CITIZEN SCIENCE:
THEORY AND PRACTICE

Citizen Science for Disaster Risk Governance: Towards a Participative Seismological Monitoring of the Mayotte Volcanic Crisis

COLLECTION:
CONTRIBUTIONS OF CITIZEN SCIENCE TO THE UN SDGS

RESEARCH PAPER

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ABSTRACT

The United Nations (UN) Sendai Framework for Disaster Risk Reduction 2015–2030 aims to mitigate natural disasters, specifically in developing regions. It promotes the adoption of people-centered disaster risk reduction approaches. Hence, citizen science represents an interesting tool to engage populations in the mitigation of disaster risk, through data collection and analysis, and in the dissemination of scientific and safety information. Herein, we evaluate the potential and feasibility of a citizen science project on the island of Mayotte (in the Mozambique Channel). Mayotte has been experiencing an unexpected volcano-seismic crisis since 2018, which has generated strong anxiety in the population. To address this, we have developed a citizen seismology program to engage Mayotte's inhabitants in seismic data processing. First, we conducted an initial test of our protocol to identify seismic events with a set of university students. We then conducted 15 interviews with members of local administrations and associations to assess the potential for engaging the general population in this project. The results show that we are able to collect reliable data from citizens with non-professional backgrounds using the protocol designed in the project. We also show a strong demand for scientific information from Mayotte's inhabitants, associated with a robust trust in science and scientists, despite the circulation of alternative explanations for the seismicity among the population. Based on these results, our citizen science project could be positively received by Mayotte's inhabitants, if advertised adequately. Finally, we discuss the value of these results for disaster risk reduction in vulnerable territories.

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INTRODUCTION

CITIZEN SCIENCE AND THE UNITED NATIONS SENDAI FRAMEWORK

The United Nations (UN) Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR) was signed on 18 March 2015, at the UN World Conference on Disaster Reduction, by 187 member states. Its general aim is to prevent and reduce disaster risks by promoting good governance in disaster risk reduction strategies, specifically in developing regions (Kelman and Glantz 2015). To achieve this goal, the SFDRR defines priorities for action (article 20) including (1) "understanding disaster risk" and (2) "strengthening disaster risk governance to manage disaster risk." To help achieve these objectives, the SFDRR also defines thirteen guiding principles (article 19). Two of them explicitly focus on citizen engagement, by highlighting that: (i) "disaster risk reduction requires an all-of-society engagement and partnership" and (ii) "disaster risk reduction requires a multi-hazard approach and inclusive risk-informed decision-making.

The coupling of priorities (1) and (2) and the guiding principles (i) and (ii) points to citizen participation in scientific research and expertise as a tool to study and collectively manage disaster risks. For this reason, the role of citizen science for disaster risk reduction has been discussed at length in the literature since the adoption of the SFDRR (Paul et al. 2018). As shown in different case studies, citizen science could be used within all five steps defined by Moe and Pathranarakul (2006) for disaster risk management: prediction, warning, emergency relief, rehabilitation, and reconstruction (e.g., Marchezini et al. 2017; Scaini et al. 2022).

Within the field of disaster risk reduction, "citizen seismology" (Bossu et al. 2011) constitutes a promising area, which is growing in different directions (Chen et al. 2020a). First, rapid information systems (e.g., smartphone apps, social networks) have proven to be reliable tools for collecting information when an earthquake is felt, such as its location, the degree of shaking, and damage. Regarding damage assessment, Sandron et al. (2021) present a method to rapidly draw maps of seismic impact on the basis of reports from trained volunteers in the Italian civil protection authority. Second, some projects have engaged citizens in the monitoring of seismic activity through the production of seismic data. For instance, Calais et al. (2020) developed a participatory seismology project based on easy-to-use seismological stations that are hosted by inhabitants of Haïti. Third, some projects have engaged citizens in the processing of seismic data, for instance, in the processing of P- and S- waves (Chen et al. 2020b). Participatory seismology has also been shown to foster the demand for information by the population and to spark interest in risk management (Calais et al. 2020).

OBJECTIVES AND RESEARCH QUESTIONS

Mayotte is a French overseas territory ("*département*") situated north of the Mozambique Channel and is characterized by a relatively low level of economic development, with more than 70% of the 256,500 inhabitants living below the poverty line as of 2017 (INSEE 2021). In May 2018, an unusual seismic crisis began, linked to the birth of a new submarine volcano (Cesca et al. 2020; Lemoine et al. 2020; Feuillet et al. 2021). This seismic activity was felt by the population for several months, and the new volcano is still active today. These events generated a great deal of anxiety in the population (Devès et al. 2021; Mori 2022).

The general objective of this study was to evaluate the potential for developing and sustaining a citizen science seismology project in Mayotte. In the long term, such a project might constitute a fruitful way to communicate with the public about the seismo-volcanic crisis, to foster dialogue between citizens and scientists, as well as being a relevant tool for engaging the local population in the production of scientific knowledge regarding Mayotte's geophysical dynamics. In this paper, we explore both its technical feasibility (i.e., the reliability of the scientific protocol) and the conditions of its success in engaging Mayotte's citizens (i.e., its perceived relevance and interest to the local population).

In summary, this citizen science project aims to engage the inhabitants of Mayotte in the manual identification of events recorded above the active volcanic system of Mayotte. Participants were invited to identify seismic events from a continuous time series of data collected using ocean bottom seismometers (OBS).

Our study was organized around two general research questions:

(Q1) Is the designed protocol adapted to produce reliable data by non-professional citizens, suitable for use in a citizen science project targeted at the general population?
(Q2) To what extent, and under which conditions, is this project able to reach different segments of Mayotte's population?

It is worth noting that the answers to these research questions will also be of interest for the development of citizen seismology programs in other locations with similar contexts.

CONTEXT

SOCIO-DEMOGRAPHIC CONTEXT

Compared with metropolitan France, Mayotte is characterized by a relatively low level of economic development: 70% of the population live below the poverty line, and 25% have no formal settlements as of 2017 (INSEE 2021). Moreover, 71% of the population have no qualifying diploma, 53% are illiterate, and only 63% of people older than 14 years were French speakers in 2007 (Fallou et al. 2020); the most common local language is a Sabaki Bantu language, the Shimaore (Mori 2022). In addition, the socio-demographic situation in Mayotte is made more complex by the large diversity (and disparity) of its population (Walker 2019). First, Mayotte is located at a migratory crossroads with neighboring countries (Madagascar, Union of the Comoros) that are characterized by a much lower level of economic development and social protection (Roinsard 2014). Consequently, it is estimated that 40% of Mayotte's inhabitants are foreigners (mostly from the Comoros), and 80% of them are there illegally (Roinsard 2014). Second, the local populations are subject to strong inequities, with the emergence of an educated middle class that has developed with the rise of public jobs since the island changed its status in 2011 and became a French *département* (Roinsard 2014).

GEOPHYSICAL CONTEXT

Before 2018, Mayotte was considered to be an area with moderate seismic activity, and the last earthquake was felt in 1993 (Bertil et al. 2021). In May 2018, intense and unexpected seismic activity started, with tens of earthquakes felt by the population that same month (BSCF 2018). The seismic crisis culminated with an earthquake of magnitude 5.9 on 15 May 2018. This seismicity was followed a month later by the start of a progressive subsidence of the island, associated with the deflation of a magma reservoir due to an eruption that started between June and July 2018 (Cesca et al. 2020; Lemoine et al. 2020; Feuillet et al., 2021). Then in May 2019, a new volcano, Fani Maoré, was discovered during a multi-institutional oceanographic campaign funded by the French government (Figure 1) (Feuillet et al. 2021). Since then, scientific missions have been regularly organized, both on land and offshore, to study the volcanic system dynamics where the activity is monitored by the REVOSIMA (*Réseau de surveillance volcanologique et sismologique de Mayotte*) (REVOSIMA 2021; REVOSIMA-IPGP 2021). From the newly recorded data, it was shown that the new volcano, Fani Maoré, is about 900 m high with a base at a depth of 3,000 m. The volcano is located 50 km southeast of Mayotte island. However, since 2018, seismic activity has been occurring

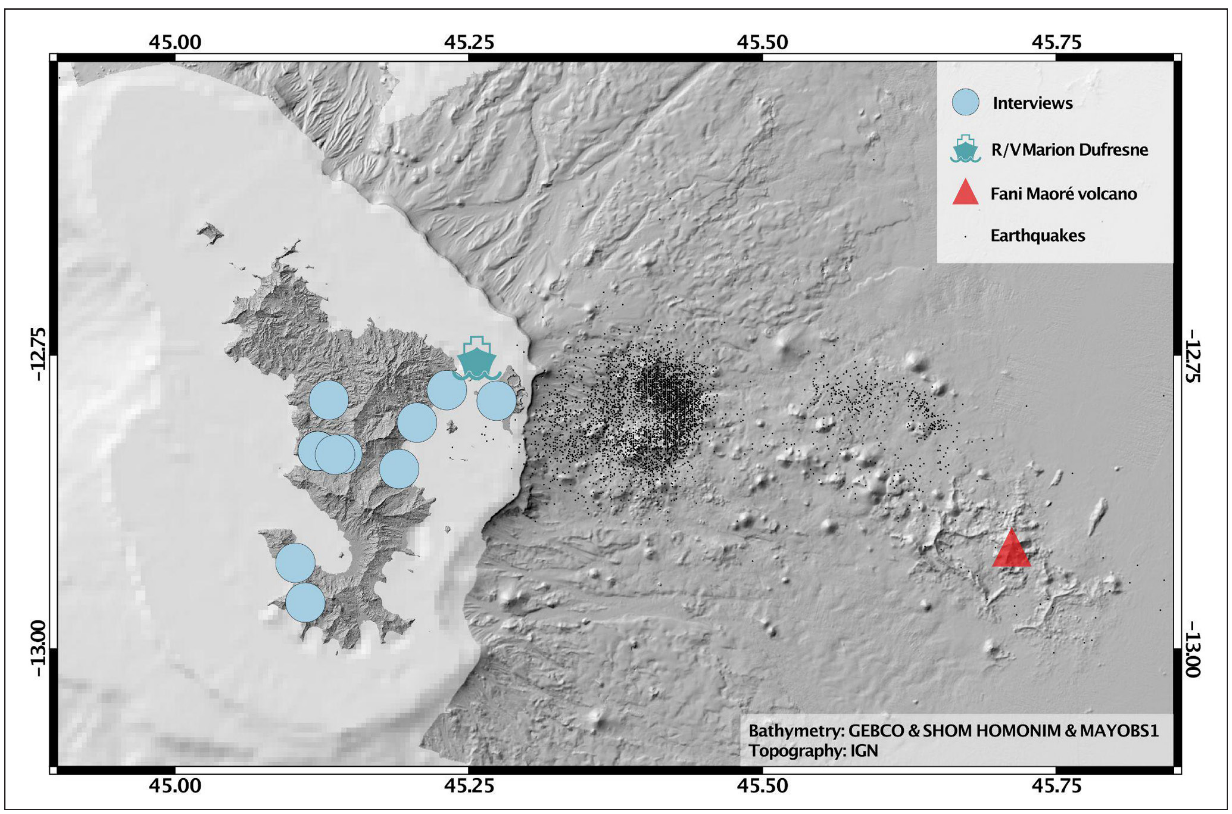

Figure 1 Map of Mayotte and the surrounding area. The red triangle shows the location of the Fani Maoré volcano and the black dots are the earthquake catalog from Saurel et al. (2022a). The blue circles show the areas where we conducted the interviews.

offshore of Mayotte in two clusters, one around 10 km away and another one 25 km from Mayotte (Figure 1) (Saurel et al. 2022a). The seismic activity is monitored in real-time by OVPF (observatoire volcanologique du piton de la Fournaise) with support from the BRGM (French geological survey) in Mayotte (REVOSIMA-IPGP 2021). The seismicity is still ongoing today, with a daily average of 10 earthquakes, with about one every few months large enough to be felt. Due to some (limited) structural damage to buildings (BCSF 2018), these repeated earthquakes (seismic swarms) have resulted in anxiety and even panic events among a population that has not been accustomed to frequent earthquakes (Mori 2022).

LOCAL PERCEPTIONS OF THE SEISMO-VOLCANIC CRISIS: STATE OF THE ART

Mayotte's local context is characterized by a complex interaction between scientific/safety information, and cultural/religion-related elements, as extensively shown by Cripps and Souffrin (2020), who reported on the perception of natural risks in Mayotte. Notably, these authors highlight the existence of traditional explanations for earthquakes (Leone 2014), and the conflicts or tensions among generations and social classes regarding the deference to scientific information. A few works have specifically studied the perceptions of the current seismo-volcanic crisis by Mayotte's populations. Fallou et al. (2020) and Devès et al. (2021) focused on the feelings of inhabitants regarding scientific and safety information about the seismic swarms. Their results highlight the difficulty for the scientists and the authorities to reach the local population with information. Both studies argue that this lack of communication reinforces a widespread state of distrust or suspicion towards scientists and the authorities. These studies use the same empirical material: an online group of Mayotte's citizens sharing information about perceived seismic activity (STTM group). Fallou et al. (2020) also circulated a survey among users of the LastQuake application, dedicated to earthquake information and the collection of reports of where earthquakes have been felt. However, these two samples exhibit specific biases. First, the STTM group may have an over-representation of inhabitants who have experienced a form of distrust or suspicion towards the authorities because of the self-selection process. Second, the LastQuake application might preferentially recruit citizens who complain about the lack of information. Hence, these studies are limited and should be completed by data collected through other channels in order to really study the local perceptions and perspectives regarding the seismic-volcanic crisis and its management. In particular, additional field work with Mayotte's population is needed to assess the level of distrust and suspicion towards the scientific and administrative authorities, and the interest of citizens for stronger interactions with scientists through citizen science.

MATERIAL AND METHODS

SEISMICITY ANALYSIS AND DESIGN OF THE CITIZEN SCIENCE PROTOCOL

Seismicity analysis is one of the main tools used to study and monitor volcanic activity remotely. Indeed, seismicity is usually recorded before and during eruptions all over the world. In Mayotte, the seismicity is monitored daily at the OVPF observatory using an automatic detection process that analyzes the signals recorded by seismic stations installed on land (Retailleau et al. 2022a). The identification of earthquakes is checked and completed daily by the OVPF agent on duty, and their locations are validated by an analyst of the REVOSIMA earthquake location group.

Contrary to data from the land surface, which are available in almost real time, the data that are recorded from the ocean bottom by OBS stations are recovered every few months during oceanographic campaigns (REVOSIMA 2021). Automatic detection is applied afterwards to the data, but no manual screening is performed, apart from the larger earthquakes. These manual screening sessions performed by a group of seismologists have been called pickathons (Saurel et al. 2022a). Whereas land stations mostly record earthquakes, OBS stations record various types of events, including earthquakes, hydro-acoustic events, and other types of signals (Saurel et al. 2022a; Saurel et al. 2022b). Pickathons have also been organized to identify "exotic" events from OBS data over a period of a few weeks. Finally, the automatic detection that is being used to monitor the seismic activity has been shown to be very efficient for studying classical Volcano Tectonic earthquakes (VT), but it is more limited for studying another type of event that is linked to the volcanic activity: Long Period earthquakes (LP) (Retailleau et al. 2022b). For these reasons, manual screening is still crucial for understanding the ongoing seismicity in Mayotte and to validate the automatic analyses, but this is time consuming. Moreover, a significant part of the data has not yet been screened. Consequently, manual screening by citizens could be very useful for the advancement of scientific research in seismology in Mayotte, among other places.

Examples of the movement of the ground recorded by OBS stations are represented in Figure 2. To identify an event, one must determine the moment when the amplitude of the signal varies and emerges from the flat background level. To do this identification, it is not necessary to be an expert in this field. Hence, we expected that with some brief training, anyone should be able to do this task.

The principle of our protocol is for the participants to screen continuous data and to identify events that have been recorded by several stations (the exact protocol circulated to the participants is in Supplemental File 1: Citizen science protocol). For this task, we use the WebObs platform, which permits users to scroll through hours of continuous signals (Beauducel et al. 2020). Figure 2 shows the platform and the seismic data. The main platform (Figure 2a) shows the aggregated data from all the stations displayed in 1-hour windows. Figure 2b shows an example from a one-hour window, and Figure 2c shows the data from a selected event.

In the citizen science protocol that we designed, each participant is assigned a sequence of continuous data (Figure 2), in which s/he can identify the seismic events. Each participant is provided with a computer and access to the OBS database through the WebObs platform. We wrote a French-English protocol to guide the participants, as one of the students was an English speaker (Supplemental File 1: Citizen science protocol). For our specific test, translation to Shimaore was not required.

INITIAL TEST WITH UNIVERSITY STUDENTS

The oceanographic campaign MAYOBS23 (Jorry et al. 2022) took place in July 2022. While these MAYOBS campaigns are recurrent and occur every few months, this one also hosted an "*Ecole flottante*" (on-board school), where students board the research vessel to learn about the work of scientists studying Mayotte's volcanic activity. The 20 students (8 men and 12 women) were from Mayotte and the surrounding region, with the exception of a student from Paris. They were recruited to join the on-board school

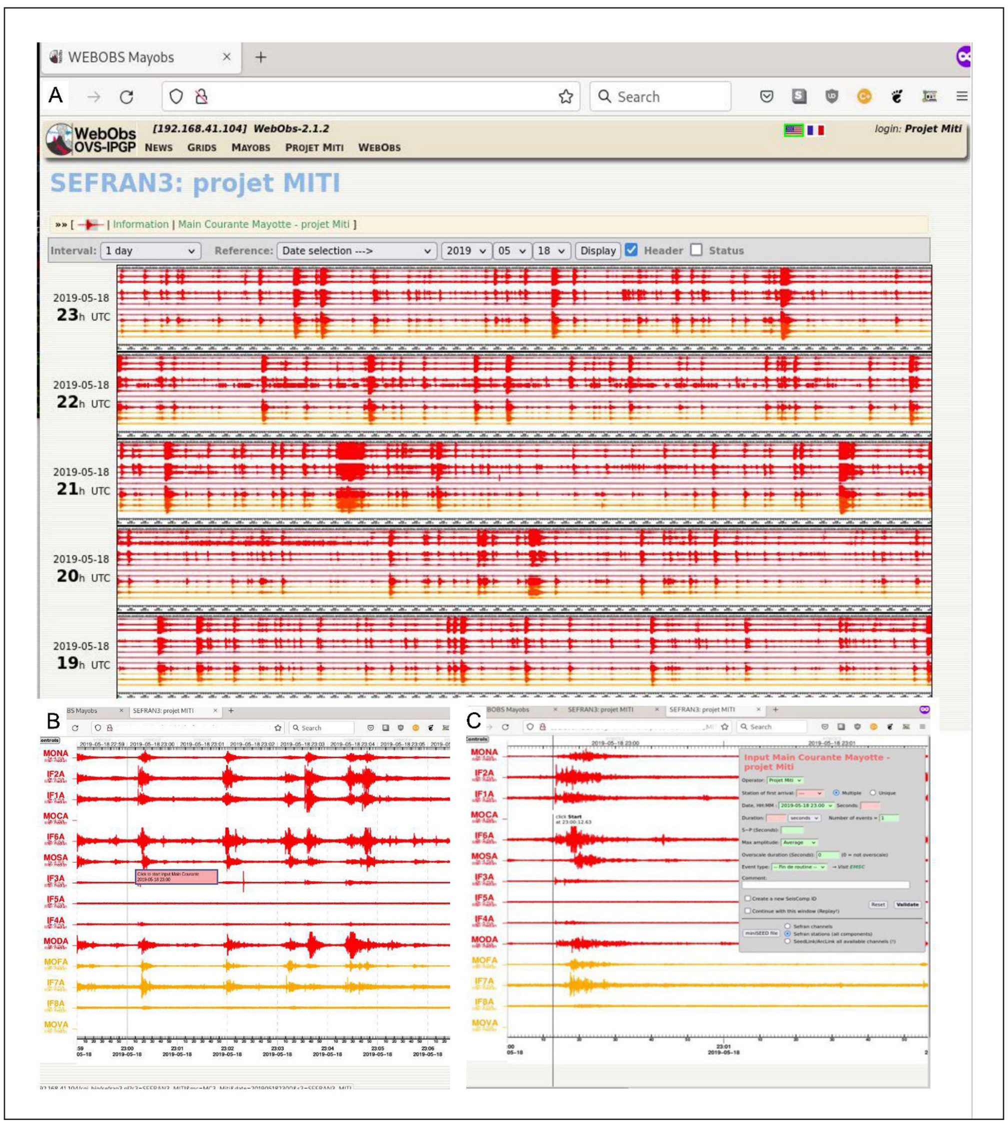

Figure 2 Screenshots of the interface used to identify seismic events. **a)** Main page with hourly windows for one day. **b)** The second interface focuses on one chosen hour. **c)** The final window focuses on a chosen event, where the identification is undertaken.

as part of a program independent from the authors of this study. Their study levels went from undergraduate to PhD. None of the students had any previous experience in seismology.

During this campaign, we tested our methodology to assess its clarity and efficiency. This kind of test is recommended prior to launching a citizen science protocol at a larger scale (Fraisl et al. 2022). We organized 4 sessions with an average of 5 students per session. For this first test, the participants analyzed seismic records from 19 April to 7 May 2019 (MAYOBS2; Jorry 2019).

We chose to study this timeframe because the data screening had not yet been done by scientists. Unfortunately, we did not have any data recorded by OBS stations from the beginning of the crisis in 2018. Each student was provided a laptop, and they identified events from different days during a period lasting 1 to 1.5 hours.

SEMI-STRUCTURED INTERVIEWS

We conducted semi-structured interviews with 15 individuals (8 women, 7 men) who live in Mayotte to explore citizens' perceptions of scientific and safety information and their motivations for participating in a citizen science seismology project. From this group, 13 interviews were done individually, and a single interview was performed with 2 persons simultaneously. Our sample consisted of the following 4 groups:

a) 3 students from Mayotte's university who participated in the test of the citizen science protocol during MAYOBS23;
b) 5 high-level employees from public administrations—3 from municipalities, 1 from the local council, and 1 former employee from the *Préfecture* (local State government representation);
c) 6 presidents or employees of environmental or cultural associations; and
d) 1 journalist.

During the intense seismic swarms of 2018, 4 out of 15 of the participants (2 Mahorais people born on the Island and 2 individuals from Metropolitan France) were not present on the island. The interviewees were selected for their expertise regarding the sociological, cultural, and ethnographical features of Mayotte's population owing to their central place in Mayotte's social network, or their acquired expertise regarding the scientific protocol (for group *a*). Consequently, our sample does not aim to represent the average background of the target population. In addition, their relatively high level of education guaranteed easier communication in French. The recruitment of the interviewees was done by contacting local authorities, which provided us with a list of people (from municipal administrations and cultural associations). We designed two different interview guidelines. The first one was designed specifically for group *a*. It was composed of three blocks in which individuals were asked about (i) who they are and what they study; (ii) their memories of the seismic crisis; (iii) their feelings about the way that scientific and safety information was communicated to the population; and (iv) their feelings about the citizen science protocol. The second guideline was designed for the other groups (*b*, *c*, and *d*). These individuals were asked about (i) who they are and what their activities are in Mayotte; (ii) their perception of the political engagement of Mayotte's citizens; (iii) their memories of the seismic crisis; (iv) their feelings about the way scientific and safety information was communicated to the population; and (v) their feelings about the opportunities to engage citizens in the citizen science seismology project that we are proposing.

All the interviews were started with a brief introduction to our study. The interviews lasted from 30 to 75 minutes. Their contents were transcribed and qualitatively assessed by thematic analysis (Nowell et al. 2017): Elements of the corpus were categorized into a certain number of themes and sub-themes, and we performed a discursive examination to draw an exhaustive map of topics and opinions expressed by the panel.

RESULTS

MAYOBS23 TEST

Results from the event identification sessions

We analyzed the event identification sessions made by the students during the oceanographic campaign. Figure 3a represents the number of events identified per student, which varied considerably. On average, each student worked on one to two hours of data, but this time period differed and could partly explain the variation in numbers. However, the seismic activity is also very varied, with periods of time that contain many events and others with none. Consequently, since each student analyzed a different window of time, there was no expectation that an identical number of events would be identified by each student. In total, 1,694 events were identified by the group during only four sessions, showing that citizen participation could greatly increase the dataset used by seismologists to study these events.

To characterize the accuracy of identification for scientific use, we analyzed the quality of the identification by each student on the first hour of analysis. The aim was to assess the ability of the scientists to easily detect poor-quality contributions, that is, participants who identified only a small number of seismic events. Although

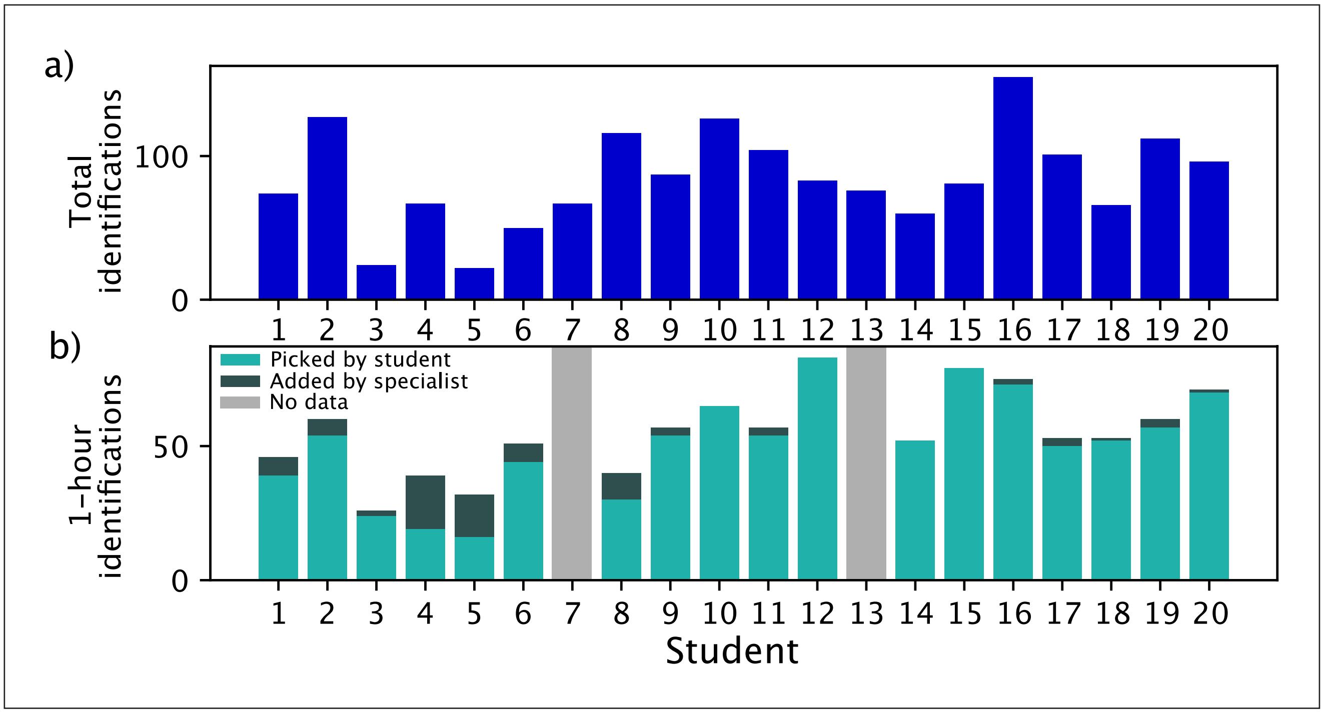

Figure 3 a) Total number of events identified per participant. **b)** Total number of events identified per participant during the first hour in green. The dark green part of the bar shows the number of events added by an expert. Gray bars show participants for which this characterization could not be done.

these contributions are not scientifically unusable, the corresponding time series will need to be checked by experts to identify any missing events. Figure 3b represents the number of events per window identified by the students (*light green*) and added by the experts (*dark green*).

Each hour of data analyzed by the students could be checked by an expert in a few minutes. In two cases, the assignment was not properly understood, and although events were identified, the student did not work on the continuous hour but on the first portion of each hour of the day. Based on the rest of the group, 91.6% of events were flagged correctly, and 83.3% of the students identified more than 75% of events correctly. We note that there were no false identifications. Although some events were missed, this means that all the events identified were real earthquakes. Hence, all identified events could be used for scientific studies, and only little supplementary work was required by the scientists to produce the complete set of major events in the time series analyzed.

Results from the participant interviews and observations

We obtained feedback from the 3 interviews we did with participants who took part in the test of the protocol regarding the interest to extend such a program to the whole population. The students we interviewed all considered that their participation in the citizen science session was useful to better grasp the logic of scientific research, with its technical dimension and repetitive tasks: "We already saw that in class, but doing it allows to understand how scientists work;" "I think these sessions were useful to show how they did before to automate the tasks;" "It is long, fastidious, more fastidious than I thought it was." In terms of science learning, one interviewee told us that most of the students were surprised to see that there were many seismic events that are not felt. This point is important because making this information available to the population is one of the aims of the citizen science project. Upon starting with their manual analysis of the signals, most students then appeared to be surprised by the number of recorded events, whether they lived in Mayotte or not. Indeed, most had felt the events that occurred at the beginning of the crisis, in May 2018, and the window of analysis for this test was a year later, in 2019. The intense seismicity recorded in 2019 was comprised of small events recorded by the sensitive seismic stations. Students commonly reported that they did not think that so much time was needed for seismologists to analyze signals in newly studied areas. However, because of the high number of events to identify (Figure 2), students found the exercise a little dull after a certain time. While this had the positive impact of showing the strength of the activity, it also led certain students to lose some focus. As a consequence, a shorter session (of about 30 minutes) or windows with less intense activity could be chosen for future scaling-up of the project.

PERCEPTIONS OF THE SEISMO-VOLCANIC CRISIS AND POTENTIALS OF OUR CITIZEN SEISMOLOGY PROJECT

Table 1 presents a summary of the results. For every topic described in the text, we provide a short summary sentence, the number of times the topic occurred in the interviews, and some illustrative quotations from the interviewees.

Sociological profile and position of the interviewees

Most of the interviewees (12 out of 15) are Mahorais people, born in Mayotte, who have spent most of their life on the island. In groups b (public administrations), c (associations), and d (journalist), 7 out of 10 Mahorais people also spent some time out of Mayotte (mostly in metropolitan France for higher education). Consequently, our sample was mostly comprised of individuals sharing a

TOPIC (NUMBER IN THE TEXT)	NUMBER OF OCCURRENCES	EXAMPLES
1-Interviewees' deference to science	9	"Let's keep a scientific mind !" (group b) "I was very interested because I work in environmental policy. At a scientific level I was also very interested" (group c) "So on my behalf I am not part of the skeptic people, I do believe that there is a volcano" (group c)
2-Mayotte's society as structured by the coexistence of various social groups	10	"There is a public who has understood that the earthquakes come from a volcano; another one who prefers other sources of information; and a last one who is not informed at all" (group c) "There are always two sides: people who went to school, who understand scientific explanations, and those who refer to God" (group c).
3-Traumatic character of the seismic crisis	10	"We have to tell it was a traumatism for Mayotte" (group b) "It was violent" (group b) "It was very frightening" (group b)
4-Latent anxiety regarding Mayotte's future	11	"They always told us: one day, Mayotte will collapse and will not exist anymore. Maybe it is the moment?" (group b)
5-The volcano as an opportunity for Mayotte's development	4	"This is a chance for Mayotte. A newborn volcano, it is the first time, no? Mayotte's population should benefit from it" (group c)
6-Interest of the inhabitants for the new volcano, and the need for scientific explanation	15	"There is a need for information. People were waiting for information" (group b) "At the beginning, there were some practical instructions, but people were totally panicked because they were not given any answer: what is happening ?" (group b)
7-The search for petroleum as an alternative explanation to the seismic swarms	4	"The most probable hypothesis was the petroleum" (group b); "Within the scientific hypothesis, there was the fact of having offshore petroleum extractions" (group c).
8-The lack of scientific information as a driver of alternative explanations	2	"The State has taken so much time to give information that people thought it was lying" (group d) "If there would have been scientific information, it would have diminished a lot the fantasms" (group b)
9-Role played by scientific findings about the volcano to eliminate those alternative explanations	8	"When the first scientific missions has started and that the population has seen it was a volcano, [the alternative explanations] have vanished" (group b) "When the scientific team revealed the hypothesis of the volcano, people believed it " (group b) "The hypothesis of the volcano imposed itself when scientists made a press communication" (group c)
10-Role of the material/scientific evidence	8	"After, there were these images, with the volcano which was perfectly localized" (group b) "They arrived with evidence, rocks, photos, analysis" (group b) "When the boat arrived for scientific research, people started to trust scientists" (group c)
11-Strategies to engage Mayotte's population	8	"You should pass by school. It is from that point that the population will get interested. It will create a new dynamic, in terms of emotions" (group e).

Table 1 The main results from the interviews. Left column: topics presented in this section. Central column: number of interviews where this topic is spontaneously evoked by the interviewees. Right column: examples of quotes from the interviewees (with the corresponding interviewee's group in brackets).

relatively high level of education, both in terms of formal education (university degree) and through the social and cultural learning provided by their experiences outside of Mayotte. In accordance with this profile, some individuals spontaneously adopted a posture of deference to science and/or rationality regarding the seismo-volcanic crisis, or showed their interest in scientific explanations (topic 1 in Table 1). In many cases, this position is clearly part of a strategy of distinction with respect to the general population (in the classical sense of Bourdieu 1984). This strategy of distinction might also prevail in the quite frequent description of Mayotte's society as structured by the coexistence of various social groups characterized by 1) socio-demographic differences in age and generation, education level, or social environment; and 2) different relations to science, scientific explanations, and/or scientific information (topic 2 in Table 1).

Memory of the seismic swarms and current interest in the volcano

Our data suggests that even if the 2018 seismic swarm and the new volcano are not topics of discussion within Mayotte's population anymore, the memory of the events still persists. Indeed, most of the interviewees indicated that there was no more reference to the earthquakes or to the volcano in daily life. However, the crisis is still present as a traumatic memory; as a challenge or opportunity for the future; and as an object of curiosity.

First, when interviewees were asked to provide memories about the seismic swarms, many of them shared both precise factual information (frequency, magnitudes, sounds) and feelings—notably, the traumatic character of the crisis and the related fear and anxiety of the population (topic 3 in Table 1). The exceptionality of the crisis, which occurred in a territory that was not known for its seismic activity, was also a recurrent topic.

Second, the volcano and the associated earthquakes were introduced as a pending challenge. This seems to echo a latent anxiety regarding Mayotte's future, specifically in relation to the ocean, which is often presented as a threatening object (topic 4 in Table 1). Interestingly, the crisis was often associated with a fear of submersion of the island through a collapse or a tsunami. Reciprocally, the volcano was also seen as an opportunity for Mayotte's development (topic 5 in Table 1). Finally, despite an often-cited difficulty to engage Mayotte's population in activities that are not directly linked to their daily life, most of the interviewees expressed the latent interest of the inhabitants in the new volcano, and a need for scientific explanation regarding both the past crisis and the current state of research (topic 6 in Table 1). In that respect, all of them complained about a lack of expert information during the peak of the seismic crisis. Moreover, the interviewees identified explicitly a demand for information on behalf of the whole population, both related to safety information and to scientific explanations.

Relations to science and scientific explanations

One of the goals of the interviews was to better grasp the diversity of the interpretations that have circulated regarding the origin of the seismic swarms. The data that we obtained point to a complex mix of scientific, cultural, and religion-related references, associated with an overall trust in scientific experts and scientific evidence. We identified two families of explanations that were influential within Mayotte's population at the beginning of the crisis. First, references to God's will or to local myths seem to have circulated during the seismic swarms, especially among elderly people. Second, these explanations have coexisted with what is presented by the interviewees as more rational, or factual ones, the most cited being the search for petroleum (topic 7 in Table 1). Several interviewees argued that they were themselves convinced by this hypothesis, and more generally, the rationality of this belief (that is, the existence of objective reasons to adopt it) was often highlighted. However, it is worth mentioning that these alternative explanations do not appear to have persisted among the interviewees once scientific insights were shared by geophysicists at the end of 2019. While the proliferation of alternative explanations was sometimes explicitly linked to the lack of scientific information by the interviewees (topic 8 in Table 1), we found a robust consensus on the role played by scientific findings to eliminate these alternative explanations (topic 9 in Table 1). Several interviewees spontaneously insisted on the positive role of the material evidence, for example the recovered volcanic rocks and the images of the volcano (topic 10).

Strategies to engage Mayotte's population in the project

When asked about the potential for Mayotte's inhabitants to participate in citizen science, six interviewees highlighted the difficulty in engaging the population in topics that are "too abstract" (group b) or "not focused on daily life" (group b). This feature is explained both as a specific trait of Mahorais culture, and as a result of Mayotte's current economic and social difficulties. On the other hand, we were also told about the motivation of the population to engage in collective actions when they are properly presented and communicated (topic 11 in Table 1). Consequently, we identified different potential conditions for success in the engagement of the inhabitants. First, the population should see a tangible or social reason for participating, for example, through personal gain (e.g., being part of a documentary focusing on the volcano, or merely having the "feeling of being useful," [group c]). Second, communication should be done in collaboration with local associations (environmental, social, cultural), which are at the center of a network of social relationships that may then be helpful in mobilizing the inhabitants. Third, schools might be a good place to apply the project, and to generate interest from the general population. Finally, the communication as well as the effective accomplishment of the sessions should consider the linguistic diversity of the island, that is, French, Shimaore, and Kibushi.

DISCUSSION

We have shown that our protocol, after some minor modifications, can be used to produce reliable scientific data by non-professional citizens. More precisely, most of the participants were able to provide results that are comparable to identifications from experts, and the protocol has proven to be relatively quick for filtering data to exclude non-reliable results. This suggests that our proposed protocol could be scaled up to the general population, which would result in benefits for generating reliable scientific data. One possibility would be to design an online platform where citizens could engage in the identification of seismic events. There are many online citizen science programs (see, e.g., the Zooniverse platform, and Chen et al. 2022b for an example in seismology) based on citizen engagement in analyzing data shared by scientists (e.g., in identifying galaxies, Aristeidou et al. 2020). These programs have developed various techniques to motivate and retain participation (i.e., gamification, challenges, etc.) that could be mobilized to scale up our protocol.

A second result concerns citizen trust in science and scientific expertise. First, our data suggests that the lack of communication has been a driver of the emergence and diffusion of alternative truths, has fueled a feeling of being abandoned by the authorities, and has increased anxiety in the population. This finding is cogent with the analyses of Devès (2021) and Fallou (2020). Reciprocally, our results indicate that Mayotte's population is characterized by a strong level of trust in and deference to science, which seems to be well spread within the population. Based on the direct expression of public trust by the interviewees, our qualitative study highlights the role played by science communication in the quick decline of alternative explanations when the volcano discovery was disclosed to the public. Specifically, our results highlight the role of scientific explanations, but also scientific and material evidence (i.e., rocks, images, etc.). One could consider that this conclusion is biased by the specific social position of the interviewees, who expressed, as individuals, a high degree of trust in and deference to science. We argue that, on the contrary, the interviewees' strategy of social distinction should lead them to insist on the distrust or irrationality of the population. Consequently, our conclusions may be reinforced by the socio-economic position of the interviewees.

To some extent, our results are aligned with Calais et al.'s (2020) inputs from their interdisciplinary "socio-seismology experiment" made in Haïti. They showed that citizens of this vulnerable territory are in demand of scientific information, that this demand is fostered by engagement in citizen science, and that they have a high level of trust towards scientists. Interestingly, their survey-based study suggests a complex relationship between deference to scientific information and to magic or religion. Our qualitative results confirm that point, while indicating that these relationships may strongly depend on the social position of the individuals, such as their age and education level. Complementary data retrieved from interviews with different segments of Mayotte's population would be necessary to describe in more detail how science and religions are mixed in the population's perception of the tangible events linked to the volcano. An important next step will be to distinguish this overall trust in scientific explanations and scientific evidence from trust in science as an institution. As shown by Achterberg et al. (2017), there is a gap between (1) trusting scientific methods and principles, and (2) trusting the peculiar social and political arrangements that give science its place and its role in society. Following Wintterlin et al. (2022), one could also consider the trust placed in scientists as individuals as a third dimension (3). Our current data suggest that Mayotte's citizens experience trust in the sense of (1) — as shown by references to scientific evidence — and of (3) — as shown by the references to the communication done by the scientists. However, it is unclear if the observed trust in scientific information involves a trust in the scientific institutions. This issue could constitute an interesting research question for the future.

Finally, our results may give some practical information for implementing citizen science programs for disaster risk reduction in developing or vulnerable territories. By studying the case of an environmental citizen science program in Argentina, Requier et al. (2020) showed that the number of local coordinators is a key determinant of citizen engagement in developing countries. Our qualitative study points to the same result, since the interviewees often highlight the importance of working with local actors as a driver of citizen engagement. In particular, the role of small, village-based associations was often highlighted by the interviewees. Through their central position in social networks, and the social position acquired by their members, these associations seem to constitute very influential local actors who communicate and engage inhabitants in a diversity of projects. When mobilized to develop citizen science projects, this local social network may contribute to the community-centered mitigation of natural risks promoted by the Sendai framework.

DATA AVAILABILITY STATEMENT

Data will be made available on demand.

SUPPLEMENTARY FILE

The supplementary file for this article can be found as follows:

- **Supplemental File 1.** Citizen science protocol. DOI: https://doi.org/10.5334/cstp.573.s1

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The authors have no competing interests to declare.

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