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K. Mayeda
R. Hofstetter
A. Rodgers
W. Walter

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Applying Coda Envelope Measurements to Local and Regional Waveforms For Stable Estimates of Magnitude, Source Spectra, & Energy

Kevin Mayeda, Rami Hofstetter*, Arthur Rodgers, & William Walter

Lawrence Livermore National Laboratory
Geophysics and Global Security Division
Livermore, CA, 94551 USA
*Geophysical Institute of Israel**

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Abstract

Magnitude estimation forms an integral part in any seismic monitoring endeavor. For monitoring compliance of the Comprehensive Nuclear-Test-Ban Treaty, regional seismic discriminants are often functions of magnitude such as m_b:M_o, high-to-low spectral ratios, and nuclear yield estimation. For small-to-moderate magnitude events that cannot be studied by a large regional or global network of stations, there is a need for stable magnitudes that can be obtained from as few as one station. To date, magnitudes based on coda envelopes are by far the most stable because of the coda's averaging properties. Unlike conventional magnitudes which utilize the direct phases such as P (P_n, P_g) or S (S_n, L_g), or M_s, a coda envelope magnitude is not as sensitive to the undesirable effects of source radiation pattern, 3-D path heterogeneity, and constructive/destructive interference near the recording site. The stability of the coda comes from a time-domain measurement made over a large portion of the seismogram thereby averaging over the scattered wavefield. This approach has been applied to earthquakes in the western United States where it was found that a single-station coda magnitude was approximately equivalent to an average over a 64 station network which used only the direct waves such as L_g (Mayeda & Walter, JGR, 1996).

In this paper we describe in detail our calibration procedure starting with a broadband recording, correlation with independent moment estimates, formation of narrowband envelopes, coda envelope fitting with synthetics, and finally the resultant moment-rate spectra. Our procedure accounts for all propagation, site, and S-to-coda transfer function effects. The resultant coda-derived moment-rate spectra are then used to estimate seismic moment (M_o), narrowband magnitudes such as m_b or M_L, and total seismic energy. For the eastern Mediterranean region a preliminary study was completed for earthquakes in the Gulf of Aqaba region using two regional broadband stations, KEG and BGIO. As was found in the western U.S., a significant reduction in magnitude scatter was achieved when using the coda. This procedure provides a means of unbiased, unsaturated magnitude estimation that will be tied to a physical measure of earthquake size (seismic moment), unlike conventional magnitudes such as m_b, M_L, M_D, and M_S. We outline a calibration procedure that can be used in software codes such as SAC on both UNIX and PC platforms. This paper describes the calibration technique and the application to regional stations of the IMS.

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Key Words: Regional Magnitude, coda, source spectra, earthquake parameters

Objective

Regional magnitudes for small-to-moderate sized crustal events using P_n, P_g, and L_g all suffer from source and path heterogeneity. As a consequence multi-station averaging is necessary to reduce the amplitude variability. Under the CTBT however, the average station spacing is larger than 1000 km and thus the ability to measure a stable magnitude becomes difficult because of limited stations over which to average. Because small-to-moderate sized events cannot be measured teleseismically, we need a stable single-station measure of earthquake size. Over the past several years we have developed and applied a magnitude based on the S_n and L_g coda envelope which is significantly less affected by source anisotropy and 3-D path heterogeneity. We have found that the amplitude of the time domain coda envelope can provide a far more stable amplitude measure than the more conventional methods that measure the direct arrivals. For small regions such as the Nevada Test Site (see Mayeda, 1993) and aftershock zones (this study) we find that a single-station coda magnitude is equivalent to roughly a 16 station network using direct waves. For larger regions (such as the western U.S.) the crustal averaging properties are equivalent to a 64-station network (Mayeda and Walter, 1996). In this paper we outline a procedure and discuss new software codes that have been developed to process broadband waveforms for coda-based M_w and m_b given a set of calibration parameters. The calibration procedure is applied to a small set of earthquakes in the region which are large enough to be modeled using 1-D velocity models.

Method

Unlike conventional magnitudes which measure peak or RMS amplitude our coda magnitude procedure fits a Green's function envelope to the actual narrowband coda envelope and measures the amplitude relative to a fixed level. We then tie the coda measurements (taken in time-domain) to an absolute scale by correcting the frequency dependent effects of S-to-coda transfer function, path attenuation, site response, and finally instrument response. Once these corrections are known, we find that our magnitudes (whether M_w or m_b) are remarkably stable and accurate. Furthermore, these magnitudes are transportable and not subject to regional bias as is often the case for the conventional magnitudes such as $mb(P_g)$, $mb(P_n)$, $m_b(L_g)$, M_s etc. The amplitude measurements can be done with either synthetic or empirical Green's function envelopes. We have found a simple functional form that can fit regional narrowband coda envelopes over a broad range of frequency bands (~0.03 to 10 Hz). For speed and simplicity, synthetic envelopes of the form shown below were the easiest to handle where A_c is the coda amplitude, f is the center frequency of the band, and t is the time in seconds measured from the origin time,

$$A_c(f,t)= A_o t^{-\gamma} \exp(-bt)$$

where γ and b are functions of frequency and distance. Note that the above functional form is similar to the single-scattering formulation of Aki(1969), where b is related to the coda Q. For our purposes however, we search for the best parameters for each narrow frequency band and allow them to change as a function of epicentral distance. We found that this was necessary perhaps because of the larger source-to-receiver distances, waveguide effects and/or multiple scattering that are not accounted for in virtually all scattering models. Therefore, for a particular region we determine as a function of distance, x; $\gamma(x)$, b(x) as well as the S-wave and surface wave group velocities for each of the frequency bands. Unlike most other magnitudes, our procedure operates on absolute source spectra and thus is transportable and will not suffer regional bias. We accomplish this by tying our time-domain coda envelope measurements to moments derived from long-period regional waveform modeling results. Since the waveform modeling results are not as sensitive to structure and site effect (at long periods (> ~10 seconds) we feel confident in using these as calibration events. What makes our procedure more attractive is its stability and ability to extend M_w down to much smaller events than can be accurately waveform modeled (< ~M_w 3.5).

SAC Command

We have developed a SAC command that will read an ASCII flatfile of calibration information and automatically processes the waveform data that will then output moment-rate spectra, M_w and m_b. The two horizontal broadband traces are read into SAC by the tool. Averaged $\log_{10}$ envelopes are formed for consecutive narrow frequency bands (the number and exact frequency bands are specified in the calibration flatfile). Using the epicentral distance in the SAC headers, the synthetic envelopes for each frequency band are generated and used to measure (in an L-1 sense) the observed envelopes in time-domain (Figure 1). Typically we use 12 frequency bands but again, this can be changed in the calibration inputfile. Each of the discrete time-domain amplitude measurements are then corrected for path, site, and instrument effects resulting in a completely corrected S-wave source spectra. The result is a plot of the source spectra and an ASCII output file with diagnostic information. To make the code automated the tool checks for degenerate cases such as aftershocks in the coda, drop-outs, and minimum coda length.

Application

We have previously calibrated two broadband stations in the eastern Mediterranean region, BGIO and KEG, for the Gulf of Aqaba mainshock and its associated aftershocks. In Figure 2 we show $m_b(L_g)$ and $m_b(P_g)$ compared to m_b(coda) using stations KEG and BGIO for a subset of the Gulf of Aqaba aftershock sequence. We see that the coda-based magnitude is 4 times less variable which is equivalent to a 16 station network using the conventional magnitudes. Figure 3 shows coda-derived S-wave spectra for two aftershocks. The November 23, 1995 event is nodal for S at BGIO, however the coda spectra at both BGIO and KEG are virtually identical, confirming that the coda is averaging over the source radiation pattern. Finally, figure 4 compares the coda-derived M_w against those obtained using 1-D regional waveform modeling. As was found in the western U.S., the coda-derived M_w is in excellent agreement with conventional methods. The advantage of the coda is its ability to extent the M_w measure to much smaller events and is more stable. We then compared the performance of our new tool with our old research-mode SAC macro which at best can be described as "clunky" (it utilizes C-shells and FORTRAN subroutines). The spectral and magnitude results were identical and the only major difference was that the new SAC tool is roughly 20 times faster and significantly more robust.

Conclusion

We have developed a new SAC command that can be used in both research-mode and large scale data processing for stable coda magnitude estimation. The success of this procedure has been demonstrated in numerous regions but is difficult to apply for those that are uninitiated. With the development of this new tool, the application to other regions by other researches should be significantly easier. In addition, we are working with Sandia National Laboratory to code a more robust version to be used in an operational setting. Currently, the calibration is handled by a set of SAC macros that operate on a small calibration dataset that have independent moment estimates. The current example in the Gulf of Aqaba region is now being extended to other neighboring regions.

Bibliography

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Mayeda, Kevin, mb(LgCoda): A stable single station estimator of magnitude, *BSSA*, **83**, 1993, 851-861.

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Figure 1: Example of coda envelope amplitude measurements for four narrow frequency bands.

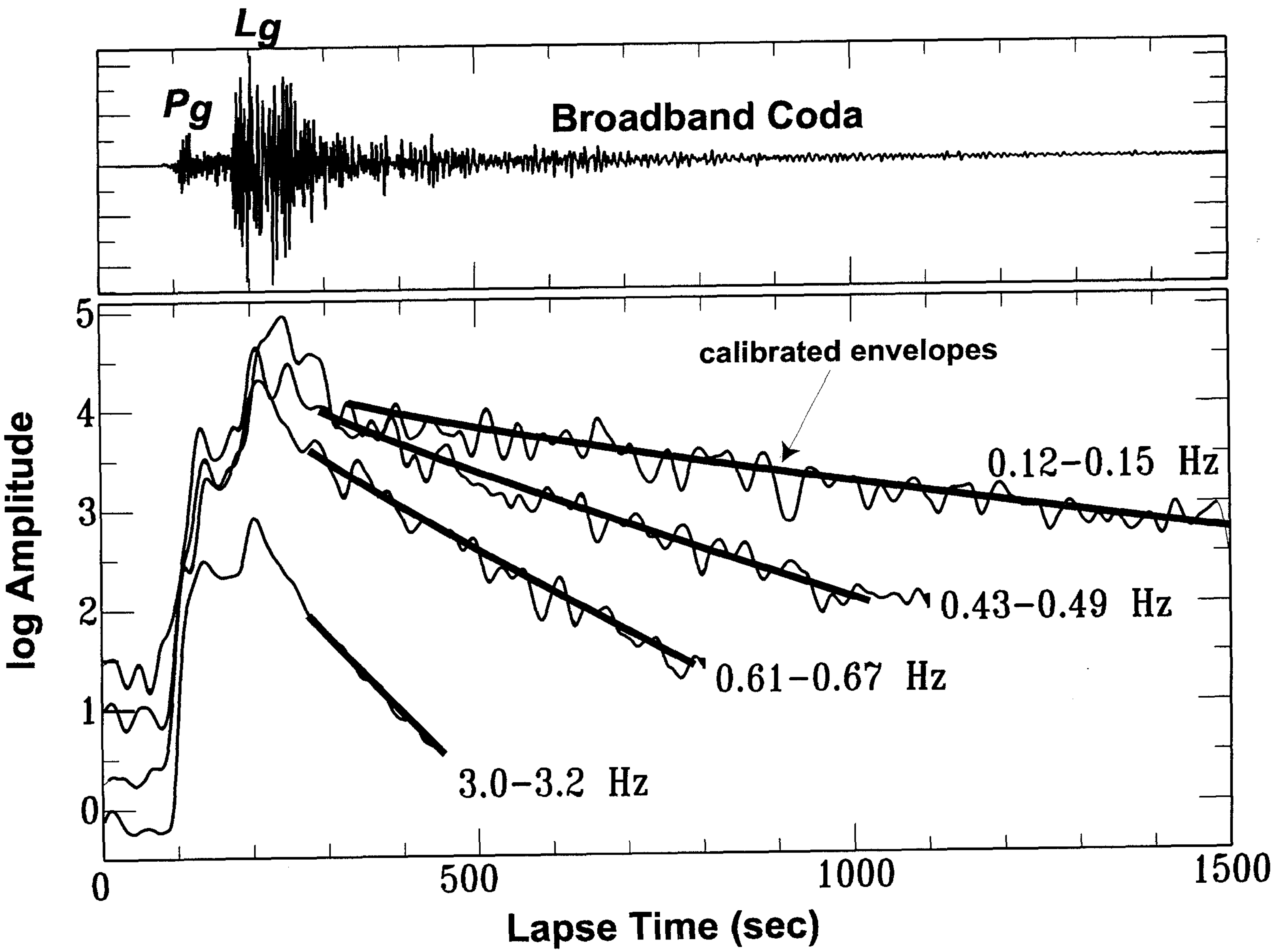
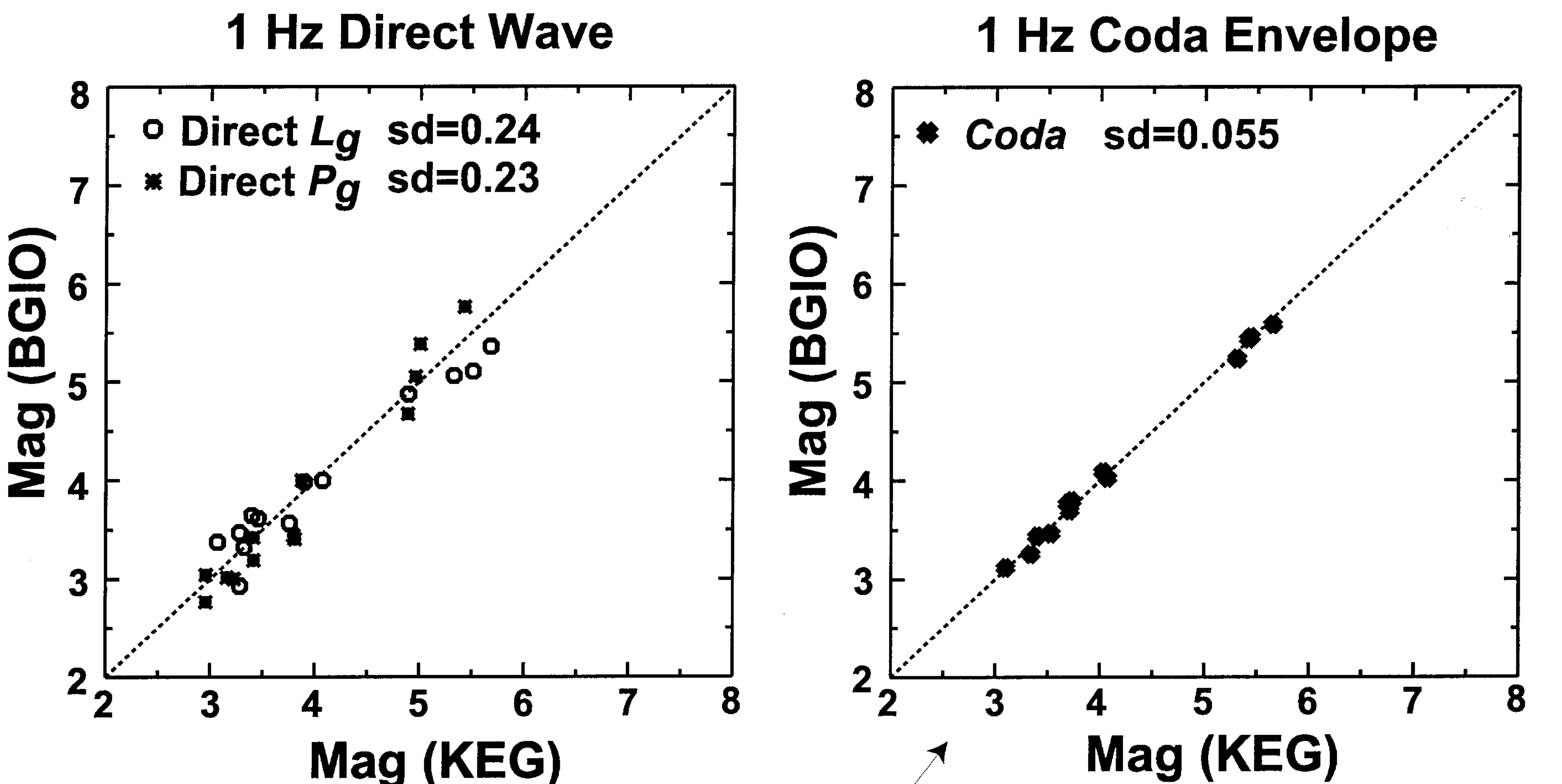
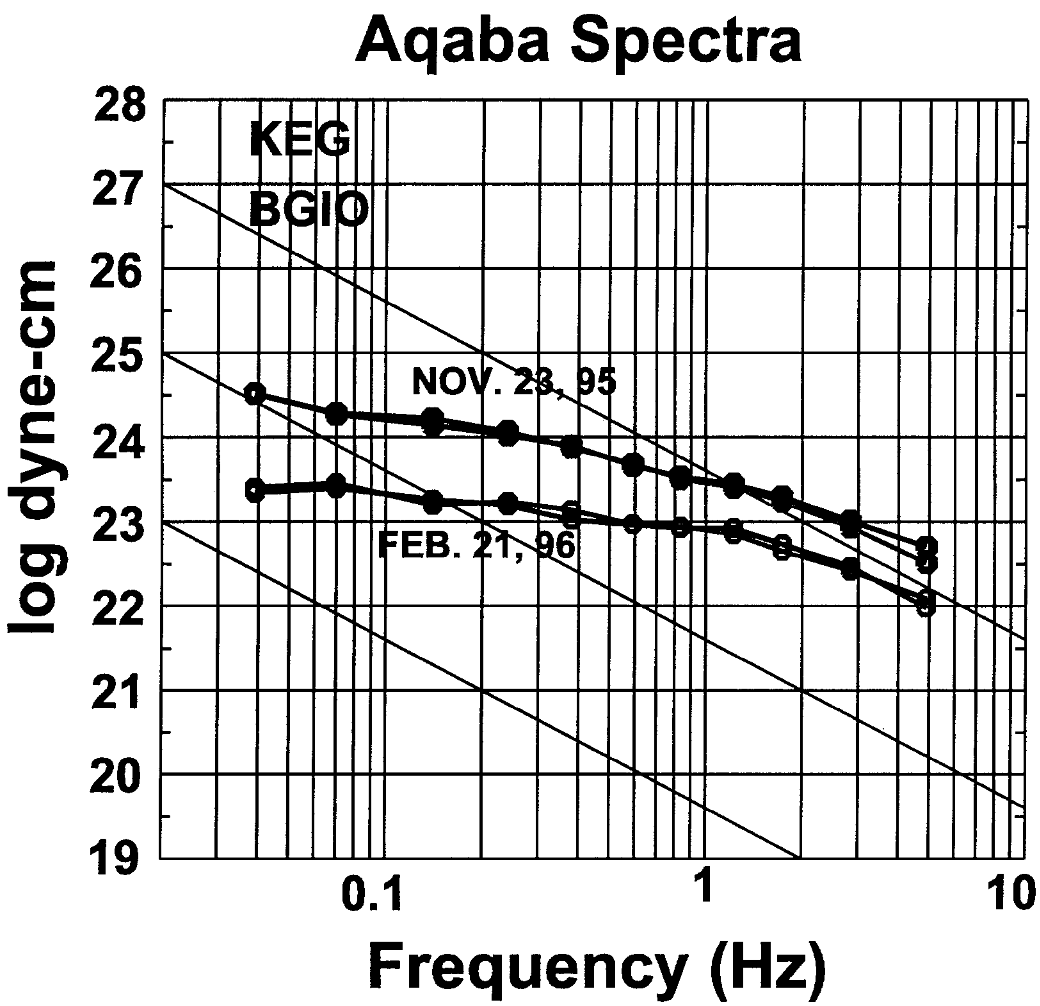


Figure 2: Interstation variation is over 4 times larger for direct *Pg* and *Lg* waves than *coda* waves.



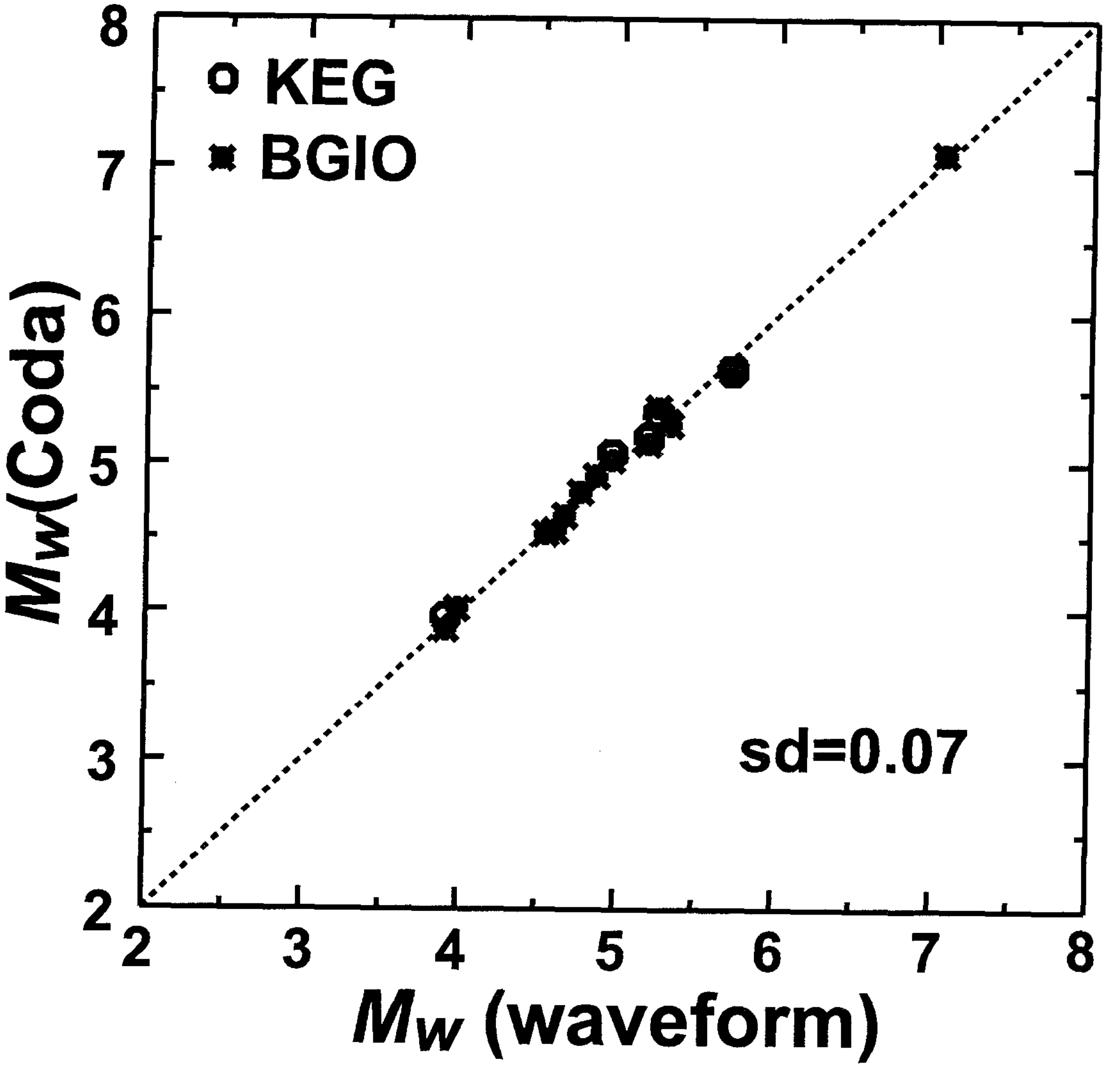
Equivalent to a 16 station network using direct waves.

Figure 3: Example of two Aqaba aftershocks at KEG and BGIO show the stability in the coda measurements.



- Coda is not sensitive to source radiation pattern.
- Coda-derived magnitudes are possible for significantly smaller events.
- Results are comparable to the Western United States.
- M_W is tied to a physical measure of earthquake size and is unbiased.

Figure 4: Single station coda moment magnitudes, M_W (coda), agree with 1-D waveform modeling results.



Note: 3-D path variation and source anisotropy do not affect the coda measurement.