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Seismic Discrimination Between Earthquakes and Explosions in the Middle East and North Africa

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ABSTRACT

The recently signed Comprehensive Test Ban Treaty provides for an international network of primary and auxiliary seismic monitoring stations (IMS) to verify its compliance. Calibration is required to confidently use these stations to identify and discriminate between earthquakes, mine-related events and clandestine nuclear explosions, particularly for small to moderate seismic events recorded regionally at only a few stations. Given the lack of regional recordings of underground nuclear tests in most of the world, we are making use of mining and industrial explosions to test discriminants. For example we use the Multimax compiled dataset of small earthquakes and quarry explosions in Israel to test regional discriminants at local distances with mixed results.

Further complicating calibration is the fact that many IMS sites have not yest been installed and others have very short operating histories. When IMS data is available, there is often a lack of independent information ("ground truth") on the seismic sources. Here we describe a procedure for calibrating stations with limited data and apply it to the IMS auxiliary station MDT in Morocco. Data was initially available for three months in 1990 when MDT was operated as part of MEDNET. An event detector was run over the continuous data and regional events identified and roughly located using S-P time and back azimuth. The procedure uses spatial and temporal clustering to identify "known" mine blasts. The spatial clustering is done using the waveform correlation technique of Harris (1991) to find events with similar sources and locations. Temporal clustering looks at the time of day and repetition in time of events with the mine blasts occurring during working hours and days repeatedly over a period of time. A set of "known" earthquakes is also determined using location, time of day, distribution in time and size criteria. With these independent libraries of identified seismic events, we evaluate promising regional discriminants such as high frequency P/L_g. We also examine distance and path effects on the discriminants. Preliminary results indicate high frequency P/L_g provides some separation between mine blasts and earthquakes at MDT.

Key Words: seismic, discrimination, identification, mine-blast, Middle East, North Africa

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OBJECTIVES

Monitoring of the Comprehensive Test Ban Treaty requires seismically discriminating between earthquakes, mining activities and any potential clandestine nuclear test. LLNL is evaluating regional discriminants in the uncalibrated Middle East and North Africa (ME&NA) and other regions of interest to improve the CTBT monitoring capability.

RESEARCH ACCOMPLISHED

As part of the overall Department of Energy CTBT Research and Development program, LLNL is pursuing a comprehensive identification research effort to improve our capabilities to seismically characterize and discriminate potential underground nuclear tests from other natural and man-made sources of seismicity. Here we present preliminary results in two parts. First, we present a methodology for obtaining ground truth from time and spatial clustering of seismically recorded events. We apply this methodology to three months of data available from MEDNET for the IMS auxiliary station MDT in Morocco. We then use the results to evaluate regional discriminants at MDT. Second, when ground truth is available, as in the Multimax dataset from Israel, we evaluate regional discriminant performance directly.

Calibration of CTBT Monitoring Stations for Event Identification: MDT, Morocco

Regional discriminants such as high frequency (>4 Hz) P/S ratios and high/low frequency ratios show great promise to discriminate events based on studies near the major test sites (e.g. Walter et al. 1995; Hartse et al. 1997). However, the physical basis of these discriminants is not firmly established, and regional phases can be strongly affected by the heterogeneous structure of the lithosphere. Therefore it is important to calibrate these discriminants in new regions like ME&NA at each of monitoring stations. Unfortunately many of these stations are not yet installed or have limited data. Further complicating calibration is the lack of ground truth data, particularly explosion data for evaluating the discriminants. Here we present techniques to obtain ground truth using correlation, and spatial and temporal clustering techniques. We apply this data the IMS auxiliary station MDT in Morocco which has limited data available. Morocco is a region of low-to moderate natural seismicity and is known to have active mines. We believe we can to follow-up this initial "blind" study by working with our university partners at Cornell to connect the seismically identified events to actual active mine provided ground truth. For all these reasons, MDT in Morocco is an ideal place to test these techniques.

We began the analysis procedure by running an STA/LTA detector over the three months of continuous data available from June-August 1990 from MEDNET via the IRIS DMC. We found 195 regional events with reasonable signal-to-noise ratios. Of these events, nine correspond to earthquakes in the NEIC catalog. We used these nine events with known locations to check regional phase propagation in the region (see figure 1). We found that events west of Gibraltar showed strong Sn phases and a notable absence of Lg. In contrast events east of Gibraltar and within Morocco itself show little Sn but a strong Lg phase. We also used these events with known locations to check the feasibility of estimating back azimuth from initial P-wave polarization. This process and other indications (long period noise) led us to discover the vertical and east components were switched and the north component had reversed polarity. We were subsequently able to confirm this with the MEDNET operators for the 1990 data. After correcting the channels we found back azimuth calculations at the broadband three component stations were generally accurate to 10 degrees or so provided the signal-to-noise ratio was good.

The 195 events were then analyzed using a waveform correlation technique (Harris, 1991; for more details please see Harris this volume). The three-component seismograms of each of the 195 events was cross correlated with all other events. Events with high correlation values must have similar mechanisms and locations and are grouped into "clusters". Using a fairly high threshold correlation value (0.7) we found twelve clusters containing three or more events, but two of these were discarded as too noisy for our discrimination study. An example of three such clusters at MDT is shown at the top of figure 2. We then applied spatial and temporal clustering analyses to the clusters. Eight clusters were found to have patterns consistent with mine blasts: they occurred only during working hours and were repeated over a period of days to weeks. Earthquakes are expected to have more random distribution in time and if aftershocks, have timing more consistent with Omori's law (exponential decay). Time of day and day of week histograms for the 43 events in these eight clusters are shown at the bottom of figure 2 . Note the working hour distribution and the lack of events on Sunday.

Two of the clusters were identified as earthquakes since in each case there was a larger event in the PDE or ISC catalog and the other events occurred within 24 hours, not necessarily during working hours. One cluster remains unidentified. For known earthquakes we made use of the 4 PDE events in the Alboran sea. Given the daylight-only distribution of the blasts we decided to use a 10PM-5AM time window to find more earthquakes, discovering an additional 10 events, some of which appeared in the ISC or PDE catalogs. (We never found a blast in the PDE or ISC catalogs). With the PDE events, earthquake clusters and nighttime events, we have 16 independently identified earthquakes.

We estimated distance away from MDT in kilometers using eight times the hand picked S-P times. Because clusters should have nearly identical S-P times were able to estimate our picking accuracy as about within one second by examining the variability within the clusters. Back azimuths were determined using a polarization analysis of the initial P onset. The approximate locations determined this way are shown in Figure 3. The eight mining clusters fall into 4 different mining areas. The earthquakes show a distribution throughout Morocco. Note all events outside of Morocco and west of Gibraltar were discarded due to lack of Lg.

We used the 43 mine blasts and 16 earthquakes shown in Figure 3 to test the regional discriminants. The Moroccan crustal thickness is 30-35 km (Calvert et al., 1997) with a Pn-Pg cross-over distance near 150 km. Since our distances ranged from 100-400 km we did not attempt to separate Pn and Pg but used a P window that included both, from the hand-picked onset time to a group velocity of about 5 km/s for P and 3.6 to 3.0 km/s for Lg. We also averaged the results from all three components to improve stability (e.g. Kim et al. 1997). The results are shown for four frequency bands in Figure 4. Note the mean value of the earthquakes and explosions shows increasing separation with frequency though there remains substantial overlap even at 6-8 Hz. While several studies show even better discrimination for P/Lg at even higher frequencies (e.g. Kim et al. 1997) 6-8 Hz was the highest achievable frequency using this 20 sps data. We are currently in the process of evaluating other regional discriminants using this data.

Evaluation of Regional Discriminants Using Israeli Ground Truth Dataset

Ground truth explosion and earthquake data is very limited in the Middle East. One such dataset was put together by Multimax Inc. (Galilee dataset - Lori Grant written communication) based on data provided by Shapiria (1996 et al.). This dataset consists of 30 earthquakes and 20 quarry blasts in northern Israel recorded by the Israeli Seismic Network. A discrimination study was done on these events by Gitterman and van Eck (1993) using a variety of measures but not relative P/S amplitude ratios. Shapira et al. (1996) looked at P/S in Israel using a 1-10 Hz band with mixed results and suggested a strong dependence on path effects in this heterogeneous region. As noted previously, higher frequency (>4 Hz) regional P/S measures show much promise in discriminating explosions from earthquakes. We tested the higher frequnecy regional P/S discriminant on this ground truth data at a number of the Israeli network stations as shown in Figure 5. Unfortunately at any given station only a fraction of the 50 events are available with good signal to noise and without glitches in the regional phases. We examined 6-8 Hz regional P/S at four of the stations with the most explosion data and show the results in Figure 6. While there appears to be reasonable discrimination at stations ADI and JVI the picture at DSI and MML is more mixed, although the mean values of the explosions are still higher than that of the earthquakes. One might consider averaging over stations, but using data with stations in common restricts the number of events even further, and averaging over not common stations mixes site effects together with discriminant separation clouding the evlauation of discriminant performance.

Northern Israel is the site of a future IMS auxiliary station PARD, but data is not yet available for it. We are examining a nearby station BGIO run by the GEOPHONE network for which data is presently available. We are currently exploring the same type of analysis for BGIO as was done for MDT in the hopes of increasing the number of ground truth explosions and earthquakes available and will present preliminary results at the meeting.

CONCLUSIONS AND RECOMMENDATIONS

The ME&NA is a challenging and tectonically complex area, requiring calibration in each of many geophysically distinct subregions. Calibration is severely limited by a lack ground truth explosion data. When available, we are evaluating discriminants on such data. When ground truth is lacking, LLNL has developed and tested an empirical procedure using correlation and clustering to independently identify groups of events to use in evaluating regional discriminants. Using this technique we are calibrating MDT, Morocco, and other IMS stations or their surrogates in the ME&NA. For regions without sufficient empirical data, we are improving our physically based discriminant models using the best available data worldwide.

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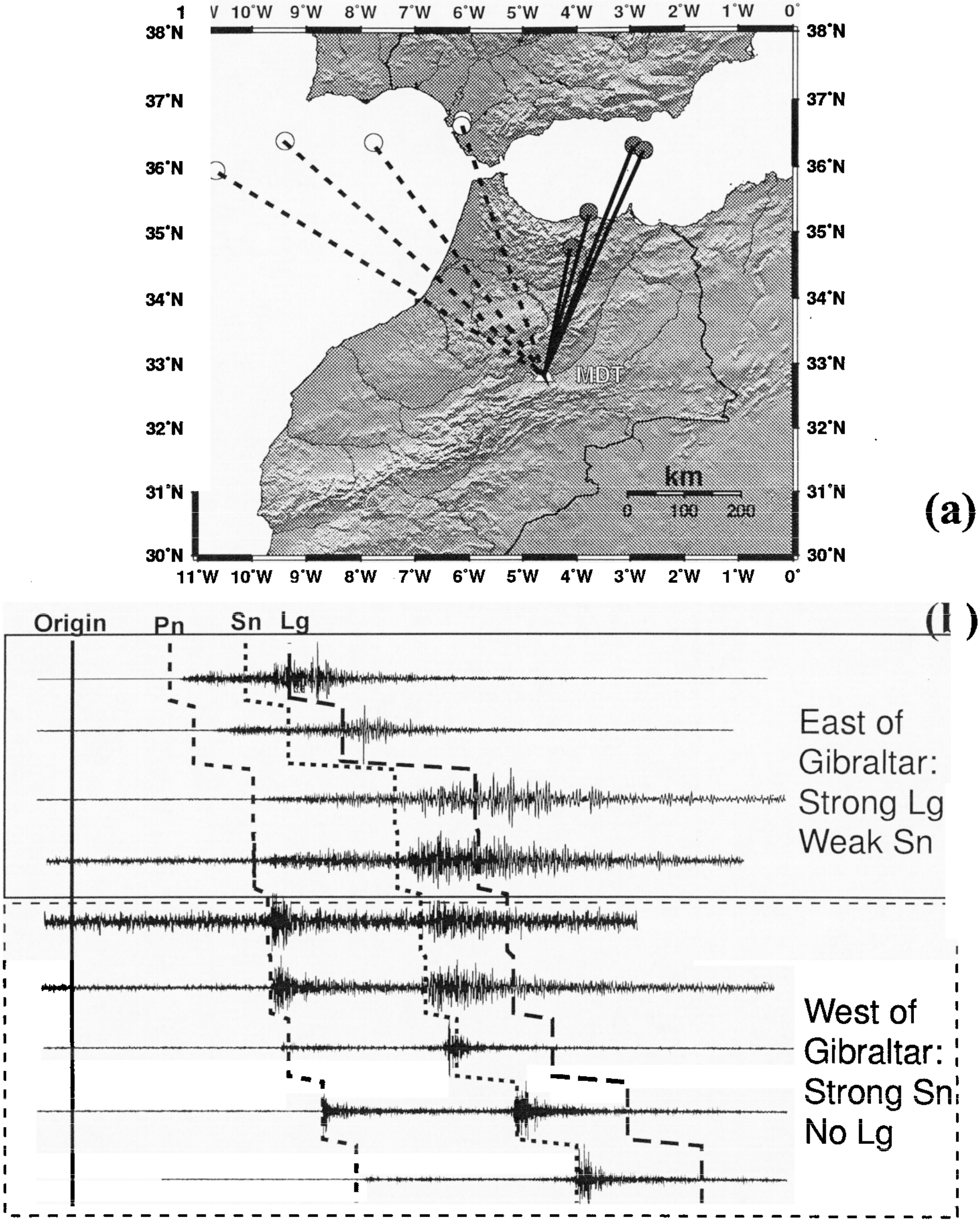

Fig. 1. (a) Map of MDT region and NEIC located events recorded at MDT. These events were used to confirm back-azimuth calculations and test regional S phase propagation (solid lines show Lg, dashed lines do not). (b) High-pass filtered seismograms. Group velocity onset times shown by dashed lines: Pn (8 km/s), Sn (4.5 km/s) and Lg (3.5 km/s). Note events west of Gibraltar show Sn but not Lg.

Example Mine Blasts Identified at MDT

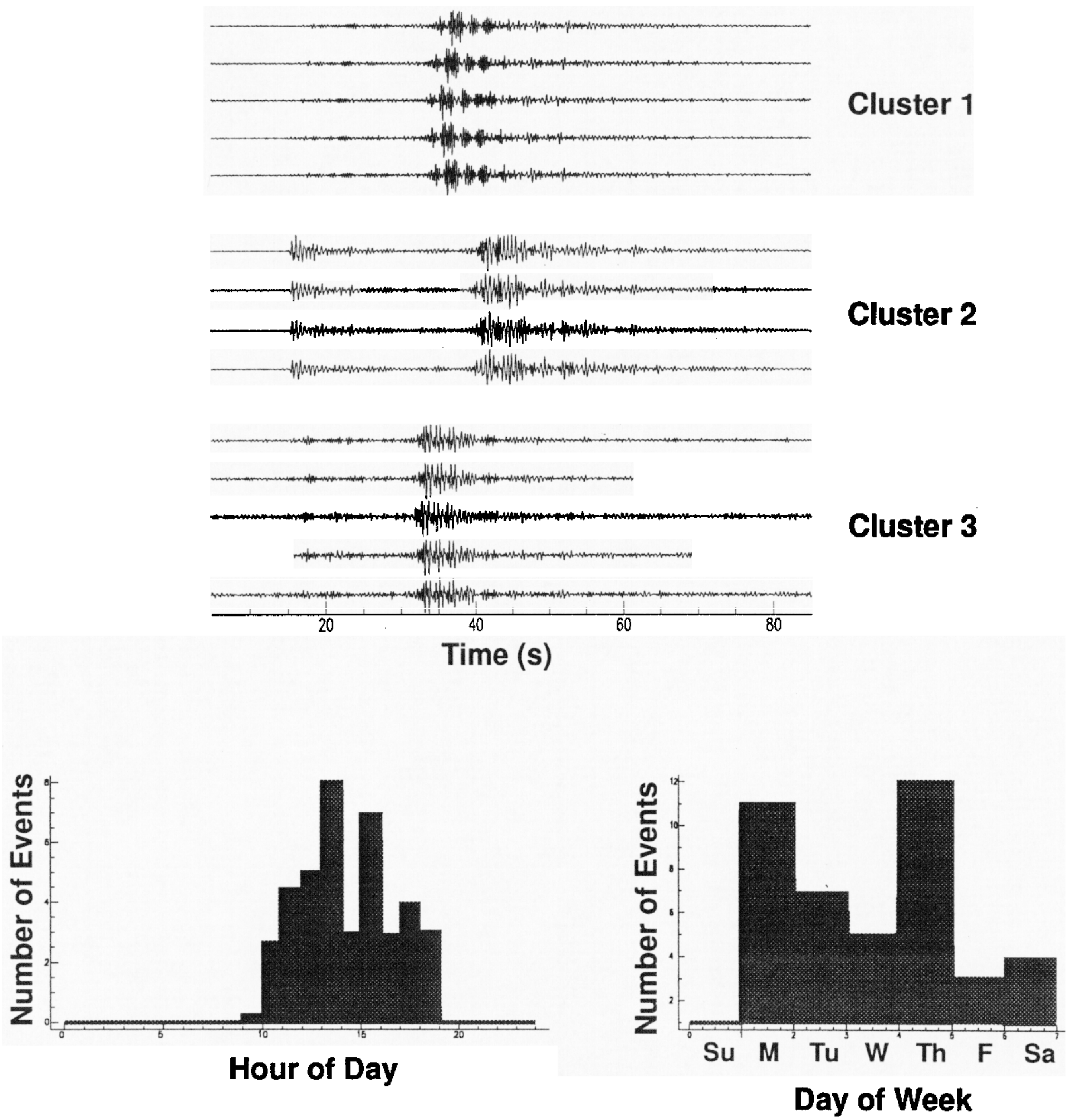

Fig. 2. Example of clustering results at MDT. Using the technique of Harris (1991) we found 12 clusters with three or more events each. Using temporal and spatial information we determined 8 clusters to be mine blasts, 2 to be earthquakes, 2 others were too noisy to use and 1 cluster remains unidentified. Shown here are 3 examples of mine blast clustered seismograms and temporal histograms made for all 8 mine blast clusters. Clustered events have high correlations indicating similar locations and mechanisms. We expect mine explosions to have different temporal behavior than earthquakes. For example mine blasts should occur during working hours and on working days and regularly over a long period of time. Earthquakes should have more random distributions in time of day and week and in the case of aftershocks show exponential decay with time.

Locations of Discrimination Study Events

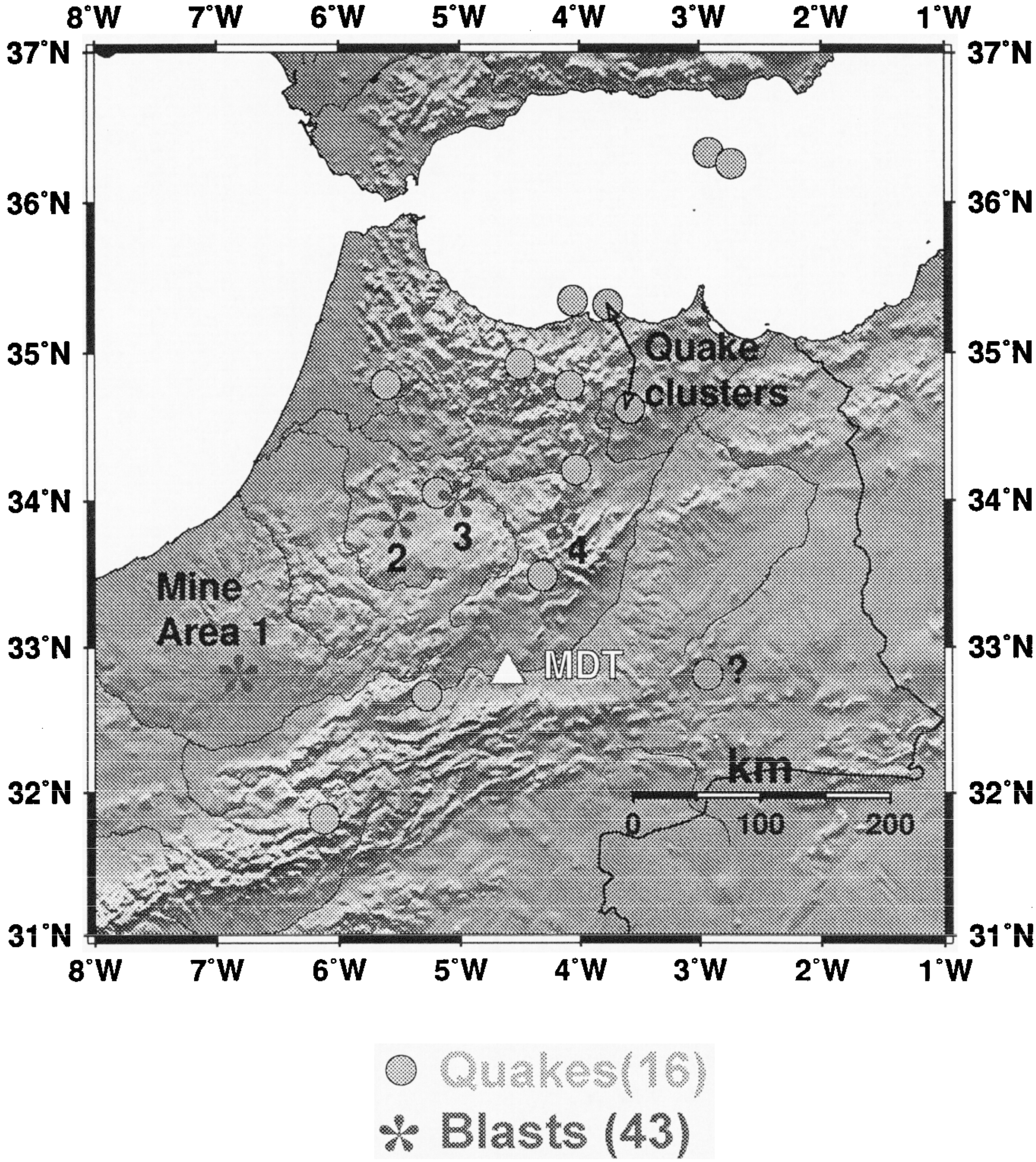

Fig. 3. Map showing approximate locations of discrimination study events estimated from S-P times and back-azimuths calculated from initial P-wave polarization using 3-component particle motion. The 43 mine-blasts are from 8 separate clusters that appear to be from 4 distinct mining regions. The eastern most mine area appears to be the phosphate mines near Khouribga. The 16 earthquakes include 10 events between 10 PM and 5 AM presumed to be earthquakes. All these events fall in the region were we expect efficient Lg propagation.

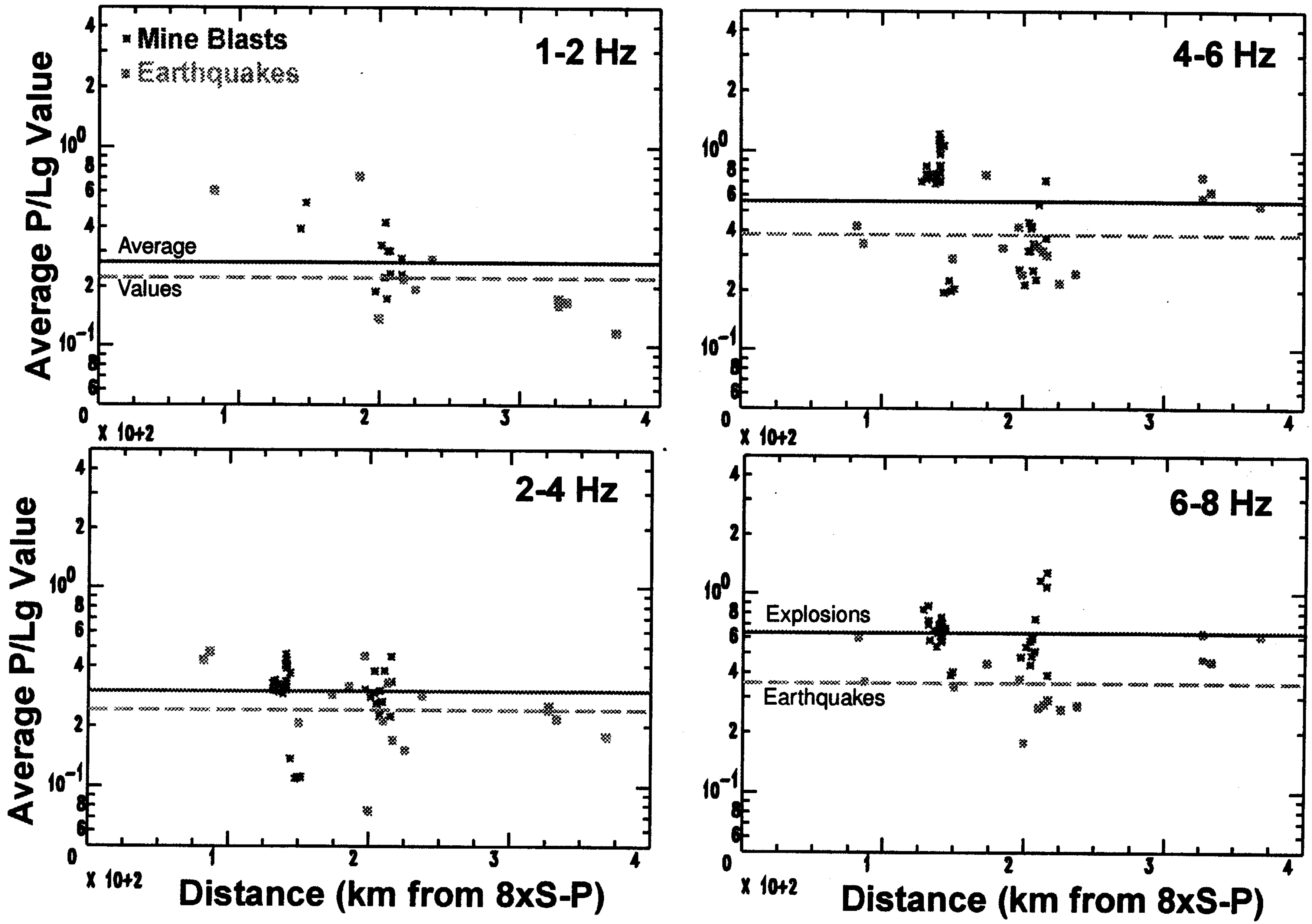

Fig. 4. Evaluating the P/Lg discriminant in four different frequency bands as a function of distance. Distance is approximated by eight times the S-P time interval. Note the separation between event population increases with frequency up to 6-8 Hz the maximum achievable with this 20 sps data. While the average value for the explosion group (solid line) is larger than the earthquake group (dashed line), there remains substantial overlap of events events even at 6-8 Hz.

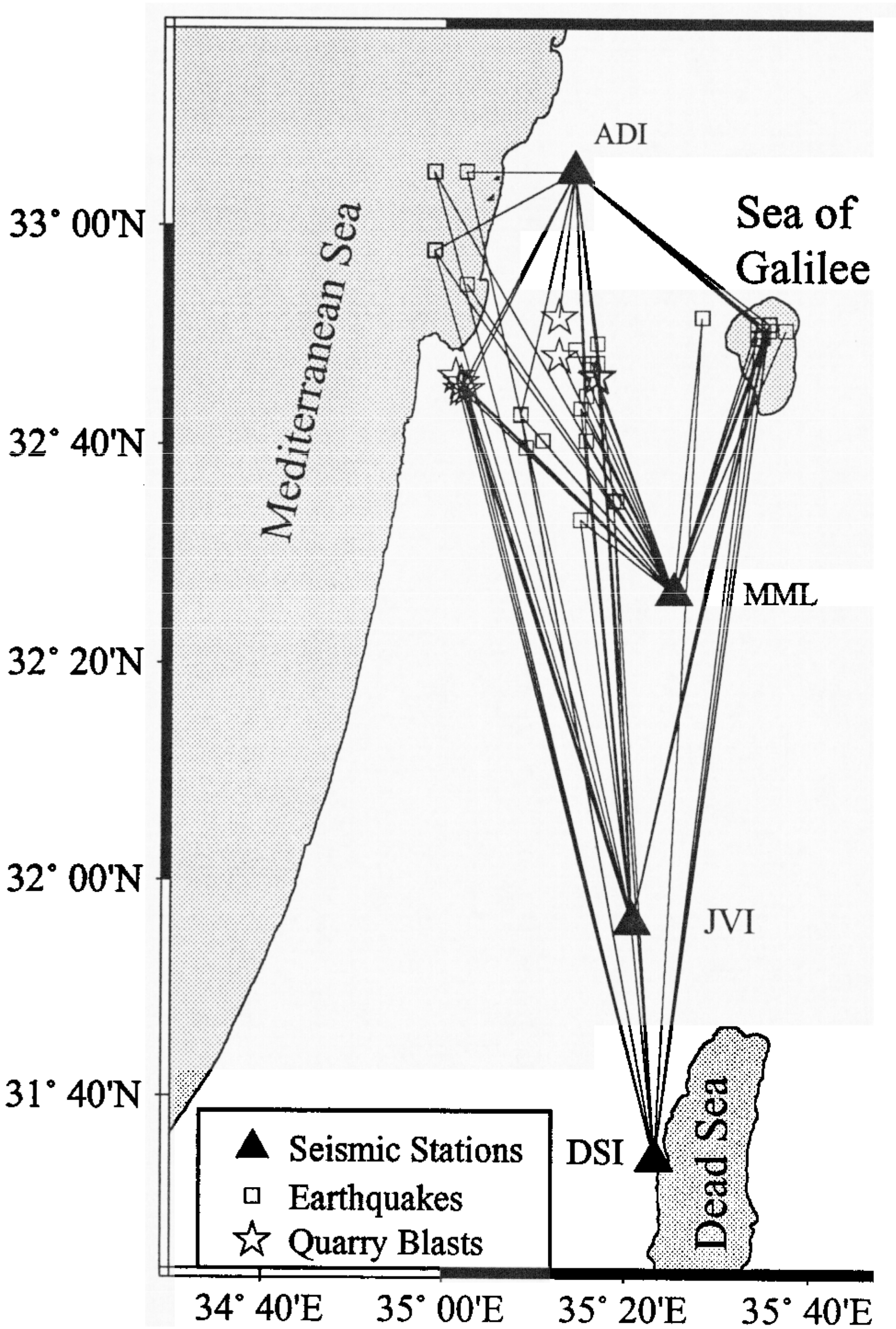

Fig. 5. Earthquakes and Quarry Blasts Recorded at select stations in the Isaeli Seismic Network. Selection criteria are Pg and Lg spectra in the 6 to 8 hz frequency band with S/N greater than twenty db. The noise spectra is taken from a pre-arrival window immediately before each phase arrival.

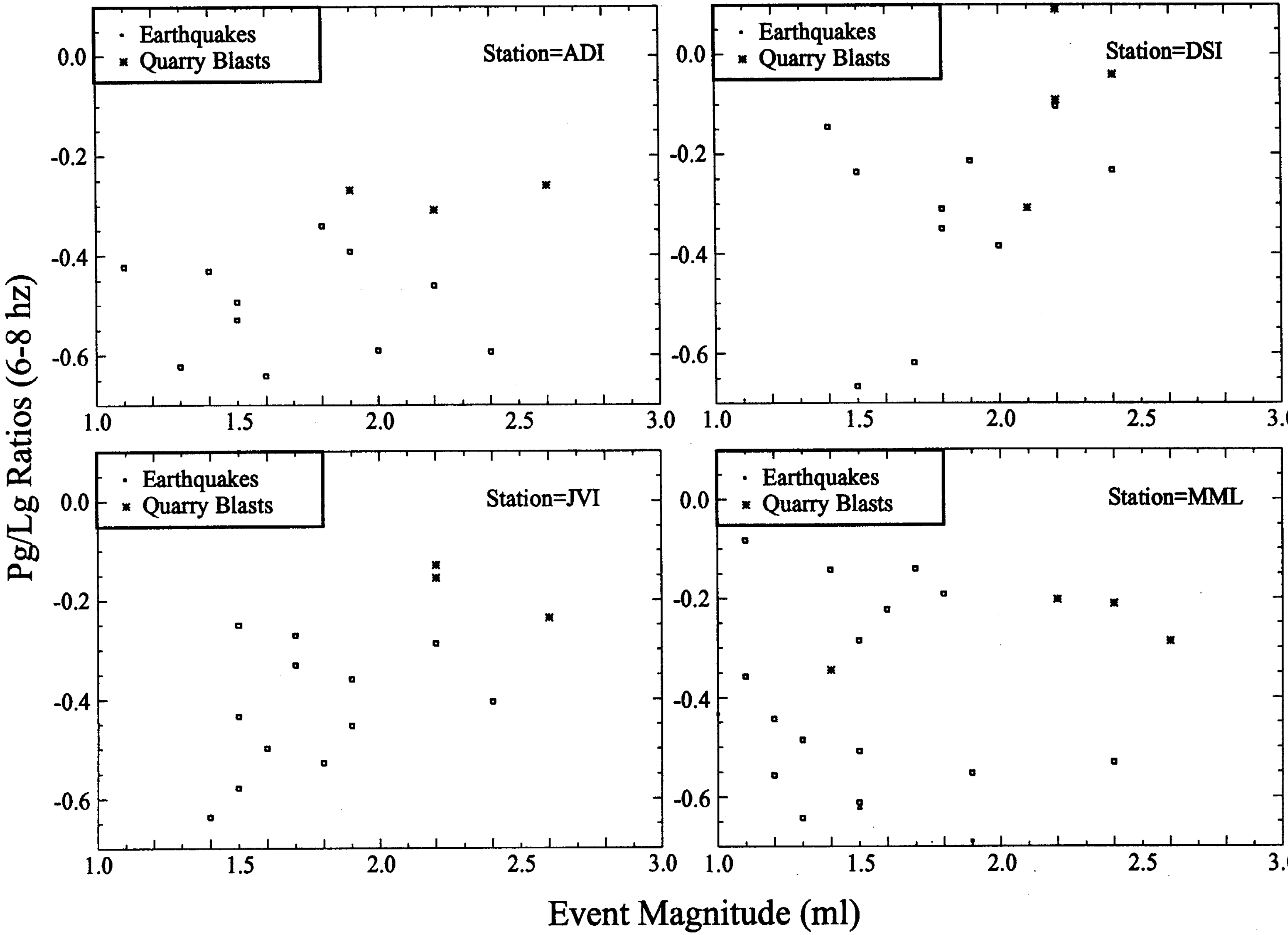

Fig. 6. Pg/Lg ratios for select earthquakes and quarry blasts recorded on four stations of the Israeli seismic network. Event/station ray paths are shown in Figure 5.

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