Unusual Seismic Activities in Northwestern Madagascar
Using: Spot Them All

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Abstract: Spot Them All, is the first localization software developed by the Laboratoire de Seismologie et Infrason Madagascar. The objective of this study is to validate results obtained from the software by comparing them with bulletin published by GFZ and the revised event bulletin of the CTBTO from April 2018 to November 2019. On May 15th, 2018 around 15:48, an unusual seismic event of magnitude 5.9 was detected in northwest of Madagascar with thousands of aftershocks. The program Spot Them All collects data from IRIS, GEOFON, DASE, IMS, Africa Array network on request. Results showed that earthquake location obtained using STA is consistent with the other two international bulletins. Moreover, 199 earthquakes of magnitude greater than 4 were detected by the IMS, 39 by the GEOFON network while 937 by STA. Depth is fixed at 10 km in the GFZ’s bulletin and at 0 km in the CTBTO’s REB. STA’s bulletin shows more constrain on events’ depth, ranging from 0 to 135 km and they are located between latitudes 11.84° S and 14.18° S, and longitudes 44.8° E and 46.78° E. Information collected from different researches showed that a magma is propagating from Moho depth to the surface. Consequently, a new mountain of about 800 m high and 5 km wide is raising above the seafloor.

Keywords: Spot Them All, earthquakes, Northwestern of Madagascar, new mountain.

Nomenclature

STA Spot Them all
GFZ GeoForschungsZentrum (Geo-research Center)
CTBTO Comprehensive Nuclear Test-Ban Treaty
IRIS Incorporated Research Institutions for Seismology
GEOFON GFZ seismic network
DASE Département Analyse Surveillance
IMS International Monitoring System
IOGA Institute and Observatory of Geophysics of Antananarivo
BRGM Bureau de Recherche Géologique et Minière
REB Revised Event Bulletin
LSI Laboratoire de Seismologie et Infrason

1. Introduction

On May 15, 2018 at 15:48:05 (GMT), an earthquake of magnitude 5.9 occurred in Northwestern of Madagascar (Fig. 1). Archive bulletin of the IOGA showed that it is the largest earthquake ever recorded from that region.

The area of study is classified in the 29th seismic zone of Madagascar and belonged to the 8th category, with 0.001 earthquake per kilometer [1]. BGRM defines those events as “Earthquake swarm” which is an episode of multiple seismic events in a particular zone [2]; seismic energy has weakened since July 2018, although some events are still being felt by the population. It is also indicated that those events are not causing any major damage and too weak to generate tsunamis. Further, in Refs. [3, 4], GPS data analysis showed that the Island is sliding more than 2.36 inches to the east and 1.2 inches to the south (Fig. 14). A magma body is squishing its way through the subsurface near Mayotte.

The objective of this study is to perform analysis and report these earthquakes using the first Malagasy localization software called Spot Them All (STA). To prove relevance of the software, we compared its bulletin results with the Revised Event Bulletin (REB) provided by the CTBTO and bulletin form the GFZ between May 2018 and November 2019. Moreover, since thousands of aftershocks are still being felt,
information from different reports, articles and researches was collected to explain what is happening in the studied area.

Analysis showed that STA can be trusted even though constrains are observed in some cases due to the energy released from the earthquakes and the seismic station distribution.

2. Materials

2.1 Spot Them All

Developed by T. Rakotoarisoa, associate researcher at IOGA, STA software is a Qt C++ based program regrouping standard tool used by seismologist in a new and friendly graphic user interface. For instance, when locating earthquakes, users can choose between Hypocenter and Hypo71 (Fig. 2), which are well known algorithm in seismology. In addition to that it is reading different data format such as SAC, Mini-seed, seed, Seisan, etc.

Before STA, the LSI was using Onyx (a DASE software) for data analysis but only local station was configured. Now, with STA, we can combine and use data from every network if accessible and if needed.

Therefore, the main advantage of this new tool is that we can adapt the software with our needs.

2.2 Data

During this study, seismic station from different network such as IRIS, GEOFON, Africa Array, IMS, DASE, and other were used after request from STA. These stations are represented in Fig. 3. STA is downloading data from these stations via our Seiscomp’s database. Therefore, data from different network and from different parts of the world are accessible. International and local stations are then synchronized in one user interface to ease the task of analysts. At this stage data are formatted in Miniseed.

2.3 Data Processing: Computer Method and Focal Mechanism

Phase picking, earthquake location and double couple solution can be calculated (Fig. 4) using STA.

First, to locate an earthquake, STA runs on its background Hypocenter (Fig. 4). In Ref. [4], they define Hypocenter as an algorithm that combines features of the two well-known algorithms HYPO71 and HYPOINVERSE. These algorithms calculate earthquake parameters (latitude, longitude, origin time and depth) based on iteration and adaptive damping.

Second, to calculate the focal mechanism solution, STA runs HASH. In Refs. [5, 6], HASH uses a grid-search to determine P-wave polarity first-motion (or P-polarity and S/P amplitude ration) to determine the solution. STA provides the input information to HASH, then shows the result after processing (Figs. 4 and 5).
Fig. 2  Phase picking and amplitude measurements. Earthquake of local magnitude 5 on June 1st 2018 at 15:39 GMT.

Fig. 3  Seismic station list from which data are accessible by the program in near real time.

Fig. 4  Earthquake location and double couple solution in one.
In addition, spectral analysis, real time monitoring and some statistics (number of events, magnitude variation, etc.) can be performed in a very friendly interface.

3. Method

The objective of this study is to verify whether the bulletin form STA is accurate or not. Therefore, we compared the events parameters from STA with the REB of the CTBTO and the bulletin from the GFZ as observed in Fig. 6. These two bulletins were chosen because earthquake location obtained from these organizations is well known and assumed as widely accepted by seismologist community.

For each earthquake of magnitude greater than 4, we compared the longitude, latitude, depth and magnitude from each bulletin.

4. Results

We are going to present the difference between the
earthquake parameters obtained from the three bulletins. Respectively, red, green and blue represent the location of the same event from GFZ, CTBTO and STA.

First, it is presented in Figs. 7 and 8 that events are located between longitude 45.4 ° to 45.7 ° and latitude -13.4 ° to -12.5 ° for both CTBTO (green) and GFZ (red) bulletins from May 2018 to November 2019.

Second, earthquakes located using STA (blue) show two groups. The first group is located from longitude 46 ° to 46.5 ° and from latitude -13.2 ° to 13.8 ° which is at 0.5 ° (~50 km) westward in term of longitude (Fig. 7) and southward in latitude (Fig. 8) compared to the REB and GFZ. The second group is between longitude 45 ° to 45.7 ° and latitude -13.2 ° to -12.5 °.

Third, from May 2018 to November 2019, 199 events were detected by the IMS, 37 by the GEOFON network while 937 by STA. Depth of all earthquakes from the REB and GFZ is respectively 0 km and 10 km while STA bulletin is ranging from 0 to 100 km (Fig. 9).

In Fig. 10, it is observed that the strongest event located from the three bulletins was on May 15th 2018 at 15:45 with local magnitude of 5.9 at 10 km deep. Fig. 6 shows the difference between the earthquake parameters obtained from the three bulletins. Respectively, red, green and blue represent the location of the same event from GFZ, REB and STA. The difference in location is around 0.03 ° (~3 km).
5. Discussions

5.1 Event Located by STA

In Fig. 11 the event located from January to December 2018 is represented.

Planned comparisons revealed three main points. First, STA detects more earthquakes compared to the other two bulletins. This can be explained by the combination of international and local seismic network and also the threshold considered by the GFZ and the CTBTO.

Second, there are two groups of events in the bulletin from STA. The first group located from longitude 46° to 46.5° and from latitude -13.2° to 13.8° which is at 0.5° (~50 km) westward in term of longitude and southward in latitude compared to the REB and GFZ. The reason is that the Malagasy seismic network is in that direction. Plus, during this work we did not have access to data from Comoros and Mayotte therefore the locations are shifting south-eastward.

The second group is between longitude 45° to 45.7° and latitude -13.2° to -12.5°. In general, difference in location is around 0.03° (~3 km) depending on the strength of each earthquake. If the event is strong then the result obtained from each bulletin does not present
a big difference. The difference in location increases when the magnitude of the earthquake decreases.

5.2 Depth

In term of depth we observe that depth of all events is fixed at 0 km for the CTBTO (green). The Comprehensive Nuclear-Test Ban Treaty, the CTBTO is looking for explosions signature (manmade activities) which is generally shallow (depth less than 5 km) in seismology. Also, depths of all events are at 10 km in the GFZ bulletin. In STA’s bulletin we observe constrained values on events’ depth, ranging from 0 to 100 km. This result is telling us that the sources of these earthquakes are deep in the upper

Fig. 11  Seismic event bulletin from May 2018 to July 2019. STA (blue), CTBTO (green), GFZ (red).

Fig. 12  Focal mechanism solutions. The blue ones represents the first cluster, the red the second cluster on the map.
mantle to the surface. Further calculation is needed to ameliorate the depth precision using the software STA. Despite its early development, this result is supporting the drainage of magma from deep by a dyke that propagated from the seafloor [9].

5.3 Source Mechanism and Cluster

In this study, we also performed focal mechanism analysis of the 937 earthquakes (Fig. 12). We observed that 59% of these events are from strike slip faults, 39% from normal faults and 2% are reverse faults.

In addition, 3 main clusters were observed in Figs. 12 and 13. The first and second cluster (in red) corresponds respectively to the magma which expands North- and South-eastward. The magma is making its way out toward all directions but mainly to the west and to the east. The third cluster (in blue) corresponds to the magma chamber.

![Similarity matrices](image)

**Fig. 13** Cluster of events.

![Seismic events from April 2018 to November 2019](image)

**Fig. 14** Seismic events from April 2018 to November 2019. Red represented events with local magnitude greater than 5, blue between 4 and 5 and grey between 2 and 4.
5.4 Underwater Eruption

In Refs. [3, 4], the Island is sliding more than 2.4 inches to the east and 1.2 inches to the south using GPS stations (Fig. 14). A magma body is squishing its way through the subsurface near Mayotte [3]. In addition, Ref. [7], while exploring the seafloor around the earthquakes location, they observed a new mountain of 800 m high and 5 km wide. Result from Ref. [8], is supporting the observation obtained with STA with 3 clusters as well from July to November 2018. These earthquakes are related to magma intrusion. Ref. [9] is suggesting that a new center of volcanic activity is developing. Recently published in Nature Geoscience, the GFZ team [10] suggests that a magma of at least 1.3 km$^3$ is drained from a reservoir of 10 to 15 km diameter at 25 to 35 km depth.

6. Conclusions

In less than one year of development, this study showed that, Spot Them All is reliable. By combining data from international and local network, STA can provide more detection and precisions on event locations.

As expected, bulletins from the CTBTO and the GFZ are considering mostly large earthquakes, but, STA can deal easily with both large and small events.

Recent articles showed that the origins of the events in Mayotte are from volcanic source. A magma is propagating from Moho depth to the surface. STA results are supporting that observation. The magma is making its way to the surface toward all direction but most of them is in the Northwest-Southeast direction. A new mountain is rising from the sea floor.

It is important to keep monitoring these events even if the intensities have decreased. This study did not consider data from the Comoros Islands, having access to these data will provide more precision in the event location and therefore relocating them is needed as they are shifting due to station distributions.

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