Earthquake epicenter location with combined T- and P-wave waveforms

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Abstract. In February 1999, a group of U.S. investigators deployed a 6-element hydrophone array for long term monitoring of the seismicity along the Mid-Atlantic Ridge between 15° and 35° N. During the 16th and 17th of March 2001, a large seismic swarm was detected by this array on the Lucky Strike segment of the Mid-Atlantic Ridge south of the Azores hotspot (~37° N) [Dziak 2003]. The highest frequency of events occurred at the beginning of the swarm, with activity becoming less frequent 1.5 hours afterwards [Dziak 2003]. This style of seismicity seems to be indicative of a diking event in the segment. The first determinations of the earthquake positions using T-wave records had a large degree of error and thus it is difficult to correlate the events spatially to determine the mechanism of the swarm. Here we report the results of a study to better define these locations using P-waves recorded by seismic stations in the Azores islands in addition to the T-waves. We acquired earthquake hydrophone logs indicating T-wave arrival times and P-wave arrival times from land-based seismogram logs. Each log was comprised of a list of earthquakes that occurred during the time frame mentioned. Events were then chosen from all listed events of the swarm according to the following criteria: number of stations that received the event, the magnitude of the event, and relative spacing between preceding and subsequent events. We then filtered out unnecessary frequencies and computed estimated arrival times as a guide to manually pick the T and P-wave arrival times. These arrival times were then analyzed using an iterative grid-search program that defined smaller and smaller grids to yield precise positions of the events selected for evaluation. These positions were compared to the positions determined previously. Preliminary results show that the addition of P waves has not significantly reduced the uncertainty of earthquake locations due to a poor signal to noise ratio and relatively large errors in P wave arrival times. It is thought that using the surface wave instead of the P-wave may improve the results..

1. Introduction

During the 16th and 17th of March 2001, a swarm of 128 earthquakes along the Lucky Strike segment of the Mid-Atlantic Ridge (MAR) near 37 degrees N was located by the hydrophone array in the northern MAR [Dziak, 2001]. This swarm lasted for 29 hours and almost half of the events took place in the first 1.5 hours. Following the peak of activity (42 events/hr), the event rate rapidly decreased to 5 events/hr. The swarm began at the Lucky Strike Seamount, but soon events were detected throughout the segment. The onset of seismicity was accompanied by 30 minutes of continuous, low frequency (3-15 Hz), tremor-like energy. The episode also produced 33 large enough earthquakes that were located by the global seismic network. This is the largest swarm ever recorded on the Lucky Strike Segment in the 25 years of monitoring the segment and one of the largest ever recorded on the MAR [Dziak 2003]. Field observations made at the Lucky Strike hydrothermal field by submersible dives following the swarm have indicated an increase in diffuse venting since the last measurements at the site in 1997. No evidence of recent pillow lava flows was found during these dives [Dziak 2003]. The Lucky Strike Segment is a slow spreading ridge that is dominated by the 8 km wide and 1 km high Lucky Strike Seamount. Within the summit depression of this seamount lies a vigorous hydrothermal system at about 1800 m depth. At its deepest, the segment is 3200 m from the surface [Smith 2003].

A similar seismic swarm occurred on the Juan de Fuca intermediate-rate spreading ridge on June 26 1993. This event began with low-level seismic activity and was accompanied by a seismic tremor. The seismic swarm showed clear propagation of the epicenters down segment and was accompanied by production of new pillow lavas [Dziak 1995]. Accompanying these events were hydrothermal event plumes that were emitted from the most seismically active regions of the ridge. These plumes are interpreted as being a result from the fracturing of the crust by an injection of magma [Baker 1995]. This event has been interpreted to be a lateral dike injection [Dziak 1995].

The Lucky Strike seismic swarm is selected for study due to its slow spreading rate [Smith 2003]. Observations have been made detailing diking events concerning both fast and intermediate spreading ridges, but there are no clear observations of diking events concerning slow spreading ridges. It is thought that the style of diking involved in slow spreading ridges may be different from the diking seen at intermediate and fast spreading ridges. In order to track the diking during a seismic swarm, hypocenters of events must be precisely located so as to understand the spatial and temporal distribution of events. This was done for the 1993 Juan de Fuca event [Fox 1995].

My research problem concerns the locations of the hypocenters associated with the Lucky Strike event. These locations were determined using only T-wave arrival times, which resulted in very large errors associated with the positions. Previous attempts to locate earthquakes in the Pacific Ocean carried with them less error due to the proximity of the hydrophone array to the center of seismicity [Schreiner 1995]. In the case of the Lucky Strike event, all of the earthquakes occurred well outside the hydrophone array and

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generally in line with it. This minimized the differences in arrival times among the hydrophones and greatly increased the errors that accompany the determination of the hypocenters using only T-waves. Due to these significant errors, the spatial distribution of events cannot be known for certain. With the current location predictions, no standard propagation of hypocenters can be determined. We decided to use P-wave arrivals in addition to T-wave arrivals to locate the events. We hoped that this additional pick would add certainty to the data set and produce precise locations. Also, since these P-wave logs came from the land-based seismometers on the Azores, this data could prove to be a cheaper and more easily available source of data to locate events on the Lucky Strike Segment.

2. Data Sets

In my study I dealt with two different data sets, those from the hydrophone array requested from the NOAA Vents program site and those from a seismometer array on the Azores Islands requested from the IRIS site. I was able to access four seismometer logs from the Azores. The Hydrophone array consists of six hydrophones deployed in February 1999 in the Northern Atlantic between 15 degrees and 35 degrees along the MAR. They are spaced ~1000 km apart and are centered on the ridge axis. The hydrophones receive T-wave seismic signals from events thousands of kilometers away with very low attenuation via the SOFAR channel [Dziak and Goslin 2003]. When choosing the events to be processed, I only selected events where at least 5 hydrophone stations recorded the event, the magnitude was above 209 dB, and there was sufficient spacing between the previous event and the subsequent event. This data set was then further refined by plotting the signals using the SAC (Seismic Analysis Code) program. Only events that had a reasonably clear and distinct T-phase arrival were chosen. It was also necessary for these events to have a corresponding seismogram data file form the Azores seismograph readings. After these criteria were met, 9 events were chosen for analysis.

3. Methods

Due to the time constraints on the project, it was decided that I would hand pick the arrival times. When manually picking the arrival times for this data, a large degree of error is possible in the pick. In order to identify the arrivals, I used a Fortran code that utilized the previous estimates of the locations of the earthquakes to produce a predicted arrival times for the T and P-phases for each event.

The hydrophone data was too noisy when first viewed (Fig. 1), so the data was filtered leaving only the frequencies between 2.0 and 10.0 Hz (Fig 2). In some cases, the frequency band had to be further narrowed to yield sufficient signal to noise ratio. Each hydrophone station was viewed separately (Fig 3) so to enable the

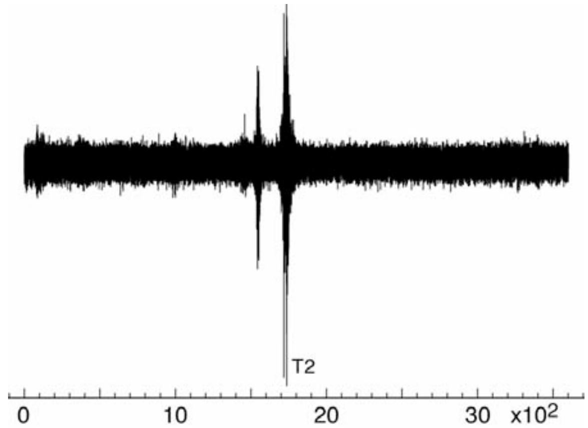

Figure 1. Example of raw hydrophone data.

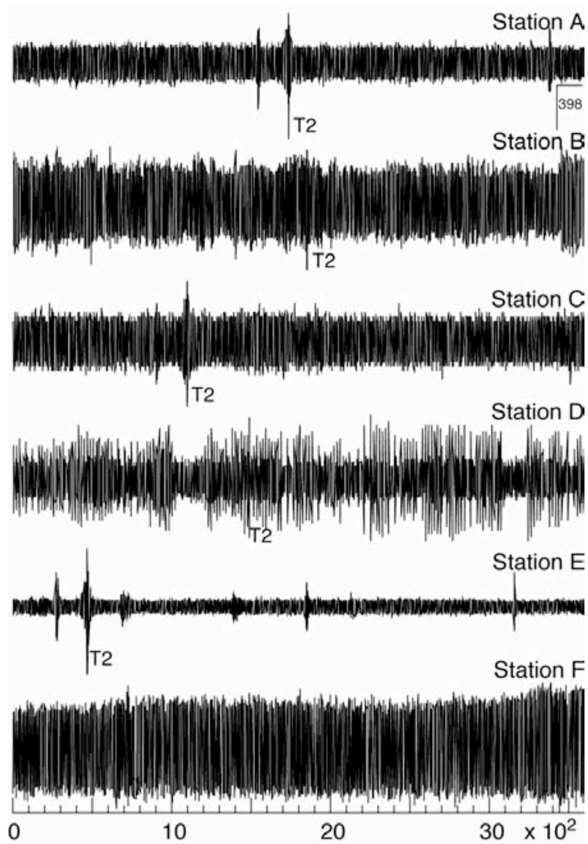

Figure 2. Hydrophone data that has been band-passed filtered leaving frequencies between 2.0 and 10.0 Hz. Hydrophone stations are located in the central North Atlantic.

examination of the most prominent wave packet (Fig 4) and chose the largest amplitude and the approximate center of the T-wave packet as the arrival time of the signal. This picking style was consistently used throughout the survey to ensure uniform results.

The land data was also extremely noisy when first viewed (Fig 5). We determined the optimum frequency for viewing the land-based seismogram data is between 0.05 to 0.1 Hz (Fig 6). The noise to signal ratio in the

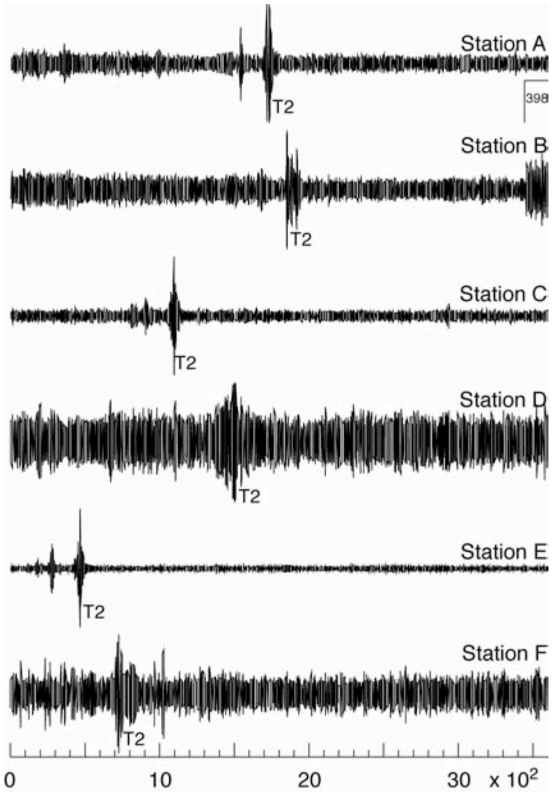

Figure 3. Hydrophone data band-passed filtered at a frequency range narrower than 2.0 and 10.0 Hz.

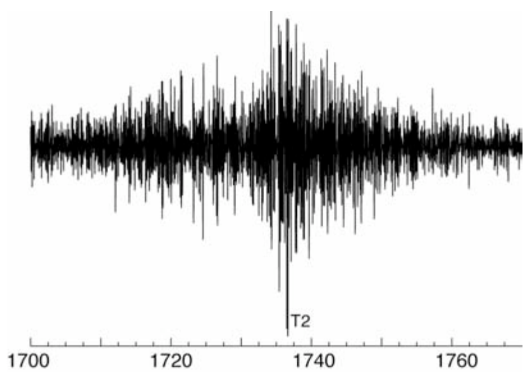

Figure 4. Selection of a prominent waveform from filtered hydrophone data.

land-based data was quite high for most of the events. I attempted to pick the P-wave arrival in some of the logs, but the pick was inaccurate due to the amount of noise present. The arrival times were then picked out of the file headers using a C-shell program. This data set was then processed by various programs to yield an output in the format needed to input into a grid search program.

We employed a non-linear grid-search method based on Rowlett and Forsyth [1984] and Wilcock and Toomey [1991] when locating the events [Shen 1997]. This program defines a grid in which each intersection in the grid represents a set of possible origin times for the events. The program searches through each set of times defined by the grid intersections until it finds the smallest misfit to the actual event times picked from the seismograph and hydrophone logs. Smaller and smaller

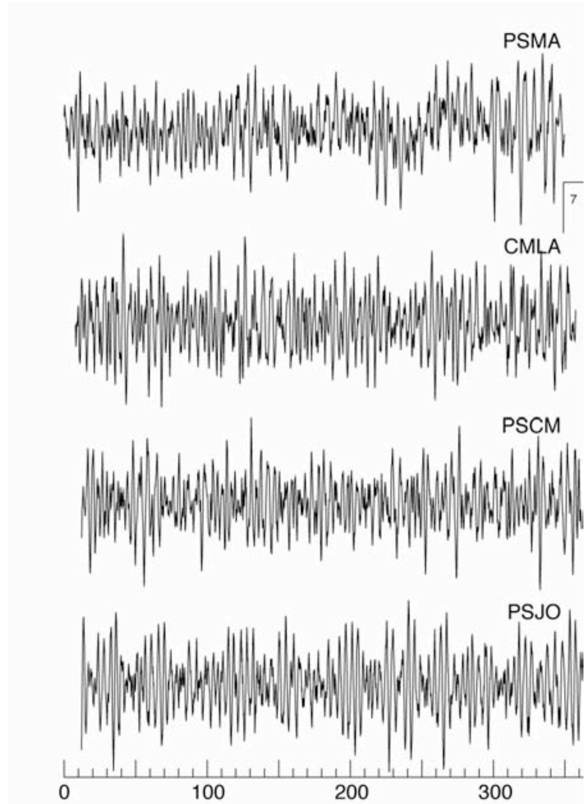

Figure 5. Raw land-based seismogram data located near the Azores in the central North Atlantic.

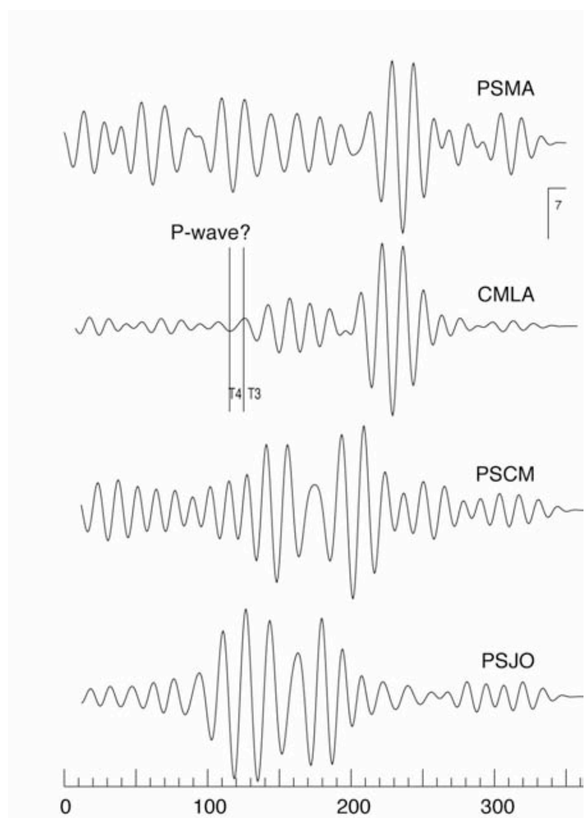

Figure 6. Land-based seismogram data band-passed filtered between 0.05 to 0.1 Hz.

grids are then implemented to refine the search and yield the lowest possible misfit for the arrival times chosen previously. When each origin time has been fitted to the single grid point with the smallest combined misfits, the program uses these times to calculate the location of the hypocenter. These locations are then mapped with bathymetry and station location (Fig 7).

4. Results

The resulting event locations were inaccurate when the picks involving the P-wave arrivals were involved. The locations involving only the T-wave arrivals were close to the previous positions, indicating that the T-wave arrivals were picked correctly. It was determined that the data was not refined enough to yield precise positions using the P-wave. The large uncertainty in event position remains and additional processing is needed to improve the results.

5. Future Work

The surface waves are more evident in the land-based seismogram data than the P-waves. We propose the use of the surface wave arrival time in conjunction with the T-wave arrival time as a possible method to determine precise positions of these events. This method is modeled after that of Forsyth and Shen used for events on the Easter-Pacific fast spreading center [Forsyth 2003]. Surface waves, like T-waves, yield excellent locations for epicentral position but poor depth constraints. We suppose that we will be able to cross-correlate the surface wave waveform of the largest event and use relative arrival times from this point for other events. It will be of interest to observe if this method, which has previously been tested on a fast spreading center, can be applied to the Lucky Strike Segment of the slow-spreading Mid-Atlantic Ridge.

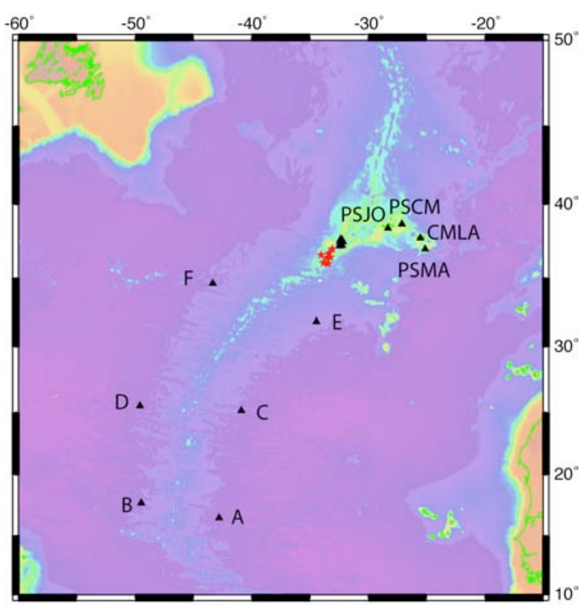

Figure 7. Location of seismic stations.

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