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A repeatable seismic source for tomography at volcanoes

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Abstract
One major problem associated with the interpretation of seismic signals on active volcanoes is the lack of knowledge about the internal structure of the volcano. Assuming a 1D or a homogeneous instead of a 3D velocity structure leads to an erroneous localization of seismic events. In order to derive a high resolution 3D velocity model of Mt. Merapi (Java) a seismic tomography experiment using active sources is planned as a part of the MERAPI (Mechanism Evaluation, Risk Assessment and Prediction Improvement) project. During a pre-site survey in August 1996 we tested a seismic source consisting of a 2.5 l airgun shot in water basins that were constructed in different flanks of the volcano. This special source, which in our case can be fired every two minutes, produces a repeatable, identical source signal. Using this source the number of receiver locations is not limited by the number of seismometers. The seismometers can be moved to various receiver locations while the source reproduces the same source signal. Additionally, at each receiver location we are able to record the identical source signal several times so that the disadvantage of the lower energy compared to an explosion source can be reduced by skipping disturbed signals and stacking several recordings.

Key words *Mt. Merapi – tomography – active seismics*

1. Introduction

The seismic wavefield measured at a seismometer site is not only a function of the seismic source, but also depends on the structure of the propagation medium. In special cases the effects of the propagation path may actually dominate in the observed seismogram (*e.g.*, Wegler and Seidl, 1997). Therefore, to localize and model seismic sources inside of volcanoes, it is necessary to have, apart from the measurements of the seismic signal at the surface, knowledge of the internal structure of the volcanic edifice. The most important parameters for seismology are the distributions of *P*- and *S*-velocity inside the volcano, but also information about scattering and attenuation properties is needed. Due to the lack of 3D models usually 1D structures are used to determine hypocenters of volcanic events (*e.g.*, Klein *et al.*, 1987). Also for waveform modelling (Goldstein and Chouet, 1994) or modelling of dispersion (Wegler and Seidl, 1997) mainly 1D velocity structures are used. In contrast to usual earthquake seismology, however, we cannot expect a 1D, layered medium is to be a good approximation at volcanoes. To achieve a 3D image of the seismic velocities inside a volcano, tomography is the most common method.

Toomey and Foulger (1989), Lees (1992), Cardaci *et al.* (1993), Rowan and Clayton (1993), Ohmi and Lees (1995), and Benz *et al.* (1996) used volcanic earthquakes as seismic sources. Since the determination of the hypocenters depends on the velocity model, a simultaneous inversion of earthquake locations and

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distribution of P- and S-velocity is necessary (Kissling, 1988). Additionally the non-linearity of the inversion is large, because the turning point of the rays is inside the target volume (Evans and Zucca, 1988).

Evans and Zucca (1988) and Achauer *et al.* (1988) used crustal phases of explosions. For artificial sources the source times and locations are known. Therefore an inversion for these parameters was not necessary. Additionally, the non-linearity of the inversion was reduced, since the sources were located ouside the target with rays at near-vertical incidence. On the other hand, ambiguity increases and only relative values for v_P and v_S could be computed, because the exact ray path and travel times of the rays outside the modeled area remain unknown. Due to financial and logistical considerations usually only few artificial sources are available. To achieve a good ray coverage a large number of receivers is therefore necessary. Another major problem in using explosion sources is the seismic activity of the volcano. The frequently occurring seismo-volcanic events are much stronger than artificial sources and often are in the same frequency range. If one uses explosion sources for tomography, one usually has only one shot at each shot point. If the signal is disturbed by a volcanic event, the data of this shot can probably not be used in the inversion.

2. A repeatable seismic source

As part of the MERAPI-project a tomography experiment using active seismic sources in-

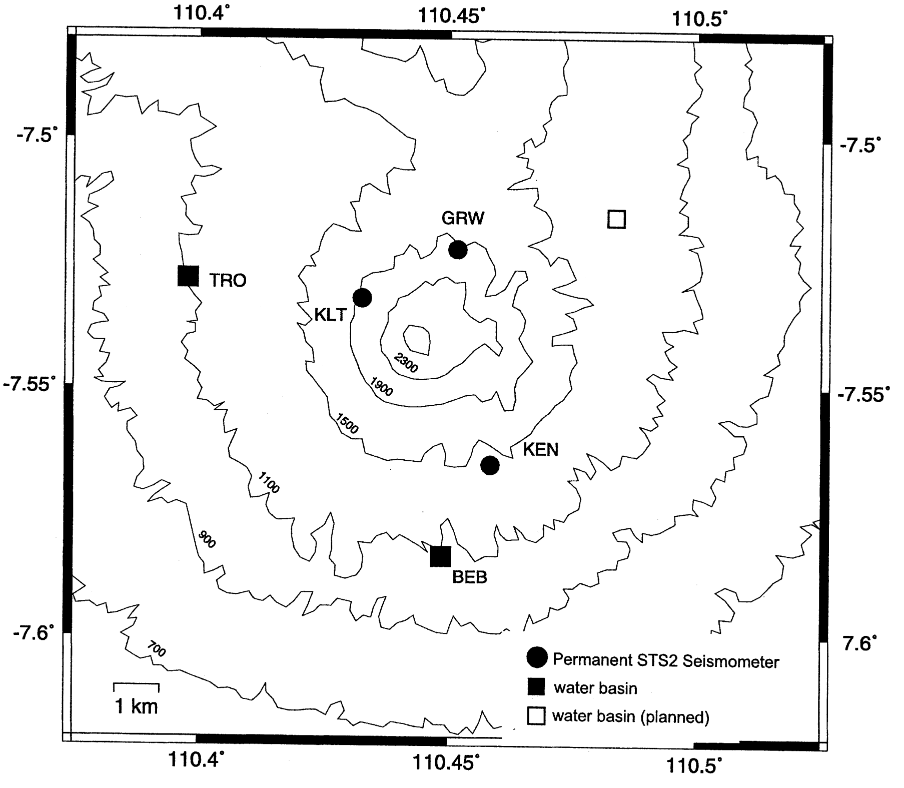

Fig. 1. Locations of water basins and permanent broadband seimometers at Mt. Merapi.

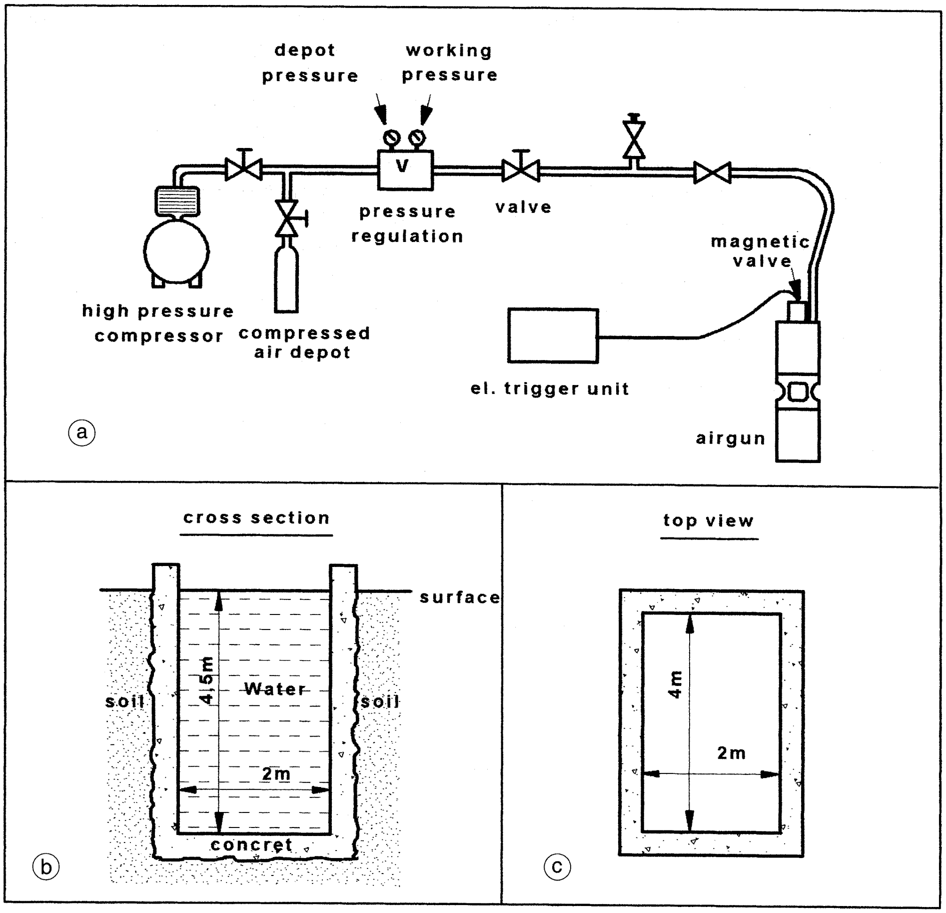

Fig. 2a-c. a) High pressure airgun equipment. The control unit triggers the airgun shot. The high pressure compressor fills the air depot, from which the airgun can be reloaded quickly. The pressure regulation is used to adjust the desired shot pressure. b) and c) Artificial water basin for the airgun source.

side the target volume is planned at Mt. Merapi (Java). Using this configuration absolute values for v_P and v_S can be obtained and an inversion for the source parameters is not necessary. (Only correction terms accounting for near source structure are needed). A possible solution to the above mentioned problems in using explosions is the use of a repeatable, artificial source. In contrast to an explosion, such a source can reproduce the same signal for several times at the same source point. Repeatable seismic sources used in exploration seismics are vibrators, airguns etc. The diameter of our target volume at Mt. Merapi is 10 km (fig. 1). Therefore we need a source that is strong enough to produce a measurable signal in a distance of more than 10 km in a volcanic environment. Furthermore, handling should be possible in the difficult terrain of a volcano. One of the strongest repeatable seismic sources are airguns, which are commonly used in marine geophysics (fig. 2a-c). We use airguns with an air chamber volume of

2.5 l at a working pressure between 5-15 MPa. For operating the airguns, two water basins were constructed in 1996 at Mt. Merapi. A third one is planned for 1997 (fig. 1). These water basins have a depth of 5 m, resulting in a water column of more than 3 m above the airgun (fig. 2a-c). In a similar experiment at the North-Anatolian fault zone (Turkey) Pittorf (1991) recorded signals on a 6.3 km long profile shooting in an artificial water basin and on a 20 km long profile shooting in a lake. The whole equipment (source and receiver) can be moved manually in rough terrain.

At the source point the source can be shot several times, while the seismometer positions are changed for each shot. In that case the number of rays is not only the number of seismometers times the number of source points, but this number is also multiplied by the number of movements of the receiver locations. At Mt. Merapi we plan to use only 3 source locations and 31 seismometers, which would traditionally lead to only 93 different rays. Using a repeatable seismic source, it is possible to move the seismometers from one location to another. Moving them, *e.g.*, 18 times and repeat the shooting at each location would lead to 1674 different ray paths.

The repeated shots can also be recorded several times at the same receiver location. The best, non disturbed recordings can be selected. Additionally, stacking of several recordings with low noise level is possible to improve the signal to noise ratio.

The seismic structure inside the volcano can change with time *e.g.* due to changes in temperature, changes in the stress field or dyke intrusions. Ratdomopurbo and Poupinet (1995) and Poupinet *et al.* (1996) observed such variations at Mt. Merapi using multiplets of earthquakes. Using a very stable, artificial source signal, it might be possible to monitor these changes. Special paths must be shot in a regular (*e.g.*, monthly) interval to observe differences in the seismograms.

3. First data

During a pre-site experiment in the summer of 1996 two of the three water basins were tested. The goals of this experiment were to test whether the source signal is stable and whether it is strong enough to reach 10 km. Figure 1 shows the locations of the two tested and the

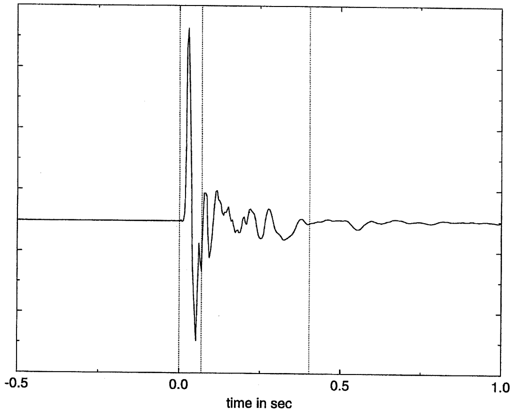

Fig. 3. Source signal of airgun shot recorded in 3 m distance from the water basin BEB (*Z*-component). The dotted lines indicate the time intervals used for cross-correlation.

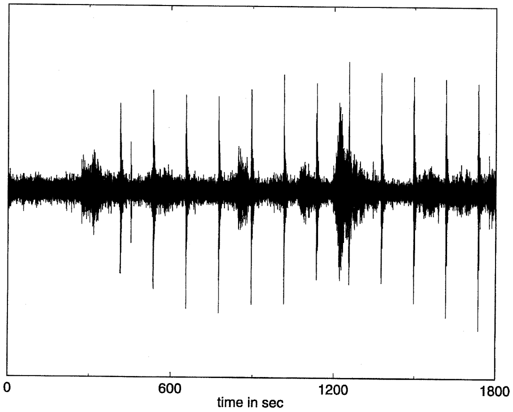

Fig. 4. 12 airgun shots (5 MPa) with an shot interval of 2 min recorded in a distance of 3 km from the shot point. The eighth shot is disturbed by a volcanic event.

third planned water basin. The altitude of the sites is about 1000 m. The area inside the 1000 m contour line is our target volume. We shot the airgun about 100 times at site BEB and about 40 times at site TRO with different air pressures. The working pressure is not limited by the airgun, but by the stability of the basins. The maximum pressure we used so far is 7 MPa.

Figure 3 shows a typical source signal of the basin BEB recorded in a distance of 3 m from the water basin. To test the stability of the source signal we computed cross-correlations of 45 different shot seismograms using two different time windows. Using the time window 0.0-0.07 s (fig. 3) we computed a mean correlation coefficient of 0.98. For the time window 0.0-0.4 s, which additionally includes the less stable air bubble signal, the correlation of different shots is still as high as 0.97. The variation of first onset times for different shots is smaller than the used sample rate of 4 ms.

As receivers we used 3 permanent 3-component broadband stations, which are all installed at altitudes between 1500 and 2000 m. Figure 4 shows a 15 min seismogram recorded at station KEN, which is located in a distance of 3 km to the shot point in BEB. 12 shots with a shot interval of 2 min are visible. The same source-receiver combination is used in fig. 5, where 19 different shots are plotted. The rather complicated signal is reproduced in the different shots. Smaller phases can be distinguished from noise, since they appear in all seismograms as coherent energy. Stacking enhances the signal to noise ratio of such signals.

The spectrum of the airgun signal has its maximum near 15 Hz (fig. 6). In a distance of 3.5 and 5 km this maximum is reduced to 7.7 and 7.2 Hz. The higher frequencies are attenuated below the noise level. At the Station KEN in a distance of 8 km the single shot was no longer visible. Unfortunately we did not have sufficient recordings for stacking.

In addition to the permanent stations, we used a line of 6 temporary 3-component 1 Hz seismometers. A short profile of 1 km length, inter-receiver distance about 200 m, is shown in fig. 7a,b. The signal shows a strong coda, which widens fast with increasing distance. The amplitudes and the frequency content of the signal changes significantly even over the short station distance of 200 m. For this distance of less than 2 km from the source, however, it is not difficult to find the first arrival (fig. 7b). It propagates with a surface velocity of 2.7 km/s.

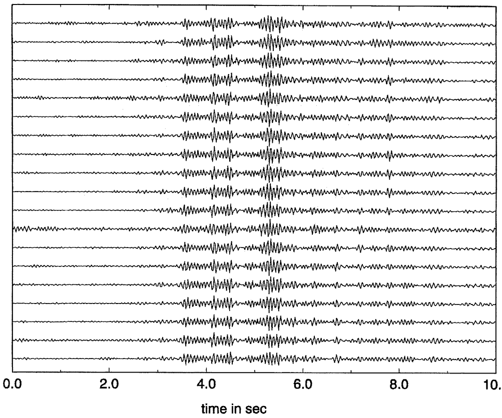

Fig. 5. 19 different shots from one source point to one receiver point (3 km distance).

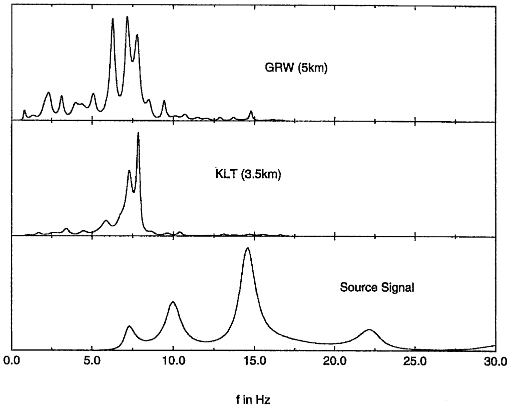

Fig. 6. Spectra at the source point, in 3.5 km distance (KLT) and in 5 km distance (GRW) recorded from a single shot at a shot site near TRO. The single shot was not visible in 8 km distance (KEN).

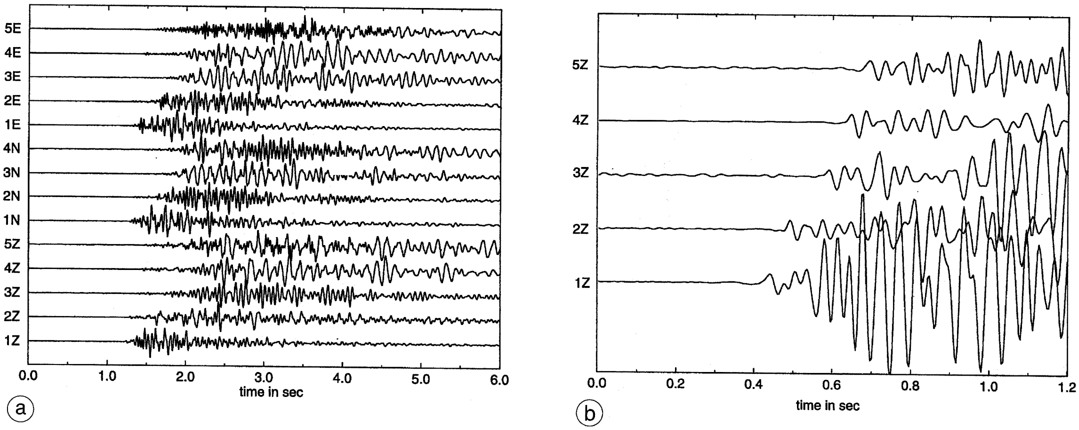

Fig. 7a,b. a) 3-component, 1-km long profile near the source point BEB (trace normalized); b) *Z*-component of first arrivals.

4. Test results

Our first experiments show that airgun shots in water basins produce a signal that is very stable. This reduces the required logistics enormously, since not all receiver locations must be occupied by seismometers at the same time. Additionally, stacking and selection of undisturbed signals is possible.

Single shots are recorded to a distance of more than 5 km. To reach the desired 10 km stacking of a large number of seismograms is necessary. 100 shots and a shot interval of 2 min lead to a total shooting time of 3 h 20 min per profile and source point. This is a realistic time and would enhance the signal to noise ratio by a factor of 10.

We found a rather complicated seismic structure at the sites we have already investigated. Even within the short station distance of 200 m we observed large differences in the seismograms. This can be explained by strong layering and resonance effects at the seismometer sites. To recognize *S*-waves and later arrivals, station distances as small as 100 m are necessary. Scattering attenuates the signal and leads to strong coda waves, which dominate in the seismograms. This makes active seismic experiments quite difficult and shows, that for the modelling of natural, volcanic seismic events the effects of propagation path and the seismometer site should be taken into account.

5. Future investigations

An idealized source-receiver geometry of the planned tomography experiment is shown in fig. 8. Three sources (two are already constructed and tested) are located at a height of 1000 m. About 18 profiles radially symmetric to the volcano are planned. These profiles also start at a height of 1000 m. The final height is 2000 m. An extension to the summit at 3000 m is not possible due to the steep topography. Each profile has a length of 3 km. Since we have 31 3-component seismometers, a seismometer distance of 100 m can be achieved. From this configuration we can expect a resolution of the final model of less than 1 km.

One profile will be built up after which shots will be fired at each of the three sources. For the sources far from this profile stacking of up to 100 times is planned. Afterwards we move the seismometers to the next profile and repeat the procedure.

Difficulties arise from the strong topography, which permits installation of instruments

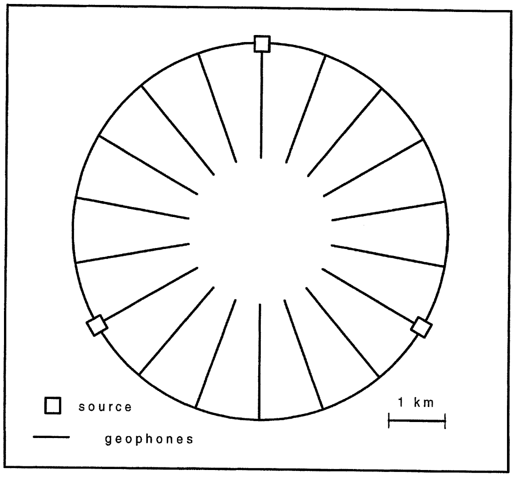

Fig. 8. Idealized source-receiver geometry of the planned tomography experiment. Squares indicate the source locations, lines the profiles. The diameter of the target volume is 10 km. Each profile has a length of 3 km.

at elevations above 2000 m only in few areas. Deep erosion valleys, radially symmetric to the volcano, force an alignment of the profiles along the topography. Especially in the rugged east flank we expect a deviation from the idealized geometry. Another critical area is the southwest part. Due to the permanent danger of nuée-ardente no profiles are planned in this area.

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