and to relate significant velocity changes to fluid injection dynamics and to the associated stress distribution.

In addition to this study, Taira et al. (2018) demonstrate that detailed analysis of velocity variations may describe the temporal evolution (5 years) of the Salton Sea geothermal field stress state. Figure 6.17 presents time-lapse measurements of seismic velocity variations in several frequency ranges that were computed as the average of the 9 components of the Green's tensor. The events marked as DBC, EMC and BS represent sudden drops in the seismic velocity and are related to some local earthquakes. Taira et al. (2018) show that the amplitudes of those drops are too great to be linked solely to the earthquakes for the BS event and suggest that the sudden evolution in the velocity variation time series is linked to an aseismic deformation related to fracture opening. In addition, a long-term upward trend (0.25% in the range 0.5–2 Hz) can be observed in all frequency bands. The authors propose that this long-term trends relate to a progressive poro-elastic contraction linked to geothermal production and the associated evolution of the stress field within the reservoir.

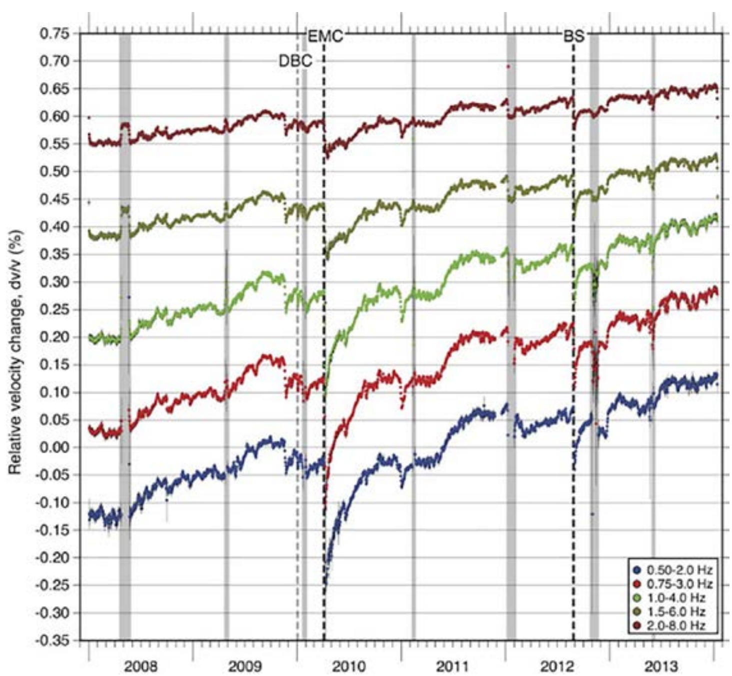

Figure 6.17 *Modified after Taira et al. (2018). Relative velocity variations time-series computed for several frequency ranges. Dashed black lines indicates sudden drops of seismic velocity, partly related to earthquake events and to deformation processes.*

Another edifying study is the work by Sanchez-Pastor et al. (2021), who present an ANSI based method to monitor the Hengill geothermal field (Iceland). This site presents a challenge inherent to geothermal systems operations which is to probe the steam fluctuation inside the reservoir. During geothermal exploitation, the estimation of the steam content is key from both operational and economical perspectives. To quantify these quantities, the authors used an array of 50 stations and compute auto-correlation (ACs) on the vertical component. The nuance of the velocity variation measurement on ACs compared to cross-correlation between two sensors is essentially that the reconstructed wavefield in ACs will be much more sensitive to volume waves, and mainly to P waves. This means that the velocity variation measurement will be correlated with the fluid content, and not anti-correlated as is classically observed in studies targeting ground water table using surface wave (for example). The velocity variations measurements obtained on the ACs are compared with some rock physics model including hydrological and gas saturation information.

The results of the various modelling work performed by the authors and the final comparison with the observations is shown in Figure 6.18. The subfigure (a) presents the pressure and temperature variation, the subfigure (b) the estimated steam cap evolution, the subfigure (c) the modelized Vp and Vs evolution over the monitoring time. Finally, the subfigure (d) shows the monitored dv/v versus the subsidence of the geothermal field. The author demonstrates than the seismic velocity values are decreasing over the monitoring time, when the steam ratio continues to rise which is consistent with the expected variation in Vp as water content decreases. This study highlights the economic possibilities to monitor the steam evolution during long periods with a low-cost method associated with robust modelling.

The examples previously presented demonstrate than the measure of seismic velocities through ANSI-based approaches is feasible and is a useful tool to monitor changes in the state of stress in geothermal reservoirs (Taira et al., 2018; Muñoz-Burbano et al., 2024) or changes of fluid distribution (Sanchez-Pastor et al., 2021).

Nevertheless, as for ANSI-based tomography, ANSI-based monitoring techniques also start evolving toward the study of other seismic attributes than seismic velocity. The work by Obermann et al. (2015) is an example of such evolution. The authors propose to survey the geothermal reservoir using another attribute called the decoherence of the reconstructed waveforms. Initially the decoherence is an indicator of the quality of the reconstructed signal between a reference waveform (e.g. at the beginning of the monitoring period) and each waveform reconstructed at a later time and on first order is affected by site-dependent noise conditions that change too abruptly. In the study by Obermann et al. (2015) though, a strong decoherence is observed that seems associated with a gas kick event which led to the failure of the St Gallen deep geothermal project. Figure 6.19 illustrates the evolution of decoherency time-series for multiple station pairs. For all the seismic stations pairs crossing the reservoir, a strong decoherence is observed between the 10th of July and the 14th of August, which period correlates with the injection procedure inside the geothermal reservoir that led to the gas kick (Figure 6.19a). Figure 6.19b shows that for the pairs not crossing the reservoir this decoherence drop is not observed.

The authors argue that the decoherence drop can also be the result of changes in the scattering properties of the subsurface (e.g. Larose et al., 2010; Obermann et al., 2013, 2014; Planès et al., 2014), which in the St Gallen case may be associated to geothermal induced processes such as pore pressure changes related to gas release, critical prestressing of a fault, or changes in attenuation properties also due to the presence of gas.

Although the physical interpretation of the decoherence variation is not clear, this study highlights the fact that other seismic attributes possibly more sensitive to some physical phenomena can also be derived from ANSI based monitoring analysis and that a strong potential also exists in the development of such novel approaches. In particular, the focus on attenuation properties monitoring is a promising research lead since attenuation is particularly sensitive to the temperature field and the nature and distribution of fluids within the subsurface, which are both key aspects of geothermal surveillance strategies. In the end, deriving attenuation properties will allow to provide the full seismic response of the geothermal system, in space, and in time.

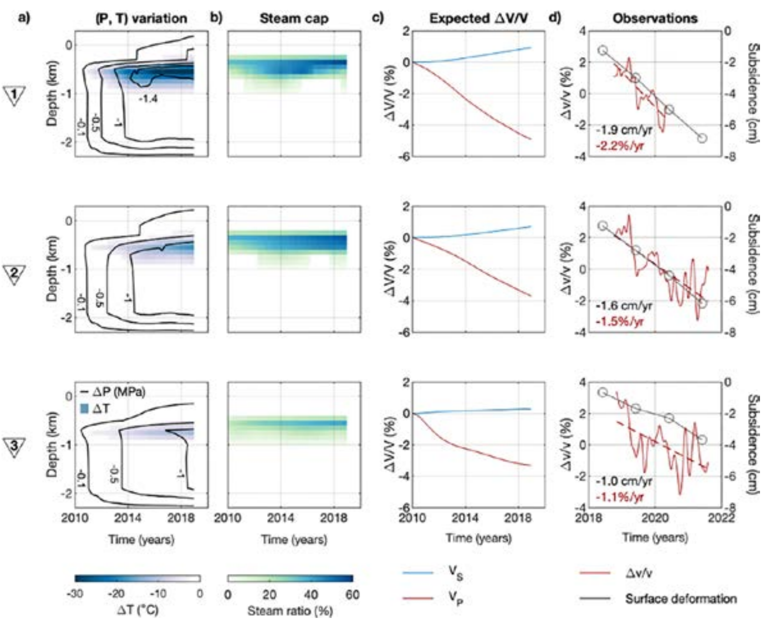

Figure 6.18	*Modified after Sanchez-Pastor et al. (2021). Each line highlights a different seismic station. (a) Modelisation of the temperature variation in the medium, (b) Estimated steam evolution (c) Vp and Vs computed from rock physics modelisation (d) Monitored dv/v and monitored subsidence.*

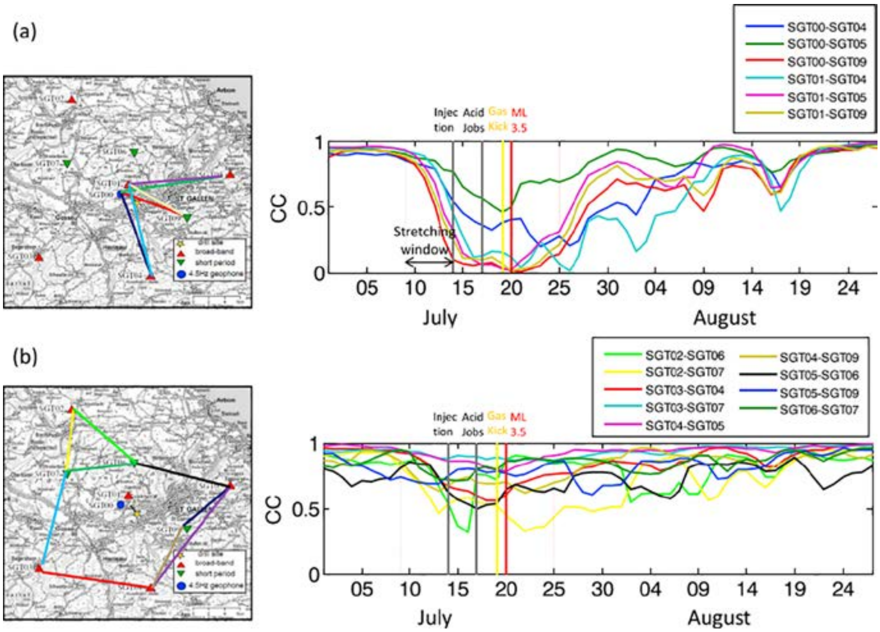

Figure 6.19 *Modified after Obermann et al. (2015). Decoherence time series measured for multiple seismic station pairs at the St Gallen geothermal field. (a) Pairs crossing the reservoir. (b) Pairs not crossing the reservoir. Colored vertical lines indicate different phases in the geothermal operations sequence leading to the gas kick.*

Concluding remarks

Passive seismic methods have been able to emerge in the geophysicist toolbox mainly thanks to the evolution of seismic acquisition technologies, which finally allowed for continuous recordings and storage of the ambient seismic signal instead of simple “triggered” recordings. This major change ultimately allowed scientists to investigate and develop a large scope of tools and methods using a passive seismic approach bringing value for many geoscience fields including geothermal characterization and monitoring. Today, enhancing the potential of passive seismic methods still depends on, and will benefit from technological advances in the acquisition process. Typical key characteristics that are being proposed in recently produced seismic sensors or in phase of implementation for future models are:

- **Autonomy**, with longer lasting batteries for autonomous nodes in the context of monitoring.
- **Real-time communication** of the data, to avoid multiple intervention on site to retrieve the data and allow quasi-continuous monitoring.

- **Low frequency sensitivity:** to allow for detection and analysis of low frequency waves, a key parameter for instance to analyze interface waves while requiring a high penetration depth (in ANSI-based approaches for instance).
- **Cost:** to allow for dense networks deployment, hence improving the accuracy of earthquake-based seismological analysis and enhancing the resolution of the seismic models derived either from ANSI methods or earthquake tomography approaches.

All those improvements will participate in further highlighting the very strong potential of passive seismic methods to serve as key methods in geothermal exploration and monitoring geophysical strategies.

Passive seismic methods are the most cost-effective way to provide information about the subsurface seismic properties. In geothermal contexts, geophysicists typically track velocity and attenuation anomalies to infer the presence of faults, heat sources, hydrothermal fluid circulation patterns, and address the general geological and tectonic context. In addition to the intrinsic value of such passive seismic characterization strategies, they can also be used to improve the accuracy of the global geophysical approach by completing other geophysical datasets and enhancing their interpretation. Further developments and applications of joint or constrained inversion schemes will likely be a cornerstone of passive seismic methods integration in geophysical assessments in geothermal contexts, as in many other geo-resource explorations (e.g. natural H_2, helium).

Monitoring strategies for geothermal operations surveillance have naturally benefitted from passive seismic methods thanks to the intrinsic continuity of the data acquisition. The most known application is microseismic monitoring, which aims to track in time and space the seismicity potentially induced by geothermal operations. In addition, methods based on monitoring the subsurface seismic properties – not only the seismic activity – have been gaining momentum in the last few years to better understand the geothermal target behavior in production phase. Methods such as time-lapse earthquake tomography and ambient seismic noise interferometry (ANSI) provide such capacities, yet developments and applications to multiple different contexts are required to improve their sensitivity to operations-induced processes and hence propagate their use as common tools in geophysical geothermal monitoring strategies.

The strength of passive seismic methods relies on the fact that they have been built while searching for the tiniest, hidden bit of information within a seismic signal that is initially not well understood, globally uncontrolled, yet continuously produced by our environment. The dedication of scientists for exploiting and enhancing the information contained in what originally appeared to be a disturbance for active seismic studies is remarkable. As of this day, and as is illustrated within this chapter, geophysicists have now the possibility to extract spatial and temporal seismic information from the whole ambient seismic signal, including both the coherent part of the signals (through earthquake and microseismic analysis) and the incoherent part of the signal (through ANSI approaches in particular). They have turned the ambient seismic signal into a highly valuable source of information from which every part can be exploited. This chapter illustrates the diversity and complementarity of the passive seismic methods which provide many means of obtaining subsurface information while all relying on the recording of the same input data that is the ambient seismic signal. It is the view of the authors that geothermal exploration and surveillance – as many other geoscience fields – can, and will benefit from full passive seismic implementation, where the multi-purposing of passive seismic networks to integrate multiple approaches is key to a complete seismic assessment of geothermal assets.

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