EPICENTRAL LOCATION OF REGIONAL SEISMIC EVENTS BASED ON LOVE WAVE EMPIRICAL GREEN'S FUNCTIONS FROM AMBIENT NOISE

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ABSTRACT

The purpose of this research is to develop and test a novel method of regional seismic event location based on exploiting Empirical Green's Functions (EGF) that are produced from ambient seismic noise. Elastic EGFs between pairs of seismic stations are determined by cross-correlating long ambient noise time-series recorded at the two stations. The EGFs principally contain Rayleigh and Love wave energy and our focus is placed on utilizing these signals between 5- and 15-sec period. Our approach and the results of several tests based exclusively on Rayleigh waves were described in detail by Barmin et al. (2011). During the past year we have refined the method and have continued to evaluate its capabilities. The main refinement is the introduction of EGFs for Love waves. The database of Love wave EGFs for the Western USA has been constructed following the methodology described in Lin et al. (2008). This database consists of more than 365,000 EGFs obtained from more than 1700 stations of stationary networks and the EarthScope USArray.

Love wave group time delays are less sensitive to event depth than Rayleigh wave group time delays. They are also less sensitive than Rayleigh waves, on average, to the source mechanism. Thus, everything else being equal, Love wave EGFs are expected to provide better epicentral accuracy than Rayleigh waves. We demonstrate this with numerical simulations of the location capabilities based on Love wave EGFs, which confirms significantly lower location bias than using Rayleigh waves alone. The advantage of Love waves to locate seismic events is mitigated somewhat by the fact that Love wave EGFs have a lower SNR than Rayleigh waves. Thus, the combined use of both types of waves is advised.

Applications of Rayleigh and Love wave EGFs to locate four Reference Events (three well located earthquakes and a mine collapse) in the Western USA (Nevada, Utah, California) have been made. The separate Rayleigh and Love epicentral locations all agree to within 1 km distance for these events with event depths for which both methods are expected to work well. Future work will continue to refine and test the location procedure and explore the ability to constrain depth and the moment tensor using ambient noise EGFs for Rayleigh and Love waves.

OBJECTIVES

The purpose of this research is to improve seismic event location accuracy and event characterization by exploiting Empirical Green's Functions (EGFs) that emerge by cross-correlating long time sequences of ambient noise observed at pairs of seismic stations. Because ambient noise EGFs are dominated by surface waves, the method uses surface wave energy for location purposes. The method of epicentral location as well as proof-of-concept applications to a set of seismic events in the western US have been described by Ritzwoller et al. (2009) and more recently and completely by Barmin et al. (2011). Present efforts apply Love wave EGFs from 5 to 15 sec period to the epicentral location problem. Love wave group time delays are less sensitive to event depth and source mechanism than Rayleigh wave group time delays. Thus, in principal they are better suited to epicentral location when hypocentral depth is poorly known. The advantage of Love waves to locate seismic events is mitigated by the fact their Love wave EGFs have a lower SNR than Rayleigh waves. A database of Love wave EGFs for the Western USA has been constructed following the methodology described in Lin et al. (2008). Several applications of Rayleigh and Love wave EGFs to locate Ground Truth events (earthquakes and mining blasts) in the Western USA (Nevada, Montana, Utah, California) have been made. Future work will continue to refine the location procedure and explore the ability to constrain depth and the moment tensor using ambient noise EGFs both for Rayleigh and Love waves.

RESEARCH ACCOMPLISHED

1. Introduction

In the paper by Barmin et al. (2011), hereafter referred to a Paper I, a new procedure was described and tested for epicentral location of shallow seismic events based on use of the Empirical Green's Functions obtained from ambient seismic noise (e.g., Shapiro & Campillo, 2004; Shapiro et al., 2005; Bensen et al., 2007). In the period band between 7 and 15 s, ambient noise is strong and shallow crustal earthquakes are energetic. Elastic EGFs are determined by cross-correlating ambient noise time-series recorded at pairs of stations. Only the vertical component of the ambient noise in the period range 7-15 s, which is dominated by the fundamental Rayleigh mode, was used in Paper I for building the EGFs. It was demonstrated that this approach has several features that make it a useful addition to existing location methods. Its accuracy does not require knowledge of Earth structure. It works for weak events where the detection of body wave phases may be problematic. The empirical Green's functions (EGFs) computed during a temporary deployment of a base network (such as the USArray or PASSCAL deployments) may be applied to events that occurred earlier or later than the temporary network using permanent remote stations even when the temporary stations are not present.

It was also shown that the method has several evident limitations. It provides the best accuracy when the frequency derivative of the source phase is relatively small; for example, when the source mechanism is a vertical force or a center of compression, when the source depth is less than 1 km or more than 5 km, and when the source mechanism is nearly purely strike-slip, thrust, or normal. It does not provide the estimate of the source depth.

In this paper we investigate one means to overcome some of these disadvantages by using horizontal components of the ambient noise. The motivation for this is in the fact that Love wave group time delays are less sensitive to event depth and the source mechanism than Rayleigh wave group time delays as discussed by Levshin et al. (1999). Thus, everything else being equal, Love wave EGFs are expected to provide better epicentral accuracy than Rayleigh waves. This is confirmed here by numerical simulations of the location capabilities based on Love wave EGFs, which demonstrate significantly lower location bias than using Rayleigh waves alone.

By converting cross-correlation functions for pairs of seismic stations into the transverse EGFs dominated by the fundamental mode of Love waves we have produced a Love wave database for the Western USA similar to that for Rayleigh waves. The database of Love wave EGFs has been constructed following the methodology described by Lin et al. (2008). This database consists of more than 365,000 EGFs obtained between more than 1700 stations from stationary networks and the EarthScope USArray. The advantage of Love waves to locate seismic events is mitigated by the fact that Love wave EGFs have a lower SNR than Rayleigh waves, however. Thus, although the theoretical motivation for employing Love waves for location is clear, the practical efficacy of the method needs to be tested. Here, we present numerical simulations that establish the theoretical characteristics of the use of Love waves for location and also present a few preliminary locations of real events prior to a more systematic study of the locations of a larger set of events.

2. Comparison of effects of source mechanism and depth on location using Love and Rayleigh wav EGFs

According to Aki & Richards (1980), the azimuthal dependence of the displacement spectrum for a Love wave at a given frequency excited by a point double couple source at the depth *h* in a laterally homogeneous Earth is given by the complex function *E*:

$$E(\omega,\varphi,h)=\left.\frac{dr_3}{dz}\right|_{z=h}\left[M_{yz}\cos\varphi-M_{xz}\sin\varphi\right]+ik(\omega)r_3(h)\left[M_{xx}\sin\varphi\cos\varphi-M_{yx}\cos2\varphi+M_{xy}\sin2\varphi-M_{yy}\sin\varphi\cos\varphi\right] \qquad (1)$$

where $k(\omega)$ is the frequency, ω, dependent wave number, M_{ij} are moment tensor components normalized by the scalar moment M_0, r_3 is the Love wave eigenfunction, and φ is azimuth taken clockwise from North. The modulus $|E|$ of the complex function *E* represents the source amplitude radiation pattern and the argument $\theta=\arg(E)$ represents the source phase delay. Both $|E|$ and θ are real functions that depend on ω, φ, and *h*. The real part of equation (1) is proportional to the tangential component of stress and equals zero for a surface source, $h=0$. As the phase of the radiation function (source phase delay) varies with azimuth, it produces different phase shifts in the spectra of the event seismograms. The phase time shift δt_C experienced by a Love wave will depend on the ratio between the real and imaginary parts of E, or the argument of E ($\theta=arg(E)$). The group time shift δt_U will depend on the frequency derivative of the phase time shift. For a double couple mechanism characterized by the strike, dip, and rake angles ψ, δ, and λ, the terms in the square brackets are frequency-independent and purely trigonometric functions of these angles and azimuth φ. The phase or argument of E will, therefore, depend primarily on the ratio of terms in which the quantities in brackets are ignored, such that

$$\arg(E) \propto \tan^{-1}\left(\frac{kr_3(h)}{dr_3/dz\big|_{z=h}}\right) \qquad (2)$$

Thus, for a Love wave, the phase time shift will depend on the ratio between Love wave eigenfunction and its vertical derivative evaluated at the source depth. Typically, the vertical derivative of the Love wave eigenfunction is smaller than the eigenfunction itself (normalized by the wavenumber), so that $arg(E)$ tends to be small, at least in comparison with the argument of the Rayleigh wave excitation. We demonstrate this here with numerical simulations.

Calculations of δt_U for a laterally homogeneous model typical of central Nevada as predicted by the CUB2 model of Shapiro and Ritzwoller (2002) for several source mechanisms and depths are shown in Figure 1. The surface wave 1-D synthetic codes by Herrmann (1978) and Levshin et.al. (1989) are used for this calculation and the following numerical simulations. These calculations indicate significantly lower group time shifts δt_U for Love waves than for Rayleigh waves. Note the differences in the scales between the Rayleigh and Love waves in this figure. To explain and generalize this conclusion we present two further figures.

Figure 2 presents the phase θ of E from expression (1). Both terms in square brackets are taken to equal 1. This simplification excludes azimuth-dependent effects and provides an average estimate of the ratio that is responsible for the source phase delay. A similar procedure for Rayleigh waves using formula (10) of the paper I provides estimates for Rayleigh waves shown in the same figure. This figure shows that the source phase range for Love waves is significantly narrower than for Love waves for source depths between 1 and 15 km. It also shows that the frequency dependence of the Love wave initial phase is weaker than for Rayleigh waves.

Figure 3a,b takes these results somewhat further by presenting the average curves of δt_U as a function of period for several source depths and both types of waves. The magnitude of the group time shift δt_U for Rayleigh waves is about 10 times larger than for Love waves. The physics behind this is the more complicated nature of Rayleigh waves. Rayleigh waves transmit not only shear but also longitudinal energy, which, for a given wavelength, is concentrated more closely to the surface than the shear energy. The eigenfunctions of Rayleigh waves are two-component vector functions, and the corresponding expressions for function E are more complicated. The largest group time delays for Rayleigh waves are for events between 2-7 km depth and generally increase with period, consistent with the results of Paper I. The Love wave group time delays also increase with period but also generally increase with event depth. The event depth dependence at 5 and 10 sec periods is shown more clearly for Rayleigh and Love wave in Figures 3c,d.

Finally, Figure 4 presents results of a more extensive numerical simulation of errors in epicentral location using either Rayleigh or Love wave EGFs. The array geometry is presented in Figure 5a. Synthetic Rayleigh and Love wave EGFs are produced, correspondingly, by vertical and horizontal forces acting at the Earth's surface for all pairs of base-remote stations shown in Figure 5a. We also calculate simulated event seismograms at remote stations for four events with a fixed geographical position within the base network. Four source mechanisms and a sequence of source depths between 0 and 25 km were used in the numerical simulations. The source mechanisms are shown in the upper part of Figure 4a,b. These mechanisms are similar to pure normal (red) and thrust (green) faults, a vertical thrust fault (navy blue), and a strike-slip fault (light blue), but the corresponding angles characterizing the double couple mechanism (dip and rake) are 15-20^{o} different from the pure mechanisms, which is sufficient to produce a significant group time shift. The polar diagrams in Figure 4a,b show the azimuthal distribution of group time residuals for the corresponding mechanisms with source depths of 1, 2, 5, and 10 km. Note that our location method is based on cross-correlating frequency-time diagrams between 7 and 15 s period following the method described in Paper I. Thus, the residuals in Figure 4a,b are frequency averaged. The difference in the accuracy of location using Rayleigh and Love EGFs may be seen from comparison of the Figure 4c and 4d. For source depths between 1 and 5 km mislocations using Love wave EGFs are ~5 times smaller than with Rayleigh waves. Above 10 km depth, the mislocations are more similar, however.

3. Application of Rayleigh and Love wave EGFs to locate a few events in the Western USA

To test the ability of Love wave EGFs to locate earthquakes and mining events, we seek Ground Truth events with magnitudes in the 3s or 4s whose epicenters and depths are well known, in particular with epicenters known to 500 m or better. Such events are startlingly rare in the western US. There are some earthquakes located to within 1 km in California, Utah, and Nevada by local agencies (Caltech, Berkeley, USGS, UNR, UU, ANF), but depths are usually poorly known. In contrast, surface mining blasts are known to be shallow but their locations are not tracked by local agencies. Here we show separate Rayleigh and Love wave locations for the Crandall mine collapse on August 6, 2007 at 08:48 GMT (Figure 6) and present statistics of location differences for the three earthquakes. The results of these tests are summarized in Table 1 for both types of waves. For shallow events and crustal earthquakes deeper than about 7 km, Rayleigh and Love waves are expected to produce similar locations. The results presented here show that locations of these four events using the two wave types are all within 1 km, and well within the error ellipse for the Love wave.

For example, Figure 6 presents both locations for the Crandall Canyon mine collapse. Both locations are within the error ellipse from the believed location of the mine collapse. The Rayleigh wave location has a smaller uncertainty because both the event and EGF waveforms are better than for Love waves. The three deep crustal earthquakes have source depths of 10 km or more which, if accurate, means that both Rayleigh and Love wave epicentral locations should be relatively unbiased by event depth. The locations also agree within 1 km from Rayleigh and Love waves. The array geometries for all these five events are shown in Figures 5b-e.

CONCLUSIONS AND RECOMMENDATIONS

The method to locate the epicenter of regional seismic events based on the envelope of Empirical Green's Functions determined from ambient seismic noise that has been described here and by Barmin et al. (2011) has several features that make it a useful addition to existing location methods. Love wave EGFs are less sensitive to unknown source parameters (moment tensor, depth) than Rayleigh EGFs and may provide smaller bias in location for source depths between 1 and 7 km. The advantage of Love waves to locate seismic events is mitigated by the fact the Love wave EGFs typically have a lower SNR than Rayleigh waves, however. Thus, the combined use of both types of waves is advised. Results presented here illustrate that Love waves EGFs from ambient noise can be used to improve location capabilities for small crustal events. Further work is underway to study a larger statistical database of events to improve the characterization of the method.

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Table 1. Comparison of location results using Rayleigh and Love wave EGFs

Event	Date (y/m/d)	Time (h:m:s)	Latitude N	Longitude W	Depth (km)	mb, mL	Ref-R (km)	Ref-L (km)	Ref-L (km)
Crandall mine collapse**,** UT*	2007/08/06	08:48:40.00	39.468	111.226	0.6	3.90	0.38	1.08	0.86
Earthquake, CA	2005/04/16	19:18:13.00	35.027	119.178	10.8	4.9	0.72	0.72	0.91
Earthquake, UT**	2007/08/18	13:16:30.46	38.070	113.323	9.0	3.65	0.39	0.39	0.25
Earthquake, NV***	2008/02/22	23:27:45.26	41.104	114.917	15.6	4.5	0.40	0.48	0.69

Ref-R is the distance between the reference and CU locations using Rayleigh EGFs.
Ref-L is the distance between the reference and CU locations using Love EGFs.
R-L is the distance between CU locations using Rayleigh and Love waves

* Origin time, depth and magnitude are from Utah University Seismic Service, believed location of mine collapse.

** Depth and magnitude are from Saint-Louis University.

*** Origin time, depth and magnitude are from University of Nevada, Reno.

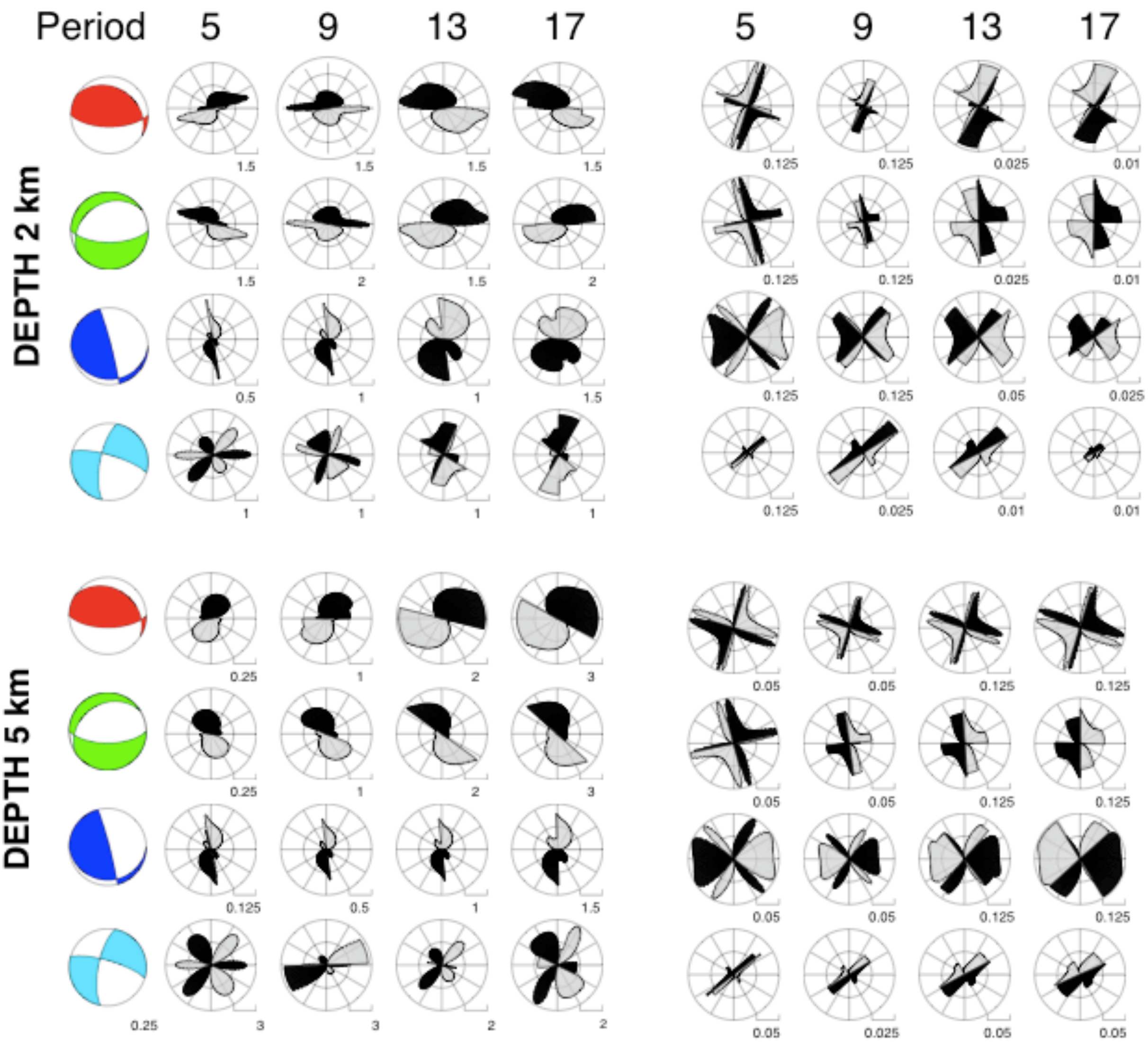

Figure 1. Theoretical prediction of group time delays at different periods. Azimuthal dependences of group time delays are presented for Rayleigh and Love waves at four periods and for four different mechanisms. Mechanism: red, near normal; green, near thrust; navy, near vertical thrust; light blue, near strike-slip. The size of the time delays scale according to the bar at the lower right-hand side of each component of the figure, in seconds.

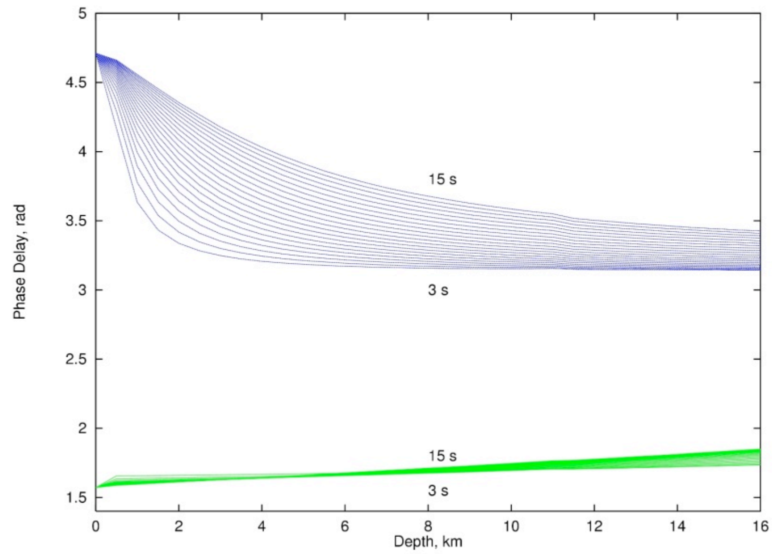

Figure 2. Average phase delays for Rayleigh (blue) and Love (green) waves at different periods from 5 to 15 s as a function of the source depth.

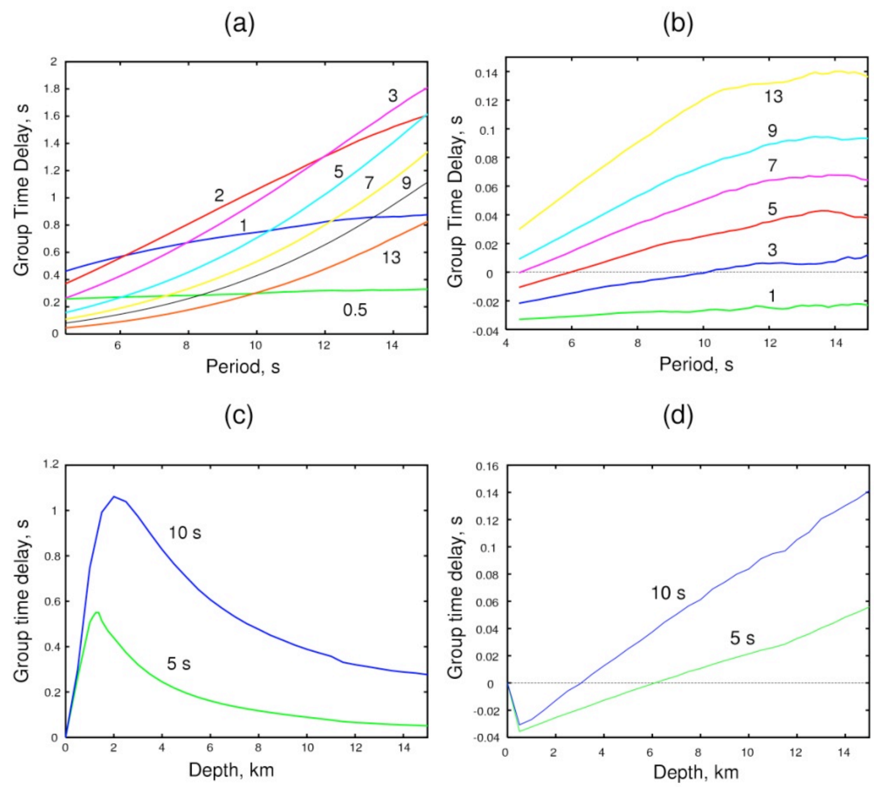

Figure 3. Average group time delays δt_U for Rayleigh and Love waves. (a) Average δt_U for Rayleigh waves as a function of period; numbers indicate source depths in km. (b) The same for Love waves. (c) Average δt_U for Rayleigh waves as a function of source depth at 5 and 10 s. (d) The same for Love waves.

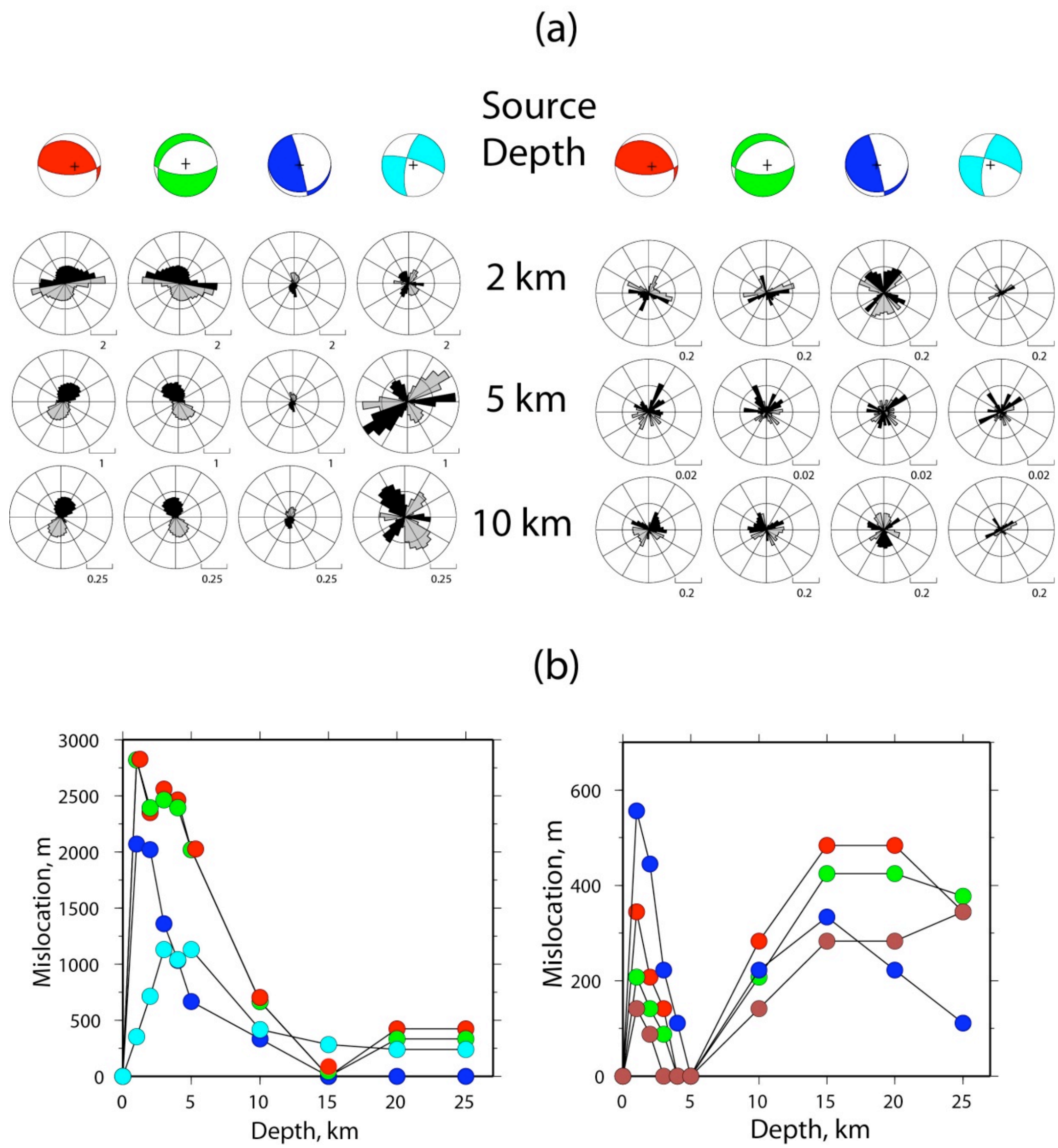

Figure 4. Simulation of the effect of source mechanism and depth on group time-shifts and mislocations using EGFs for Rayleigh and Love waves. Location of the virtual event (TA station Q10A) is shown in Figure 5a. (a) (Top Panel) Source mechanisms and corresponding polar diagrams of group time residuals for the indicated source depths. Mechanisms are the same as in Fig. 1. (Bottom Panel) Event mislocations using (Left) Rayleigh and (Right) Love waves separately for the four different source mechanisms as a function of depth. Symbol colors correspond to the source mechanisms shown in (a).

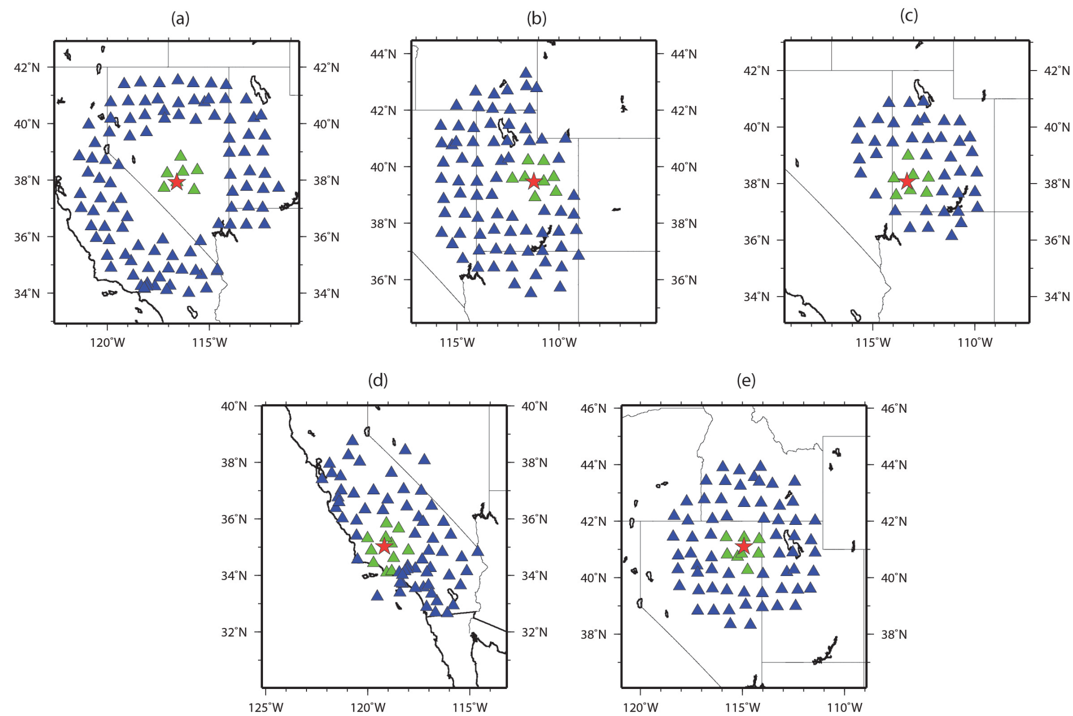

Figure 5. Station configuration for virtual and actual events. Symbols: base stations (green triangles), remote stations (blue triangles), red star is the virtual or actual source. (a) Virtual event (TA station Q10A). (b) Crandall mine collapse. (c)-(e) Earthquakes in Utah, Southern California, Nevada.

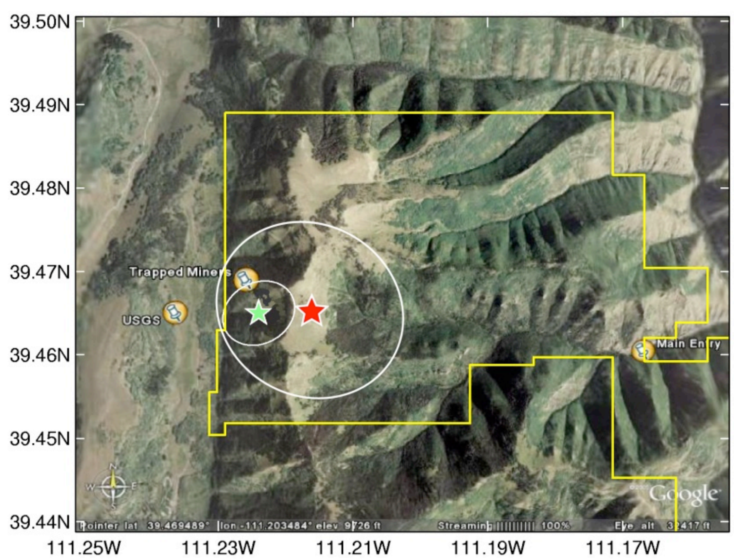

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Figure 6. Schema of the Crandall Canyon mine and location of mine collapse. Our locations of the mine collapse (green star based on Rayleigh waves and red star for Love waves) and the corresponding 90% confidence ellipses. The left yellow push-pin marks the USGS event location using the local UUSS network, and the right push-pin is the approximate location of the mine collapse and trapped miners. The map is made with Google Earth.