

Michoacán Seismic and Tremor (MIST) Network: Perspectives, preliminary results and future directions to understand the role of the Cocos plate and the monogenetic volcanism

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Abstract

The Michoacan Seismic and Tremor (MIST) network is a follow-up project of the Middle America Subduction Experiment (MASE) and the Veracruz-Oaxaca Network (VEOX). These former experiments consisted of linear arrays perpendicular to the trench that generated large waveform datasets to characterize the subduction of the Cocos plate better. While the MASE array focused mainly on the flat segment of the subduction zone in the state of Guerrero, Mexico the VEOX array examined the changes in geometry towards a steep subduction in the Tehuantepec Isthmus. The MIST network is being deployed in Michoacan state in western Mexico in an area where volcanic and seismic processes coexist. Besides the joint goal of characterizing the shape and rheology of the subducting slab, the MIST array will also explore the seismic swarms likely due to the magmatic process that forms the monogenetic Michoacan-Guanajuato volcanic field. Here, we review previous studies to gain an understanding of the subduction of the Cocos plate, as well as the current knowledge regarding seismic and volcanic activity. Additionally, we present the results of applying H/V directional ratios at low frequencies and how they may be used to infer the dip and strike of the subducting slab. We also report tremor detections along the array and what the relationship with both the subduction process and volcanic processes might be. Finally, we discuss our plans to expand the network and how we may continue to develop further analysis.

Resumen

La Red Sísmica y de Tremores de Michoacán (MIST, por sus siglas en inglés) es un experimento que da continuidad a las redes sísmicas temporales MASE (Middle America Subduction Experiment) y VEOX (Veracruz-Oaxaca). Estos dos experimentos consistieron en arreglos lineales de estaciones sísmicas de banda ancha perpendiculares a la trinchera con el fin de obtener extensos registros de formas de onda para caracterizar la subducción de la placa de Cocos. Mientras MASE se enfocó en el segmento plano de la zona de subducción en el estado de Guerrero, México, VEOX se enfocó en determinar la geometría de la placa inclinada en el Istmo de Tehuantepec. En este trabajo presentamos la red MIST que está siendo desplegada en el occidente de Michoacán, un área donde convergen procesos sísmicos y volcánicos. Estas tres redes tienen como objetivo conjunto caracterizar la geometría y reología de la placa en subducción, así como analizar los enjambres sísmicos asociados a los procesos magmáticos que originan el campo volcánico monogenético Michoacán-Guanajuato. En este trabajo se muestran los resultados de aplicar la técnica del cociente espectral entre las componentes horizontales y la vertical (HVSr) y su comportamiento direccional en bajas frecuencias para determinar si es posible inferir rumbo y buzamiento de la placa, además de la detección y análisis de tremores a lo largo del transecto, con énfasis en su relación con procesos volcanotectónicos. Por último, se delinean las perspectivas de expansión de la red y los análisis futuros orientados a integrar la dinámica tectónica de la región.

1. Introduction

The state of Michoacán in Mexico is well known for being the birthplace of the Parícutín volcano one of the youngest monogenetic volcanoes of the world, the Parícutín volcano

(Luhr and Simkin, 1993). Its coastal Pacific area is widely recognized as the epicenter of the $M_s=8.1$ 19 September 1985, Michoacan earthquake, the most catastrophic and deadliest seismic event in Mexico, until now (Beck and Hall, 1986; Esteva 1988; Campillo et al., 1989). Despite holding large hazards (Sawires et al., 2021 and 2023), fewer studies and seismotectonic experiments have been carried out here compared to other Mexican states along the Middle America Trench (MAT). In the past, large instrumentation extensive arrays were deployed in other states, such as Jalisco, Colima, Michoacán, Guerrero and Oaxaca. Between 2006 and 2007, with the objective of studying the Rivera plate subduction, the transition to the Cocos plate subduction, and the Jalisco Block, an array of 50 seismic stations was deployed in Jalisco, Colima, and western Michoacán, called the Mapping the Rivera Subduction Zone (MARS) array. To the Southeast, perhaps the most widely studied area in Mexico is the state of Guerrero which has been instrumented geodetically and seismically, both onshore and offshore. Between 2005 and 2007, a large seismic array consisting of 100 seismic stations provided a high-resolution seismic dataset. The so-called Middle America Subduction Experiment (MASE array) was deployed in a linear array perpendicular to the coast (Husker et al., 2008; Pérez-Campos et al., 2008), see Figure 1. The main goal of this experiment was to collect a large waveform dataset to finely image the geometry, rheology and tectonic history of the subducting Cocos plate. Additionally, a novel amphibious network deployed offshore the Guerrero coast (Cruz-Atienza et al., 2018a) provided the first seismic and geodetic observations of the near-trench seismicity and deformation (Chen et al., 2025; Cruz-Atienza et al., 2021, 2025; Plata-Martinez et al., 2021). A complementary experiment was deployed further east in the states of Oaxaca and Veracruz, called VEOX (Melgar et al.,

2011). This experiment examined the changes in geometry that produce drastic changes in the distribution of seismicity and the formation of volcanic field area ~385 km away from the trench (Espíndola et al., 2016; Nelson et al., 1995). Through these experiments, new insights about the past tectonic configuration of central and southeastern Mexico and their relationship with modern structures were established. However, there are still several issues that need to be understood such as the precise location and extension of seismic anomalies related to fluids and partial melt, and the accurate location of the slab interface and its mineralogy.

In this study, we present a new deployment of seismic station in the state of Michoacán, aimed at generating a dataset to map the geometry of the subducting slab at the western flank of the flat segment of the Cocos plate. The western flank is geotectonically relevant due to the presence of the Michoacán-Guanajuato Volcanic Field (MGVF) that produces episodic seismic swarms, active volcanism and large subduction earthquakes. The Michoacan Seismic and Tremor (MIST) network was strategically set up to complete a long-term effort to investigate the subducting slab further.

In this contribution, we present the MIST network as a new observational framework to investigate a key unresolved problem in western Mexico: the link between slab geometry, crustal magmatic transfer, tremor-like seismic signals, and monogenetic volcanism in Michoacán. Specifically, we explore whether the first observations from the MIST array are consistent with: (1) along-strike changes in the geometry of the Cocos slab, (2) tremor-like signals associated either with slow slip or magma migration, and (3) the spatial relationship between active seismic swarms and the most hazardous sector of the Michoacán-Guanajuato Volcanic Field. This paper is therefore conceived as a

preliminary-results and network report that establishes the scientific basis for future high-resolution studies.

2. Data and Instrumentation

In the first stage, ten seismic stations were deployed in a linear array roughly parallel to the MASE and VEOX networks, and nearly perpendicular to the strike of the MAT (see Figure 1). Furthermore, the layout was mainly established so that MIST array would complement the set of previous observations to image the western flank of the flat subduction interface. At the beginning of the project, three strong motion sensors and seven broadband stations were deployed starting in June 2023. Data availability and data gaps for each individual station are shown in Figure S1. The array layout was chosen to cover an area that had not been previously instrumented by other experiments in the region such as the Mapping Rivera Subduction (MARS) temporary array and the Servicio Sismológico Nacional (SSN, National Seismological Service) permanent network. The total length of the MIST network extends approximately 270km, from the coastal city of Playa Azul to the town of San Cristobal de Ayala at the Michoacan-Guanajuato border, with an average interstation distance of ca. 30 km. The SSN IGIG station is located along the strike of the array about 50 km north of the northernmost sensor of MIST, this station was used as part of the network to extend the array's length to 320 km. The first three stations (AZUL, TAHU, PARE) included novel low-noise Silicon Audio optical accelerometers with data cube digitizers. The rest of the array were equipped with five broadband sensors Reftek 130 sensors (BARA, TOME, HUIR, CONE), two Guralp 40T sensors (NARA, CRIS) and one Trillium Compact 120s sensor (PURU). All the originally

136 installed sensors were later replaced by Guralp 3T sensors previously used in the MASE
137 and VEOX experiments to collect broadband data for other studies such as receiver
138 functions and seismic anisotropy. In all cases, we collected seismic records of 100
139 samples per second and decimated them according to the needs of each analysis.

140 A partner array of four stations was deployed west of the MIST array in collaboration
141 among the United States Geological Survey (USGS), the Universidad Michoacana de
142 San Nicolas de Hidalgo (UMSNH), and the Centro Nacional para la Prevención de
143 Desastres (CENAPRED, National Center for Disaster Prevention). The Paricutín-
144 Tancítaro Monitoring Network (PT-VMN) started operations in May 2024 and consists of
145 four broadband 120 Trillium compact sensors located around the Tancítaro and Paricutín
146 volcanoes. In addition to the seismic sensors, each station is equipped with geodetic and
147 meteorological instrumentation. The distribution of this network is shown in the inset of
148 Figure 1.

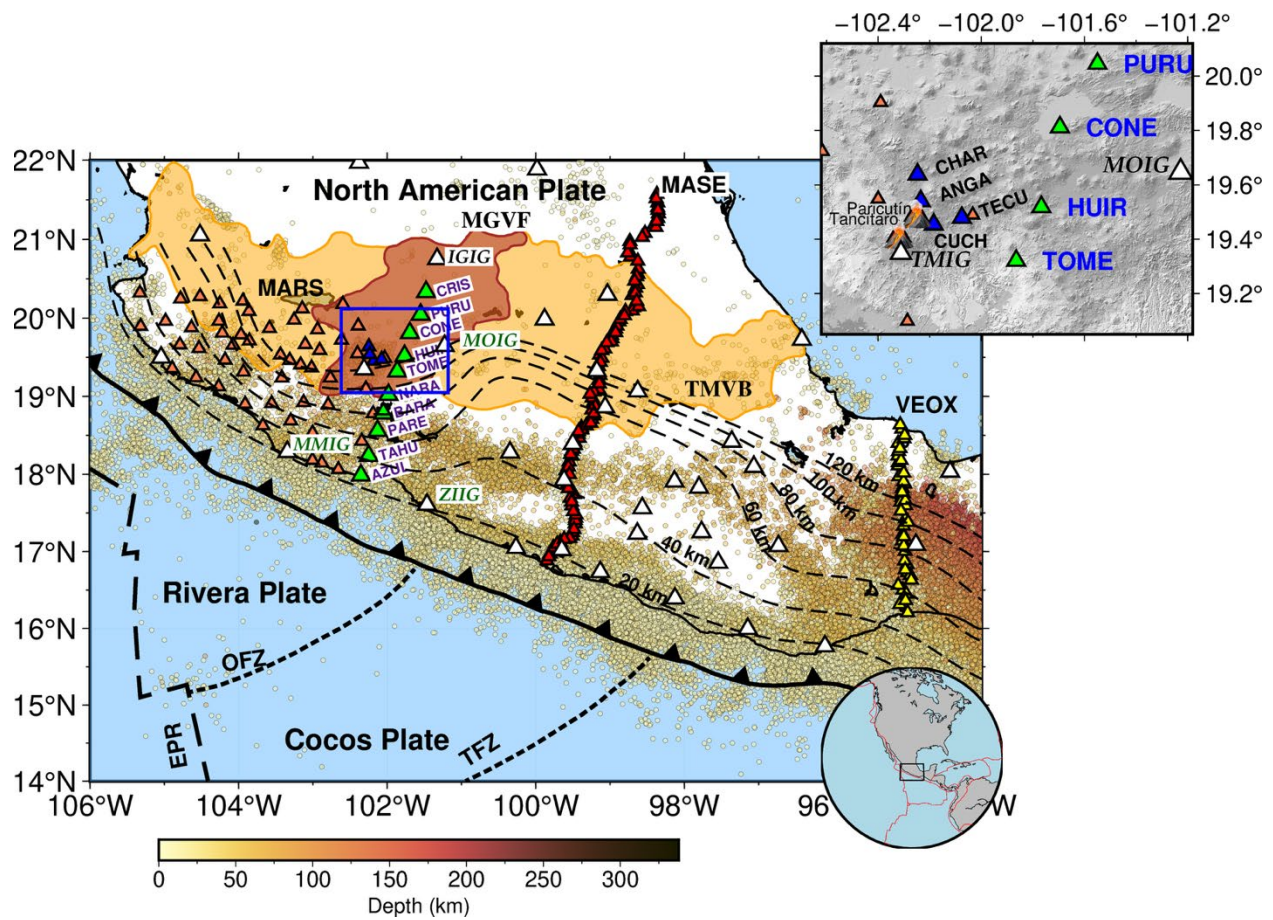


Figure 1. Map of stations of the MIST network and complementary arrays both temporary and permanent. The location of the MIST array is shown as green triangles and annotated with the four-character station codes. Circles color-coded by depth show the seismicity from 2000 to 2025 reported by the SSN (SSN 2025a). Orange triangles indicate the MARS (2006/01-2007/06) array. Location of the MASE array (2005/01-2007/05) and VEOX (2007/07-2009/03) arrays is shown with red and yellow triangles, respectively. Blue triangles indicate the location of Paricutín-Tancitaro Volcanic Monitoring Network (PT-VMN) (see upper inset). Broadband stations of the SSN (SSN, 2025b) are shown in white triangles; labeled stations correspond to those surrounding the MIST array. Orange and brown shaded area indicates the location of the Trans Mexican Volcanic Belt (TMVB) and

the Michoacán-Guanajuato volcanic field, respectively (Sosa-Ceballos et al., 2021). Blue square indicates the region in the top right inset. Rivera and Cocos plates boundaries are shown offshore. OFZ – Orozco Fracture Zone, TFZ – Tehuantepec Fracture Zone and EPR – East Pacific Rise. Dashed lines show the iso-contours of the subducting slab (Hayes et al., 2018). Lower inset shows the global location.

3. Subducted plate geometry in the state of Michoacán.

An ongoing question to solve in the Michoacán state is: What are the factors that determine the shape of the subducting slab and the elements that produce changes in its shape. Both global and regional studies suggest that the geometry of the subduction slab suddenly changes in the Michoacán region. Hayes et al. (2018) presented a global study of all active subducting zones around the world including Mexico. This study presents a general overview of the area that agrees well with regional studies such as those by Gaite et al. (2012) and Spica et al. (2016). In the eastern flank of the subduction zone, in the state of Oaxaca, Dougherty and Clayton (2014), Castellanos et al. (2018), Caló (2021) and Celis et al. (2024a, 2024b) imaged the fragmentation of the Cocos plate. In this case, the change in the Cocos plate geometry is most likely due to the subduction of the Tehuantepec ridge due to differential plate motion rates and the age of the slab. This observation is consistent with the shear-wave splitting tomography obtained by Celis et al. (2024a), which suggested a toroidal mantle flow around the dipping segment of the Cocos plate. In the case of Michoacán, the location of the Orozco fracture zone may be a factor to consider as a possible fragmentation mechanism in the west side of the flat segment, Dougherty et al. (2012) proposed that the fracture zone acts as barrier for the ultra-low velocity zone and therefore eases the bending of the slab. Furthermore, the

younger and hotter slab suggests a more ductile regime that may explain the ductility of the subducting slab, in combination with a highly viscous mantle wedge as possible factors for the bending of the slab. The bending of the slab provides the thermochemical conditions needed for partial melting and the generation of monogenetic volcanism.

4. The Michoacán-Guanajuato Volcanic Field (MGVF)

The Michoacán state is characterized by two major geological provinces divided by the backarc basin called the Tepalcatepec depression (Garduño et al., 1999). In the South, the Sierra Madre del Sur is a thrust belt composed of volcanic sedimentary rocks. In the central and northern sectors, it stands the largest monogenetic volcanic field in the world which holds around ~1000 volcanoes (Hasenaka and Carmichael, 1985). It consists of a few stratovolcanoes, cinder cones, maars, lava flows and domes (Hasenaka, 1994). The magmatism in the MGVF started during Early Pliocene, ~5 Ma (Guilbaud et al., 2012) or ~6 Ma (Osorio-Ocampo et al., 2018) with intense activity during the Holocene (Macías and Arce, 2019), including nowadays. This field includes the youngest continental volcanoes in Mexico, Jorullo and Parícutin (Guilbaud et al., 2011; Luhr and Simkin 1993). One of the major landmarks in the Michoacán state is the Parícutin volcano. This monogenetic cone emerged in a cornfield on 20 February 1942; its eruptive process lasted nine years until 1952 (Foshang and Gonzalez, 1956). Nonetheless, the largest volcanic structure in the state is the Tancítaro andesitic-dacitic stratovolcano. This volcanic structure rises ~2,000 meters above the surrounding terrain, reaching a maximum height of 3,840 meters above sea level (Ownby et al., 2007). In the last 30 years, at least six seismic swarms have been reported around this area (1997, 1999, 2000, 2006, 2020 and 2021) (Caballero-Jiménez et al., 2024; Legrand et al., 2023;

Mendoza-Rosas et al., 2024; Pacheco et al., 1999). Analysis of the seismic records from an ad hoc network installed weeks before the 2021 seismic swarm revealed a possible migration of the magma chamber towards the surface (Legrand et al., 2023; Perton et al., 2024). Thus, a critical question to address is whether we can accurately forecast the emergence of a new volcano or the activation of the Tancítaro volcano. In the Parícutin–Tancítaro region, morpho-chronological analysis of cones using Average Erosion Index (AEI) and Voronoi tessellation indicates increasing rates of monogenetic volcanism over the last ~120 ka, with the highest probabilities located NE of Tancítaro, in strong agreement with the distribution of recent seismic swarms (Zarazúa et al., 2024).

Figure 2 shows the reported seismicity by the SSN (SSN 2025a) from 2019 to July 2025. On these plots, three distinct seismic swarms are observed and shown in shaded areas in red, blue and purple (see Figure 2d). The first swarm of this seismic sequence occurred in the first quarter of 2020 being the most active in terms of the reported number of earthquakes per day, with a peak of up to 150 earthquakes per day above a completeness magnitude of M3.6. This swarm was exhaustively studied by Perton et al. (2024). Using a local network these authors were able to identify nearly 100,000 earthquakes in two months with a successive reduction of the S-P time which suggested an upward migration of the seismicity. Earthquakes within this sequence have hypocentral depths mostly above 20km depth. A year later, a less energetic swarm reemerged at shallower depths, between 10 and 20 km (Legrand et al., 2023). The 2021 swarm lasted about 3 months; though it was less energetic than the previous one (see Figure 2a, b, d). Finally, a third swarm, longer and more energetic than the 2020 and 2021 swarms, occurred between 2022 and 2023. This swarm was located northwest of the former sequences. During the

activation of this swarm, a $M_w=4.6$ earthquake (2023/03/15) produced moderate damage in the nearby communities. Preliminary indicators of a new swarm began in late June 2025. Unlike previous crises, the swarm is being monitored by both the central segment of the MIST array (stations HUIR and TOME) and the Parícutín-Tancitaro Volcanic network. The analysis of this swarm is beyond the scope of this paper, but it will be addressed in subsequent works.

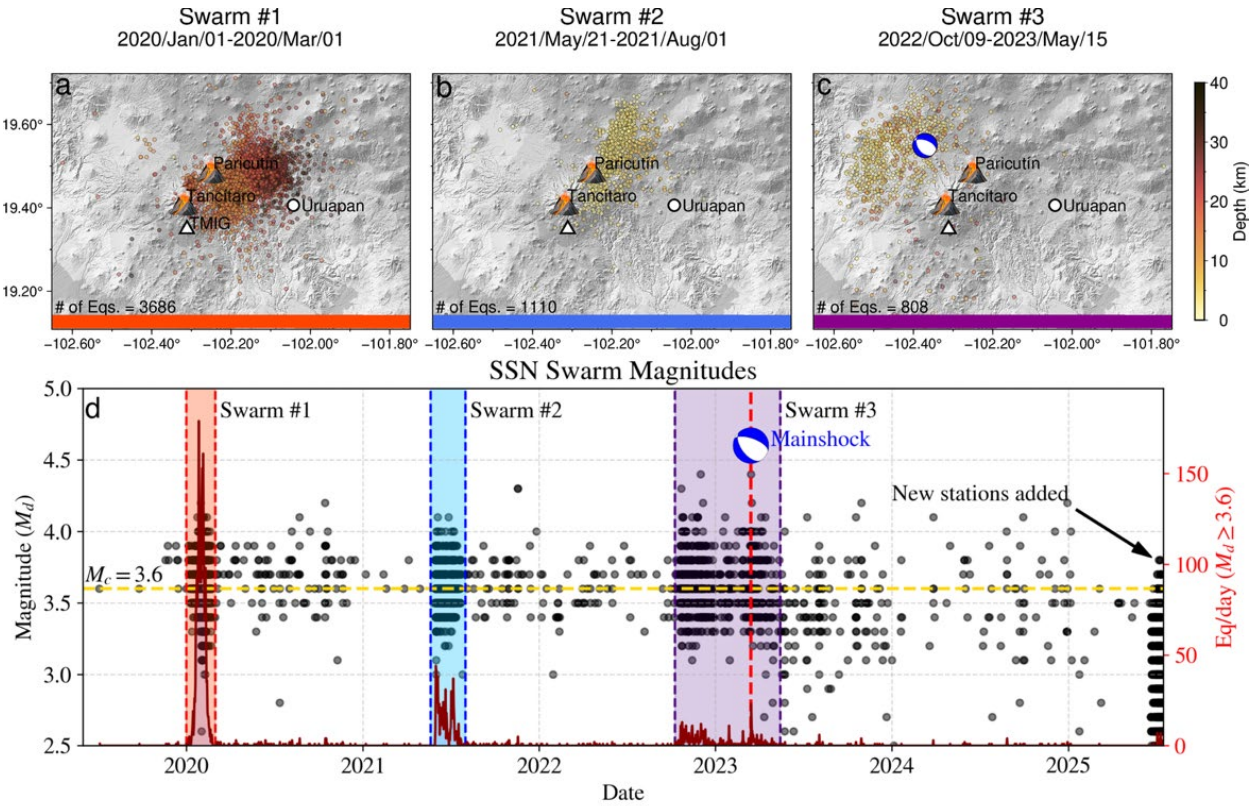


Figure 2. Reported seismicity from SSN from between January 2020 and July 2025/07. (a), (b) and (c) show map views of the earthquakes associated with three major seismic swarms. Earthquakes are color-coded by depth; the white triangle marks the location of the permanent SSN station TMIG, and the white circle indicates the location of the nearest major city, Uruapan. The colored bars at the bottom of each map (red, blue and purple)

corresponds to the time periods of the three swarm as shown in panel (d). Panel (d) shows the temporal variation and cumulative number of reported earthquakes. Circles represent reported earthquakes (SSN, 2025a), while the red line shows the number of earthquakes per day with magnitude $M_d \geq 3.6$ (horizontal yellow dashed line). The beachball shows the occurrence of the largest event ($M_w=4.6$) during the 2022-2023 seismic swarm. The focal mechanism was computed using the method described in Franco et al. (2020).

5. Tectonic tremors and volcanic signals

Tectonic tremors in Mexico are primarily documented in the state of Guerrero, in the so-called sweet spot, approximately 215 km from the trench (Cruz-Atienza et al., 2015 and 2018b; Husker et al., 2012; Payero et al., 2008; Maury et al., 2016; Villafuerte and Cruz-Atienza, 2017) and in small clusters near the trench along the Guerrero Seismic Gap (Chen et al., 2025; Plata-Martinez et al., 2021). Numerous studies have proposed a strong connection between the aseismic slip and tremor activation (Ghosh et al., 2009; Ito et al., 2007; Wech et al., 2007). In the east of Oaxaca both tremors and slow slip events (SSE) have been documented (Brudzinski et al., 2010; Cruz-Atienza et al., 2025b; Fasola et al., 2016) with a relatively short recurrence time of 1-2 years. An obvious question is whether tremors may occur in the state of Michoacán. If so, whether SSE events take place in this area or not. Brudzinski et al. (2016) reported the location of tremor and slow slip along an elongated band in the states of Colima and Jalisco. This study also reported some tremor activity, mainly in the western part of the Michoacán state. Until now, several studies targeting the detection of non-volcanic tremor agree that tremors are the result of aseismic slip of the plate interface between 40-60 kilometers (for

example, Ide, 2012; Maury et al., 2016; Husker et al., 2019; Villafuerte and Cruz-Atienza, 2017, Cruz-Atienza et al., 2026).

We performed a spectral analysis for all stations of the MIST network during the first year of data. The analysis targeted the identification of narrow, high-energy bands in the 1–10 Hz range of the spectrogram. This feature is commonly associated with tectonic tremor and, more specifically, with the slow aseismic slip of the plate (Beroza and Ide, 2011). Nonetheless, due to the complex tectonic setting and the existence of magma reservoirs, tremors may be associated with different phenomena. Figure 3 shows the map of stations and examples of possible tremor-like signals for two stations (NARA and BARA), as well as the time series for BARA station. The red rectangles in Figure 3a and 3b, indicate time windows where strips of energy in the 1-10Hz band resemble to those observed in the state of Guerrero. Around this area the slab upper interface is expected to be at 60 to 80 km. Therefore, two possibilities may explain the existence of these signals on this specific region. First, this area roughly connects the tremors reported by Brudzinski et al. (2016) and Maury et al. (2018) in the state of Jalisco and the western segment of the state of Michoacán and the tremor sources in Guerrero (e.g. Cruz-Atienza et al., 2015; Husker et al., 2012; Payero et al., 2008) in the flat segment of the slab. In this case, the activation of tremors would be an indicator of the existence of SSE at the interface, until now unreported. The second hypothesis suggests that these signals may be related to magma migration associated with disseminated reservoirs in the crust. Under this assumption, tremors will not be connected to aseismic slip on the plate interface, but rather to the gradual upwelling of partially molten rocks and fluids. However, due to the station spacing and the volcanic nature of the region, large uncertainties remain regarding the origin of

these signals. Consequently, it remains unclear whether the source of this activity is originated from magma migration or from aseismic slip processes. Based on present data, we favor the magma migration hypothesis for most of the tremor-like signals detected. The high dipping angle of the subducting slab in this region contrasts with the shallow angles in the Guerrero region where colder and pressurized fluid may favor aseismic slip at the interface as the main driving process for tremor radiation. If SSE does exist in Michoacán, the recurrence time interval is unknown, and it may be occurred at time intervals beyond the current observation window. If that is the case, the detection of SSE and tectonic tremors will be achieved once enough data is collected and GPS data becomes available.

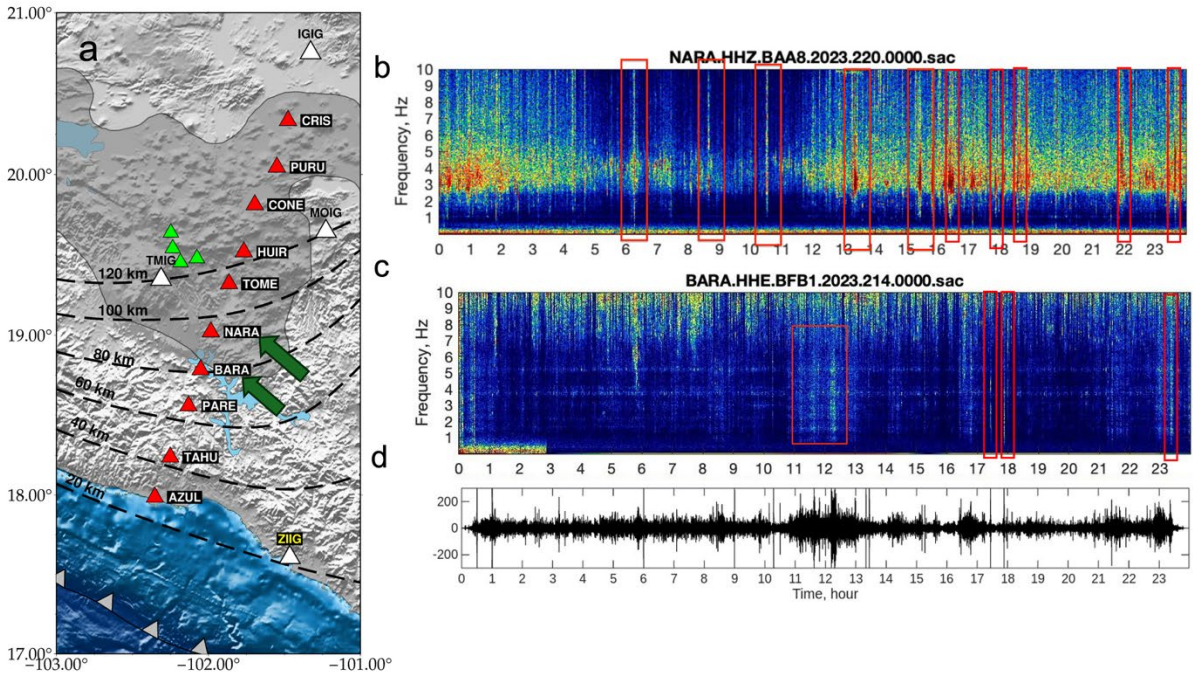


Figure 3. Location of the stations, spectral analysis and time series. (a) Map of stations including the MIST stations (red triangles), multiparameter volcano-monitoring network (green triangles), and the SSN (white triangles) stations. The arrows indicate the two

stations whose spectrograms are shown, NARA and BARA. (b) Spectrogram for the vertical component of station NARA (2 August 2023) and (c) spectrogram for east component of BARA station (7 August 2023). Red rectangles in (b) and (c) show possible tremors in the band of 1-10 Hz. (d) Original record at the BARA station bandpass filtered between 1-5Hz.

6. Directional HVSR analysis

The horizontal-to-vertical spectral ratio technique (HVSR) was first proposed by Nagoshi and Igarashi (1971) and popularized by Nakamura (1989). This technique is widely used to assess the seismic site response based on the ratio between the horizontal and vertical components. A broad range of applications has been proposed over the years, such as the analysis of the structure at archeological sites (Piña-Flores et al., 2021), volcanoes (Spica et al., 2015), and sedimentary basis (Pertou et al. 2020) among others. In controlled experiments, it has been shown that the HVSR has strong azimuthal dependency. For example, Matsushima et al. (2017) observed large differences in the HVSR when using either EW or NS components. They observed that the azimuthal direction that provides the largest ratio between two rotated components correlates well with the location of a buried channel structure. Furthermore, Baena-Rivera et al. (2024) conducted a directional HVSR study along the lakebed zone near Mexico City, showing strong azimuthal dependence most likely related to lateral irregularities of the interfaces. These observations have been validated analytically (Sánchez-Sesma et al., 2025) through numerical models that confirm the dependence of the angle that produces the largest difference in the estimates of the HVSR with the geometry of interfaces that induces this response. Here, we follow the methodology proposed by Baena-Rivera et al.

(2024) to examine whether the HVSR at low frequencies below 0.03 Hz can support previous measurements of the strike and dip angle of the subducting slab. First, let us consider the standard formulation of the HVSR ratio,

$$\frac{H}{V}(f) = \sqrt{\frac{\langle |NS(f)|^2 \rangle + \langle |EW(f)|^2 \rangle}{\langle |V(f)|^2 \rangle}}, \quad (1)$$

where, H/V is HVSR, f is the frequency, and NS, EW, and V, correspond to the North-South, East-West and vertical components, respectively. $\langle |\cdot|^2 \rangle$ denotes the spectral densities average over time windows. Here, we follow the criterion proposed by Arai and Tokimatsu (2004) of computing the ratio of averages instead of the average of ratios, as the first way to compute it constitutes a solid theory for the HVSR based on the diffuse field assumption (Sánchez-Sesma et al., 2011). This theory asserts that the ambient seismic noise (ASN) wavefield contains all kinds of elastic waves, understanding this as an elastic medium uniformly illuminated by equipartitioned energy.

The directional HVSR, which corresponds to the HVSRs computed with the horizontal movement components rotated between 0° and 180° , follows the next equations,

$$\frac{H'}{V}(\varphi, f) = \sqrt{\frac{\langle |H'(\varphi, f)|^2 \rangle}{\langle |V(f)|^2 \rangle}}, \quad (2)$$

where $H'(\varphi, f)$ is a horizontal rotated component an angle φ around the vertical axis from the EW direction, counterclockwise, using the 2D rotation transformation matrix,

$$\begin{bmatrix} H'_1(\varphi, f) \\ H'_2(\varphi, f) \end{bmatrix} = \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} NS(f) \\ EW(f) \end{bmatrix}. \quad (3)$$

Considering the two horizontal rotated components $H'_1(\varphi, f)$ and $H'_2(\varphi, f)$ are symmetric at 90° , that is, $H'_1(\varphi, f) = H'_2(\varphi \pm 90^\circ, f)$, only the use of one of the two horizontal rotated components, $H'(\varphi, f)$, is necessary. This means that they are complementary.

A measure of the amplitude difference between $H'(\varphi, f)$ and $H'(\varphi \pm 90^\circ, f)$ at a frequency of interest or in a range of frequencies gives us an indicator of the possible irregularities present in the interfaces of the soil in the site of ambient seismic noise recordings. This measure is the coefficient of the lateral irregularity, $\gamma(\varphi)$, computed using the following equation (Baena-Rivera et al., 2024),

$$\gamma(\varphi) = \frac{1}{N} \sum_{f_1}^{f_2} \frac{|H'/V(\varphi, f) - H'/V(\varphi \pm 90^\circ, f)|}{\min(H'/V(\varphi, f), H'/V(\varphi \pm 90^\circ, f))}. \quad (4)$$

In a plane-layer case the directional HVSR does not depend on the rotation angle φ , then $\gamma(\varphi) \approx 0$ for every $\varphi \in [-90, 90]$, this indicates that the layers underneath the station at the depth expected for this frequency range are overall horizontal and planar. Conversely, in the case of the presence of lateral irregularities in the interfaces, i.e. non-planar layers or dipping, the directional HVSR depends on the rotation angle φ , then $\gamma(\varphi) \gg 0$. In summary, $\gamma(\varphi)$ is a measure of the lateral irregularity of an interface. This has been clearly tested for near-surface man-made structures in Onahana, Fukushima, Japan by Matsushima et al. (2017). The hypothesis has also been tested near Mexico City in the remains of a lakebed (Baena-Rivera et al., 2024).

In this study, we assume that low enough frequencies (< 0.1 Hz) may provide insight into the deeper structure. Hence, we compute the directional HVSR for all the stations of the MIST array and four of the PT-VMN array using Eq. 2 and estimate $\gamma(\varphi)$ by applying Eq. 4. The directional HVSR was calculated following the diffuse field assumption (see

Sánchez-Sesma et al., 2011) using six days of ambient seismic noise velocity records, with 1000-s window lengths to ensure a frequency step of 0.001 Hz, and 10% overlapping. The STA/LTA criterion was applied to avoid windows with spurious signals, transients, and monochromatic waves from anthropogenic sources. In addition, window normalization was applied before calculation using the unitary energy window criterion described in Baena-Rivera et al. (2024). Under the diffuse field assumption, the HVSR modeling is based on a spectral ratio of the windows averages for each principal direction, implying that the arithmetic mean of the energy represents the directional energy densities (DED). These DEDs are directly linked to Green's function and allow for a consistent inversion formulation. Therefore, in this study the uncertainty of the HVSR was performed by employing the bootstrapping method. This method takes the sample data and resamples it to create many simulated samples that have their own properties as mean and standard deviation. The method has an equal probability of randomly drawing each original data point for inclusion in the resampled datasets and can select a data point more than once for a resampled dataset. When applying the bootstrap method 200 HVSR were calculated by randomly selecting the first point of each time-average window of the original total signal. From the 200 HVSR, the HVSR mean ($\overline{H/V}$) and its standard deviation ($\sigma_{\overline{H/V}}$) was calculated.

Figure 4 shows the results for station CRIS (see location in Figure 1) as an example. The directional HVSR is shown in Figure 4a, where there are two important peaks, at low frequencies (below 0.03 Hz), susceptible to analysis. The first at 0.012 Hz with an amplitude of 178, and the second at 0.081 Hz with an amplitude of 10.4. Figure 4b shows the H/V total (black line) computed using Eq. 1, $H'/V(\varphi, f)$ (red line) and its counterpart

386 $H'/V(\varphi + 90^\circ, f)$ (blue discontinued line) computed using Eq. 2. In this case, these last
387 two curves are plotted for the rotation angles of 34° and 124° , respectively, where the
388 maximum value for $\gamma(\varphi)$ is found for the frequency of interest. Also, the frequencies of
389 the peaks of interest and the value of $\gamma(\varphi)$ for those frequencies are indicated.
390 Uncertainties in the estimation of the HVSR using the bootstrap method are shown in the
391 Figure 4b.

392 At all stations, the same behavior of two main low-frequency peaks is observed: the first
393 located between 0.005 and 0.02 Hz, and the second between 0.07 and 1 Hz.

394

395

396 **Figure 4.** Directional HVSR for CRIS station of the MIST array. (a) Colormap of the
 397 directional HVSR. (b) H/V total and $H'/V(\varphi, f)$ for 34° and 124° rotation angles; the black
 398 thin vertical lines locate the frequencies of the two main peaks of the H/V total at low
 399 frequencies; error bars show the uncertainties within $\pm\sigma_{H/V}$; $\gamma \gg 0$ suggests a subsurface
 400 irregularity beneath the station.

401 From the φ at which $\gamma(\varphi)$ is maximum (i.e. a measure of the amplitude difference
 402 between $H'/V(\varphi, f)$ and $H'/V(\varphi \pm 90^\circ, f)$) at each station, and the value of $\gamma(\varphi)$, maps
 403 of the maximum lateral irregularity vectors of the directional HVSR like those in Figure 5
 404 can be constructed. These types of maps can serve as support to detect the possible
 405 shape of interface irregularities.

406 Figure 5 presents two maps: the first (Figure 5a) shows the azimuthal behavior of the
 407 lateral irregularity vectors calculated between 0.005 and 0.02 Hz, where is located the
 408 first peak of the HVSR observed in Figure 4; and the second (Figure 5b) shows this
 409 behavior in the range 0.07 and 0.1 Hz, where the second peak of the HVSR observed in
 410 Figure 4 is located. The patterns of the two maps are similar, and few stations do not

411 follow these patterns, such as CONE and PURU, which lack particularly good records.

412 The common direction of the lateral irregularity vectors is the same.

413 Since the directional HVSR behavior is inherent to lateral variations and interface
414 irregularities, it provides valuable information about structural complexity, thus the results
415 can also be influenced by local heterogeneities, particularly in tectonically and volcanically
416 active regions such as the study area. As shown in Figure 5, the slab strikes predicted by
417 the HVSR technique (green arrows), yield strike values that are similar to those predicted
418 by global models such as Slab2 (Hayes et al. 2018), mainly for those stations between
419 the expected 40 km and 80 km isodepth lines (stations: TAHU, PARE, BARA). For the
420 northern segment of the array (beyond NARA station), the predicted strikes become more
421 randomly oriented. According to the Slab2 model, the slab in this area is either too deep
422 (> 100 km) or it may not be even present at all. Therefore, the measurement may be most
423 likely influenced by the crustal heterogeneity introduced by the presence of the TMVB.
424 Interestingly, the predicted strikes for the PT-VMN are more coherent between stations
425 and mainly oriented in the north-south direction. This is clearly a crustal effect due to the
426 volcanic nature of the region while the estimates south of the TMVB may be more likely
427 due to sampling of average strike direction of the slab beneath the station.

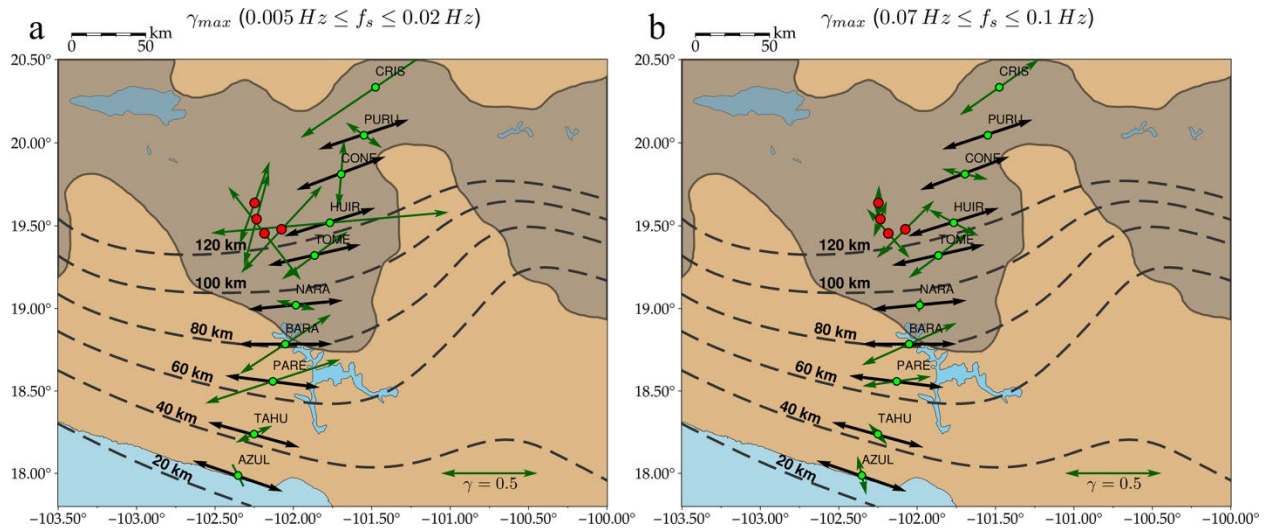


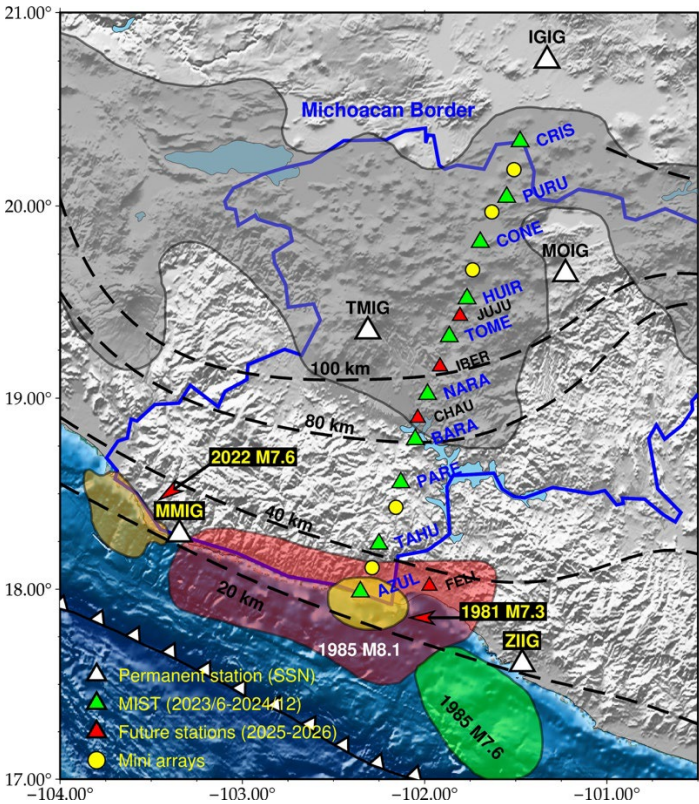
Figure 5. Azimuthal behavior of the maximum lateral irregularity vectors of the directional HVSR at MIST and PT-VMN stations, calculated at the peak frequencies of the HVSR between: (a) 0.005 and 0.02 Hz; and (b) 0.07 and 0.1 Hz. The sizes are their corresponding directionally dependent coefficient, $\gamma(\varphi)$. Dotted lines show the slab iso-depth lines from Slab 2 (Hayes et al. 2018), black arrows show the expected at each station. Green arrows show the predicted strike direction for the largest value γ in each frequency range. The length of the green arrows is scale by γ .

7. Expansion plans and perspectives

Achieving high-resolution images of the subducting slab requires both a dense network with short inter-station distances (≤ 10 km) and relatively long recording periods (> 2 years). Given the current financial and instrumental resources, the MIST project will extend its recording window for the next two years (2025-2026). Five more stations will be deployed near the transition zone where the slab is expected to sink into the mantle. Figure 6 shows the proposed layout of stations, including the location of five 3-station temporary mini-arrays. This configuration is aimed at increasing the resolution of the studies. In the case

444 of the station FELI, it is intentionally located off the array, to the South, for a better location
 445 of the near-trench seismicity. The mini arrays will support seismic ambient noise-based
 446 studies and will fill the gaps between stations, except for the middle point between stations
 447 PARE and BARA due to extremely difficult conditions.

448 **Figure 6.** Future deployment of stations and temporary mini arrays. Color-shaded areas
 449 indicate the rupture areas of large earthquakes and the location of the TMVB (gray color
 450 shade), and the black dashed lines correspond to the iso-depths of the top of the slab
 451 according to Hayes et al. (2018). Green triangles show the location of the current MIST
 452 stations. Red triangle shows future deployment of five new stations. Yellow circles mark
 453 the location of five mini arrays of three stations each in between MIST stations for noise
 454 recording.



8. Conclusions

The MIST array represents an overdue project to understand better the variations in the geometry of the Cocos plate and its relationship with the formation of the Michoacán-Guanajuato Volcanic Field. The layout of this array was carefully chosen to mimic previous studies such as MASE and VEOX arrays. Although it is less dense in terms of the number of stations, the MIST array is recording enough broadband data needed to carry out multiple studies such as receiver functions, teleseismic and ambient noise tomography and volcano monitoring. In this paper, we presented a review of the past studies and the relevance of deploying the network in this area. One critical point to consider is the occurrence of periodic volcanic swarms. Some initial evidence of tremors and H/V directional properties along the network including a newly deployed 4-station broadband network in the Tancítaro volcano has been presented. First, we present the occurrence of earthquake swarms around the Tancítaro volcano. This phenomenon is currently a major concern among local communities and authorities, mainly because the 2023/03/15 $M_w=4.6$ earthquake that caused moderate damage. By including the central stations of the MIST array alongside the SSN and Parícutín-Tancítaro volcanic network, we will be able to determine the depth of the events with greater accuracy which is a fundamental parameter for assessing the volcanic hazard. Having a larger number of stations will provide a better constrain on the depth of the events and a better velocity model, which is a critical parameter to determine whether evacuations may be required. Additionally, we could better constrain the focal mechanism for relatively small earthquakes and monitor changes in V_p and V_s velocities. These factors are critical to properly characterize changes in the background seismicity and the properties of the

medium. Furthermore, we found tremor-like signals, although it was not possible to determine their origin due to the large interstation distance. Their possible existence suggests that SSE may also rupture within the state of Michoacán, forming a continuous band between the states of Guerrero and Jalisco where they had already been reported. The future deployment of additional stations will confirm or rule out whether this hypothesis holds or not.

Finally, we examined directional HVSR to evaluate whether this technique, at low frequencies, can determine the strike and dip of the subducting slab. Current estimates show promising results compare to global models and may provide an additional constraint to better model the geometry of the subducting slab. Moreover, the use of this technique also serves as a tool to examine the complexity of the crustal structure. These initial results provide a baseline study for further instrumentation and investigation of the volcano-tectonic features in the state of Michoacán.

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