Numerical Modeling of Microearthquake Monitoring at the Utah FORGE Site

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Summary

We conduct numerical modeling of microearthquake (MEQ) monitoring at the Utah FORGE site. We study microseismic-wave responses of EGS stimulation-induced MEQs at six surface geophones and a borehole geophone array in Well 68-32. Through this study, we would understand the smallest MEQ magnitudes that could be recorded at the surface geophone and the borehole geophones, respectively. In addition, we study the accuracy of MEQ event locations and focal mechanism inversion using the currently deployed surface and borehole geophones.

MEQ magnitudes expected at borehole and surface geophones

We conduct numerical modeling of MEQ-wave responses at the Utah FORGE site, and study the smallest magnitudes of MEQs that could be recorded at the deployed surface and borehole geophones shown in Figure 1. We use a reflectivity modeling code to simulate MEQ-wave propagation in a layer model with P- and S-wave velocities displayed in Figure 2. Figure 3 illustrates three parameters of earthquakes, strike ϕ, dip δ, and rake λ. We calculate the moment tensor components using earthquake parameters and the following equations:

$$M_{xx} = -M_0(\sin\delta\cos\lambda\sin 2\phi + \sin 2\delta \sin\lambda \sin^2\phi),$$

$$M_{xy} = \quad M_0(\sin\delta\cos\lambda\cos 2\phi + 0.5\sin 2\delta\sin\lambda\sin 2\phi),$$

$$M_{xz} = -M_0(\cos\delta\cos\lambda\cos\phi + \cos 2\delta\sin\lambda\sin\phi),$$

$$M_{yy} = \quad M_0(\sin\delta\cos\lambda\sin 2\phi - \sin 2\delta\sin\lambda\cos^2\phi),$$

$$M_{yz} = -M_0(\cos\delta\cos\lambda\sin\phi - \cos 2\delta\sin\lambda\cos\phi),$$

$$M_{zz} = \quad M_0\sin 2\delta\sin\lambda\,,$$

where the seismic moment scalar M_0 is converted from the MEQ magnitude M_w. We use the strike, dip and rake of 188.6, 90 and -90 degree, respectively, for an MEQ event at the depth of 2218.9 m for numerical modeling. Figure 4 shows example Green's functions computed using the reflectivity code for a borehole geophone located at the depth of 987.646 m.

We convolve a Ricker source wavelet with the computed Green's functions and sum them together according to the moment tensors to obtain synthetic seismograms at the borehole and surface geophones as depicted in Figure 5 and Figure 6, respectively. The center frequencies of the Ricker source wavelets are 200 Hz and 50 Hz for borehole and surface geophones, respectively.

We then obtain the relationship between the logarithmic scale of the average amplitude of synthetic seismograms at borehole geophones and the MEQ magnitudes as displayed in Figure 7. In Figure 7, the horizontal line is the noise level of the borehole geophones. The result in Figure 7 demonstrates that the expected smallest MEQ magnitude to be recorded at the borehole geophones would be approximately -2.2, depending on the geophone noise level.

We conduct similar numerical modeling of MEQ seismograms at the surface geophones, and obtain the relationship between the logarithmic scale of the average amplitude of synthetic seismograms at surface geophones and the MEQ magnitudes as shown in Figure 8. The horizontal line in Figure 8 is the noise level of the surface geophones. The result in Figure 8 shows that the expected smallest MEQ magnitude to be recorded at the surface geophones would be approximately -1.

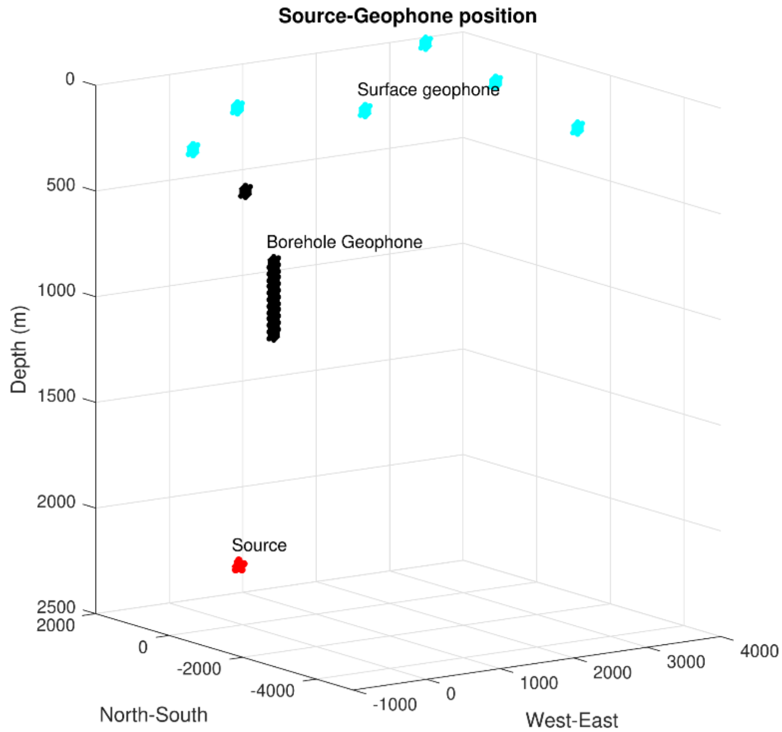


Figure 1: Surface and borehole geophone locations at the Utah FORGE site. “Source” denotes the MEQ location around the EGS stimulation region for numerical modeling.

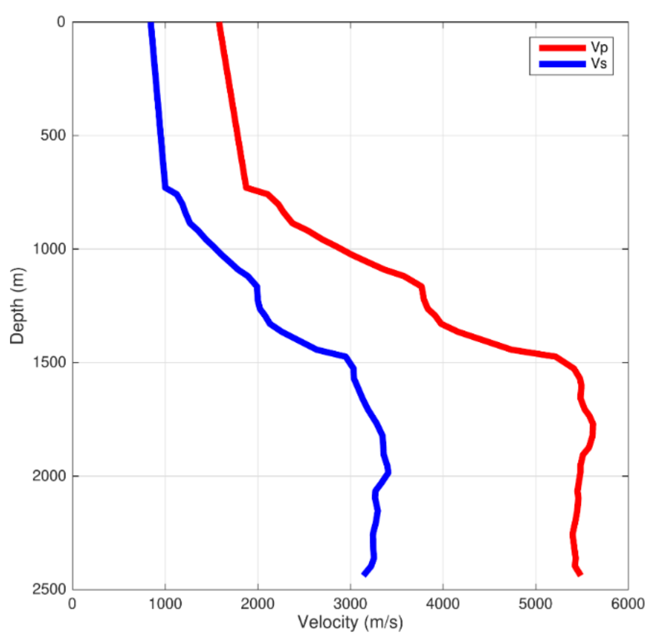


Figure 2: P- and S-wave velocity models at the Utah FORGE site used for numerical modeling of MEQ wave propagation.

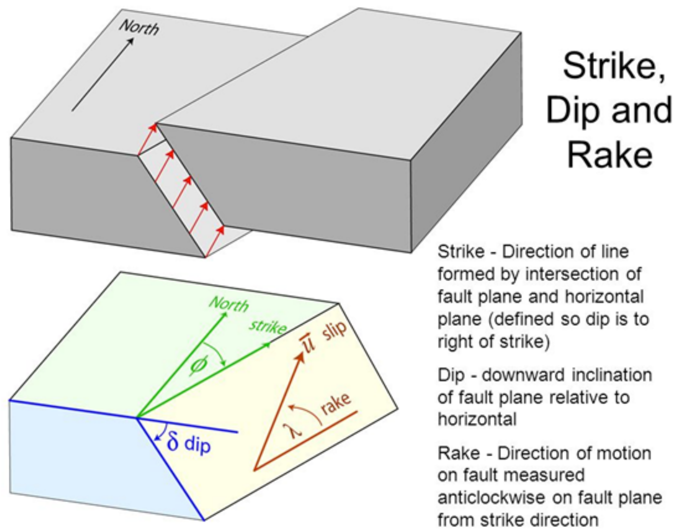


Figure 3: Illustration of parameters, strike ϕ, dip δ, and rake λ, of an MEQ event.

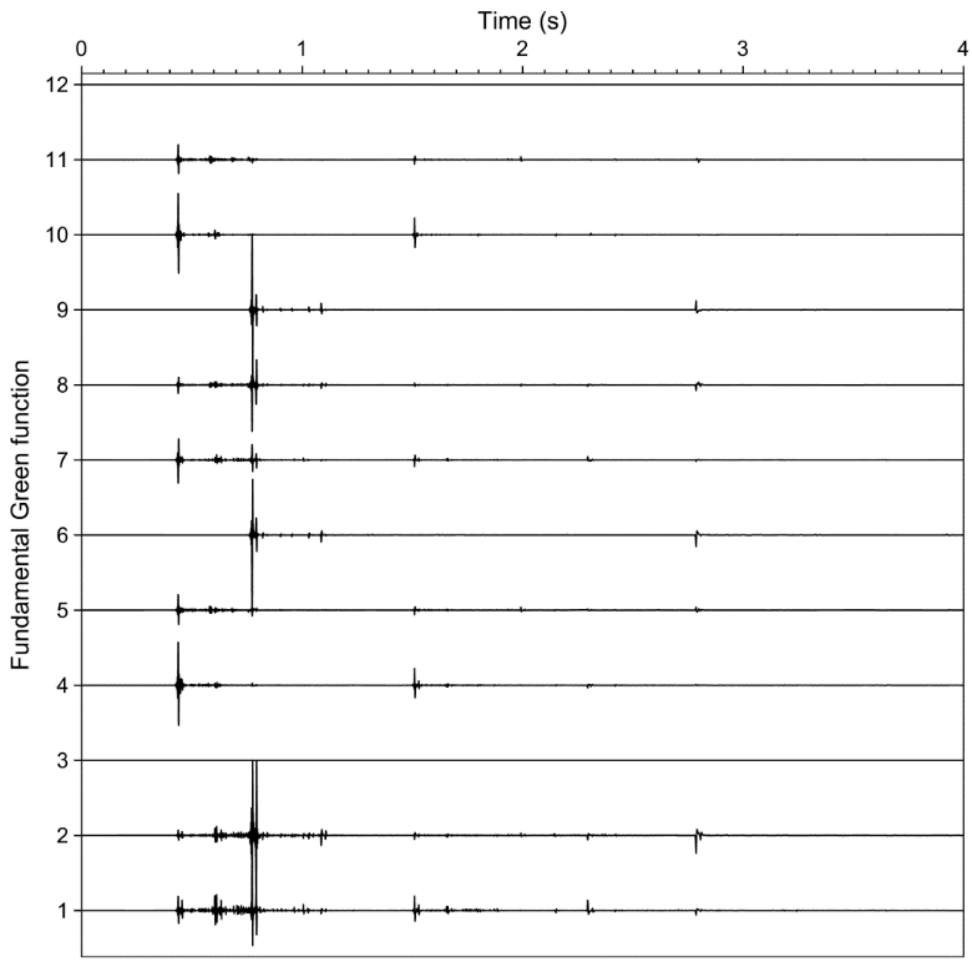


Figure 4: Synthetic three-component Green's functions of four fundamental moment-tensor sources for the MEQ source and a geophone at the center of the borehole geophone array in Figure 1

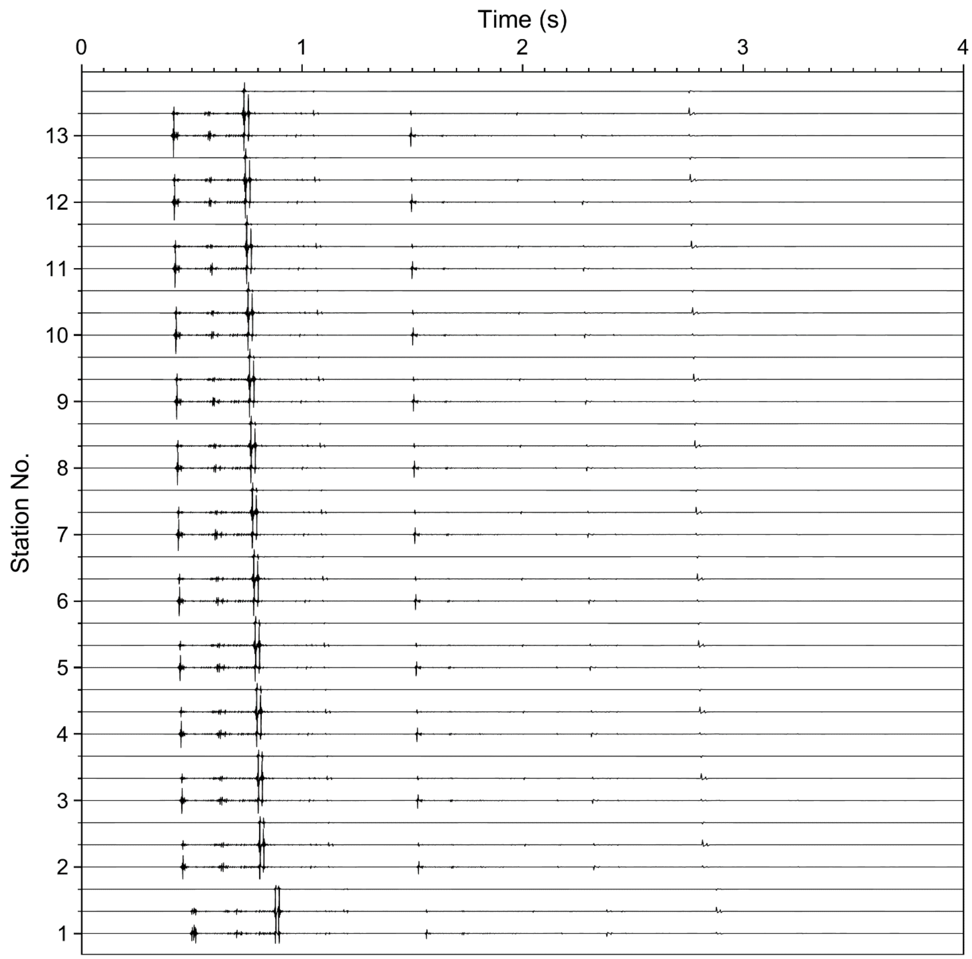


Figure 5: Vertical, radial and tangent components of synthetic seismograms at the 13 borehole geophones for an MEQ of M_w=-2 located at the red spot in Figure 1.

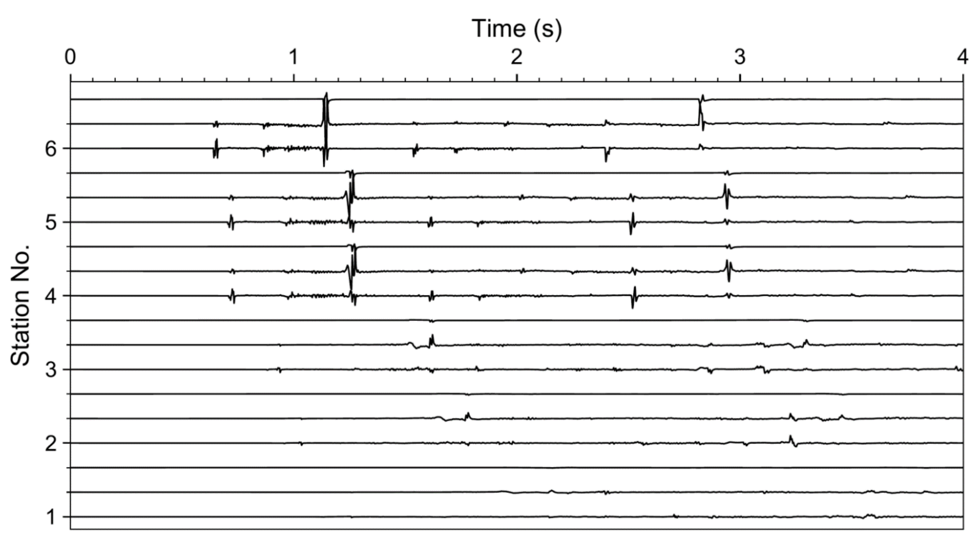


Figure 6: Vertical, radial and tangent components of synthetic seismograms for the 6 surface geophones for an MEQ of M_w=-2 located at as the red spot in Figure 1.

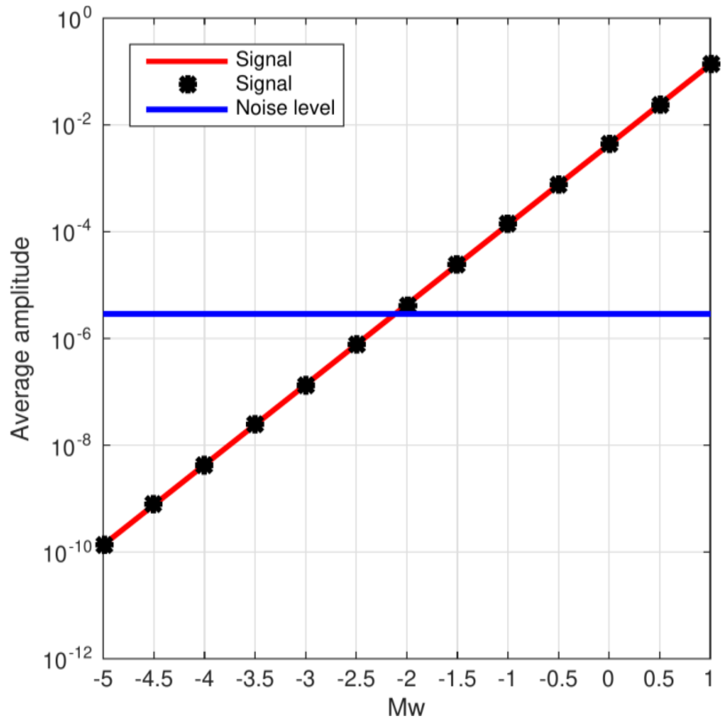


Figure 7: The logarithmic scale of the average amplitude of the synthetic seismograms versus the MEQ magnitude for the borehole geophones at the Utah FORGE site. The horizontal blue line is the geophone noise level.

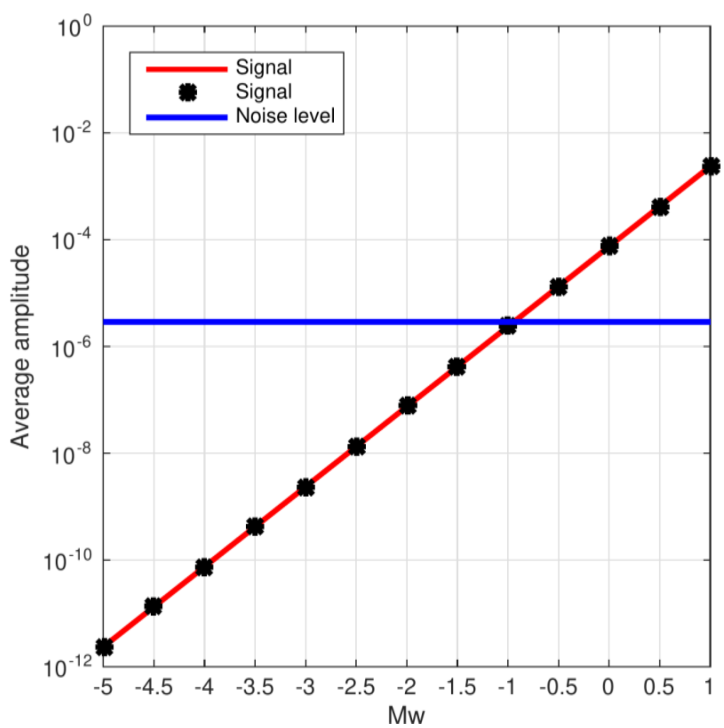


Figure 8: The logarithmic scale of the average amplitude of the synthetic seismograms versus the MEQ magnitude for the surface geophones at the Utah FORGE site. The horizontal blue line is the geophone noise level.

MEQ monitoring accuracy

We study the accuracy of microearthquake event locations and focal mechanism inversion using the surface and borehole geophones deployed at the Utah FORGE site. This study helps us understand what accuracy of MEQ event location and focal mechanism inversion can be expected with the deployed borehole and surface geophones during monitoring for the EGS stimulations.

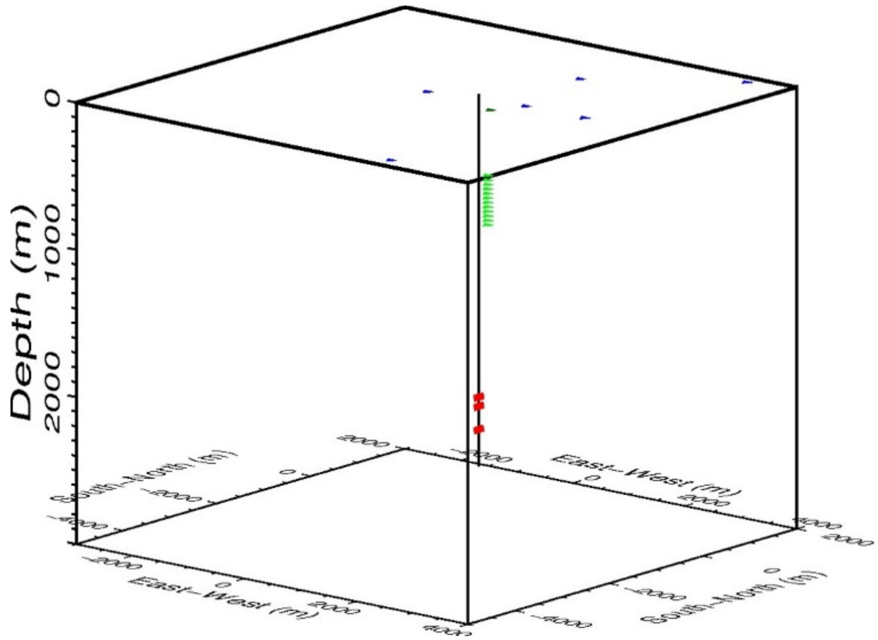
The Utah FORGE project plans to stimulate fractures at three depth ranges: 7386 – 7536 ft, 6942 – 6952 ft, and 6736 – 6746 ft beneath the surface in Well 58-32. We assume that the strikes of the fractures are approximately along the South-North direction, and that three simulation fractures (red lines) are located at depths of 2274 m, 2117 m, and 2055 m.

For microearthquake (MEQ) monitoring, the Utah FORGE project deploys six surface geophones and a borehole geophone array in Well 68-32 as depicted in Figure 9. We use P and S velocity models shown in Figure 2 to generate MEQ arrival times and waveforms at the surface and borehole geophones for 951 synthetic events in the red regions in Figure 9.

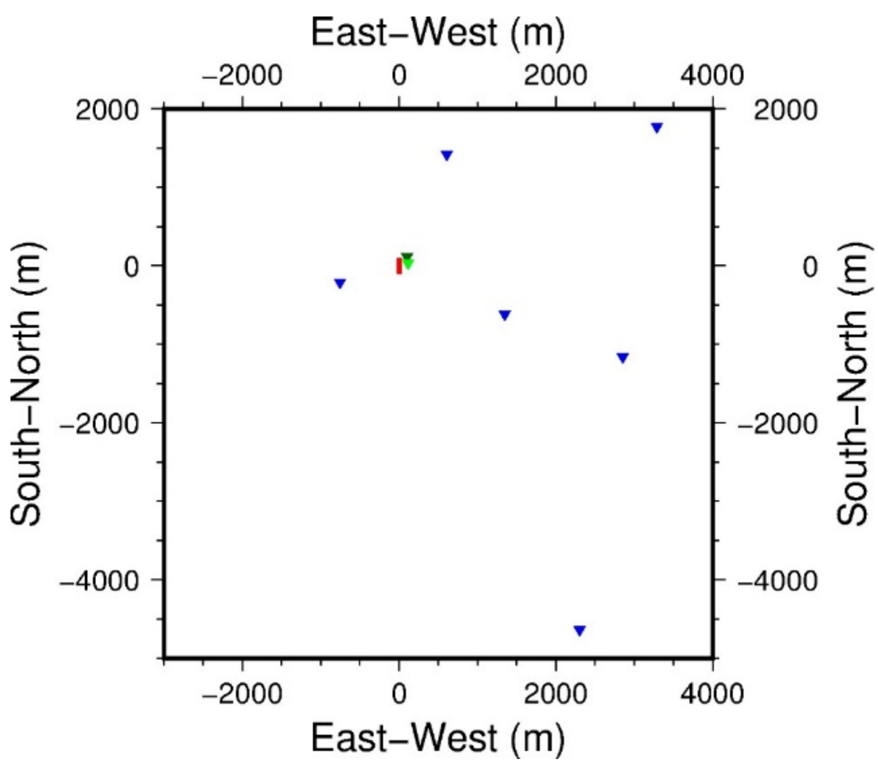
We use these arrival times and waveforms to invert for MEQ event locations and focal mechanisms, and compute their standard deviation errors relative to those of synthetic MEQ events. We add a Gaussian random perturbation of arrival times from 0% to 5% to the computed P- and S-wave arrival times during inversions of MEQ event locations and focal mechanisms, and calculate their standard deviation errors for various Gaussian random perturbation of arrival times. Figure 10 displays the results of standard deviation errors of the MEQ event locations versus the Gaussian random perturbation of arrival times from 0% to 5%, showing that the horizontal location uncertainty varies approximately from 1 m to 70 m, and the vertical location uncertainty varies approximately from 0.1 m to 10 m. Our computed the standard deviation errors of focal mechanisms show that the strike/dip/slip angles have an uncertainty of 7 degrees, and the non-double-couple component has an uncertainty of 12%.

Conclusions

We have conducted numerical modeling of microearthquake monitoring at the Utah FORGE site using 6 surface geophones and 13 borehole geophones. Our study shows that: (1) the expected smallest MEQ magnitude recorded at the surface geophones is approximately -1; (2) the expected smallest MEQ magnitude recorded at the borehole geophones is approximately -2.2; (3) the MEQ event location uncertainties are approximately from 1 to 70 m in the horizontal direction, and 0.1 to 10 m in depth for the Gaussian random perturbation of arrival times from 0% to 5%; and (4) the corresponding standard deviation errors of MEQ focal mechanism are 7 degrees in the double-couple components and 12% in the non-double-couple component.



(a)



(b)

Figure 9: Panel (a) shows the locations of six surface geophones in blue down-pointing triangles, the borehole geophones in green triangles in Well 68-32, and the red regions of synthetic MEQs around Well 58-32 for the numerical study of MEQ monitoring at the Utah FORGE site. The down-pointing triangles in blue on Panel (b) are locations of the 6 surface geophones.

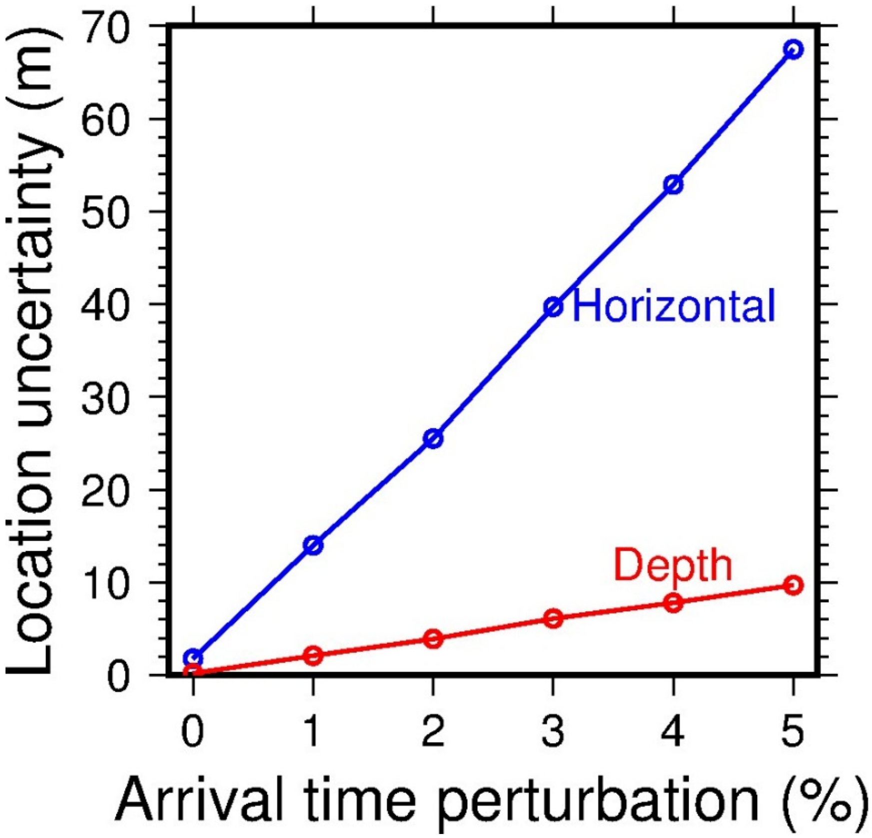


Figure 10: Standard deviation errors of the MEQ event locations versus the Gaussian random perturbation of arrival times from 0% to 5% using the surface and borehole geophones at the Utah FORGE site.