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Source Parameters of the March 31st, 2006, Dorud Earthquake in Iran

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The occurrence of the western Iran earthquake of 31 March 2006 provided an important opportunity to study the source properties of earthquakes in this region. Although moderate in size ($ML = 6.1$, IIEES), this earthquake was the largest to have occurred in the region since the deployment of the Global Digital Seismograph Network. The far-field data determination of body wave (P) spectra, interpreted in terms of the circular seismic source model, are used to estimate the parameters seismic moment (M_O), corner frequency (f_0) , source radius (r) and stress drop ($\Delta\sigma$). P waves recorded at teleseismic distances can be obtained from stations of this network that are flat to displacement, in a frequency range of 0.19 to 0.32 Hz. The average seismic moment ($M_O = 14.92 \times 10^{19}$ N-M) and source radius ($r = 9281$ m) were calculated from the long period spectral levels, which were corrected for the radiation pattern of a double couple point source. In addition, the stress drops ($\Delta\sigma = 87 \times 10^6$ N/m^2) of this event have been calculated by using an average seismic moment and source radius. Additional errors in the stress drop determination are produced by uncertainty in the seismic moment. Scatter in the seismic moment values is caused by such factors as site condition and errors in the radiation pattern.

INTRODUCTION

The March 31st, 2006 Dorud earthquake, $M_w = 6.1$ (Harvard CMT and USGS/NEIC), occurred at 01:17:02 GMT, in the west of Iran (Lat: 33.62, Lon: 48.91) (Figure 1) near the city of Dorud, which had a population of about 100,000. The earthquake killed around 66 people and there were about 1280 injuries. Seismic body waves are used to determine the rupture pattern of an earthquake. The rupture pattern is generally very complex and the results are interpreted in terms of a distribution of "asperities" [1] and "barriers" on the fault plane [2].

The principal purpose of this study is to determine the source characteristics of the March 31st, 2006 earthquake in western Iran from the high quality long period data that were digitally recorded at teleseismic distances by stations of the Global Digital Seismic Network (GDSN) (Figure 2). Body-wave spectra will be used to determine the dynamic characteristics of this event from the P waveform of the selected stations.

A general feature of theoretical, far-field displacement spectra $\Omega(\omega)$ generated by a spatially stationary seismic or explosive source is the corner (or peak) frequency f_0 (ω is circular frequency and $f = \omega/2\pi$ is frequency in Hz), which can be related to the source dimension [3,4].

Natele et al. [5] utilized this result and spectral data obtained from P waves to determine source dimensions for shallow earthquakes in Italy. Choy and Kind [6] estimated source dimensions and stress drops for December 13th, 1982 north Yemen earthquake by using Broad Band data. Wyss et al. [7] used spectral information in the frequency band $0.03 < f < 2$ Hz to demonstrate that three nuclear explosions had source dimensions almost in the order of magnitude of less than four earthquakes of comparable magnitude, mb.

For frequencies higher than corner frequency (f_0), $\Omega(\omega)$ reflects the short time behavior of the source displacement function; for a frequency band (f) greater than a corner frequency (f_0), ($f > f_0$), the spectral amplitudes must decay at least as fast as $f^{-\gamma}$, $\gamma > 1.5$, so that the energy integral is bounded. An important aspect of the Brune model [3] of shear-wave spectra is that $\Omega(\omega)$ falls off only as f^{-1} in the range $f_0 < f < f_0/\varepsilon$, where ε is the fractional stress drop.

$$\varepsilon = (\Delta\sigma/\sigma_{\text{eff}}). \tag{1}$$

Here, $\Delta\sigma$ is the stress drop and σ_{eff} is the effective stress (Pre-stress minus frictional opposing motion on the fault surface).

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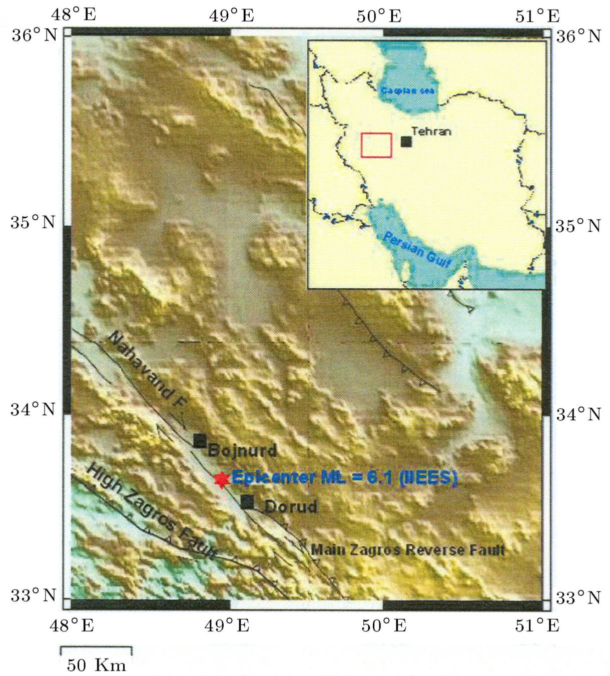

Figure 1. Epicenter location of March 31st, 2006 earthquake and fault map of the region.

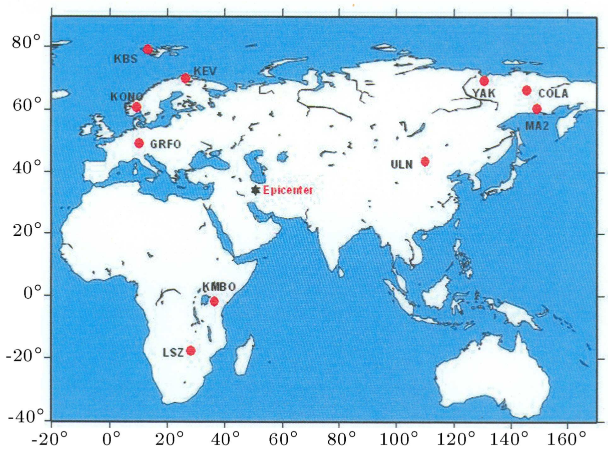

Figure 2. Distribution of international stations that are used in this study.

An equally important result follows from the dislocation model of a seismic source, for $f < f_0$, $\Omega(\omega)$ assumes a constant value that can be related to the seismic moment, M_O [8]. Aki [9] demonstrated that the seismic moment can also be obtained directly from field (F) observations.

$$M_O(F) = \mu A \overline{u}, \tag{2}$$

where μ is the shear modulus, A is the area of the fault surface and $\overline{u}$ is the average displacement across the fault surface. The seismic moment determination obtained from the spectra of radiated waves has not been systematically compared to field observations, because reliable long-period azimuth coverage has only been available since the installation of the Global seismic station system worldwide and because large earthquakes often occur in regions inaccessible to field measurements.

Body-wave spectra are also preferable for determination of the source dimension, since f_0 is generally in a period range at which surface-wave amplitudes are a sensitive function of the propagation path.

The intent of this paper is to demonstrate that both the source dimension and seismic moment can be reliably and relatively easily obtained from the interpretation of the body-wave spectra in terms of Brune's seismic-source model [3].

DISCRIMINATION OF SEISMIC SOURCE MODELS

Dahlen [10] and Burridge [11] have calculated far-field radiation when the initial phase of rupture is a self-similar circular rupture zone and the rupture slows and stops in such a manner that the initial break governs the high-frequency spectral content. Dahlen [9] assumed rupture speeds less than the S-wave velocity; Burridge [11] used rupture propagation at the P-wave velocity appropriate for a purely frictional fault lacking cohesion. Burridge [11] finds P-wave corner frequencies greater than S-wave corner frequencies in 83.7 percent of the focal sphere. Molnar et al. [12] suggested that observations of P- and S-wave corner frequencies could provide a constraint on the various earthquake source models. Again, with the exception of shallow earthquakes, body wave spectra are also preferable for determination of the source dimension, since f_0 is generally in a period range at which surface wave amplitudes are a sensitive function of the path propagation. The intent of this paper is to demonstrate that both the source dimension and seismic moment can be reliably and relatively easily obtained from interpretation of the body wave spectra in terms of Brune's seismic source model [3]. This calibration check provides justification for its use in current studies of source parameter determination, no field evidence for which is available.

Determination of Source Parameters of March 31st, 2006, Earthquake

In such procedures, values of earthquake moments must, first, be estimated by spectral analysis or the integration of displacement records. In addition, methods based on coda wave analysis have been applied for moderate sized earthquakes [13,14]. The purpose of using such methods is to allow evaluation of the seismic moment; thereby reducing the need for spectral analysis. It would be preferable, of course, to base the estimation of M_O on records from broadband seismographs [15]. The theoretical foundation for the proposed method comes from the well-known analytical expression derived by Keilis-Borok [8] and has already been applied to a number of earthquakes.

$$M_O(P) = \frac{\Omega_0(P)}{R_{\theta\varphi}} 4\pi\rho R\alpha^3, \tag{3}$$

where:

$M_O(P)$	seismic moment determined by the P-wave spectrum,
$\Omega_0(P)$	spectral amplitude at low frequencies,
$R_{\theta\varphi}$	depends on the source radiation pattern (assume 1.66 [16]),
ρ	the density (2700 kg/m^3),
R	the hypocentral distance,
α	P-wave velocity (assume 6 km/sec),

and:

$$r(P) = \frac{2.34\alpha}{2\pi fo(P)}, \tag{4}$$

where $r(P)$ is the radius of a circular source area determined by the P-wave spectrum and $f_0(P)$ is the corner (Peak) frequency of the P-wave spectrum. The physical meaning of Ω_o is the product of pulse width and amplitude, which is closely related to the mean value of seismic energy arriving in the time window considered. In practice, the determination of the Ω_o level in the amplitude spectrum is affected by the particular selection criterion used, and routine measurement procedures introduce further uncertainties to the estimates obtained by the spectral method [15,17]. The corner frequency, f_0, was selected as the intersection of the low frequency levels, (Ω_o), and a straight line that fit the spectral roll of the slope of the lower of the two frequency bands was used (see Figure 3). The data set for computing the seismic moment comes from the Global Digital Seismic Network (GDSN). The portion of the record encompassing the body phase was windowed, tapered with cosine bells in the first and last 10 percent of the window and then entered into a fast Fourier transform. The P wave spectrum was taken from the vertical component that appeared to have the largest pulse-like signal, the largest moment, or the component that best fit the Brune model [3]. The spectra were corrected for the effects of filter and instrument response.

Generally, the body-wave spectra admit an interpretation of a flat long-period level with some indication of a peaked spectrum. In any case, the primary interest here is to determine whether the moment calculated based on such an interpretation, together with Equation 3, has any relationship to the moment determined from the field data. A summary of Ω_o, f_0, for the P spectra, seismic stations, distance of stations to epicenter, seismic moment, M_O, and source radius, r, are given in Table 1. Average estimates for the multiple station events were obtained using methods described by Archuleta et al. [18] (shown in Table 2). For calculation of the average displacement (u) on the fault, Equation 2 can be used, where μ is the rigidity ($\sim 3 \times 10^{10}$ Nm^{-2}) and A is the fault area. Let it be assumed that the fault is roughly circular in area, with diameter L (18562 m) and ratio u/L being $\sim 5 \times 10^{-5}$ (see e.g. [19]). Displacement value (0.18 m) was observed for this event.

The mean stress drop, $\Delta\sigma$, was calculated using seismic moment and radius [3].

$$\Delta\sigma = (M_O, r) = 7M_O/16r^3. \tag{5}$$

The stress drop of this event was calculated by using average moment ($M_O = 14.92 \times 10^{19}$ N-m) and source radius (r = 9281 m). An estimate of the earthquake stress drop is important in the understanding of the

Table 1. Source parameters calculated using P phases in teleseismic stations.

Station	**Distance (deg.)**	**Phase**	$\Omega_0(P)$ ($\times 10^{-2}$ m-sec)	F_0 (hz)	R (m)	M_O ($\times 10^{19}$ N-M)
MA2	67.29	P	0.34	0.32	6572	11.2
ULN	45.34	P	0.34	0.25	8938	7.55
LSZ	52.44	P	0.45	0.29	7705	19.1
KBS	47.96	P	0.66	0.19	11760	15.5
KEV	38.16	P	1.10	0.21	10640	20.05
KONO	36.57	P	1.28	0.23	9715	22.9
KMBO	36.22	P	0.96	0.24	9310	17.0
GRFO	31.95	P	0.40	0.21	10640	6.26
YAK	56.76	P	1.05	0.25	8938	29.2
COLA	80.98	P	0.50	0.26	8594	0.49

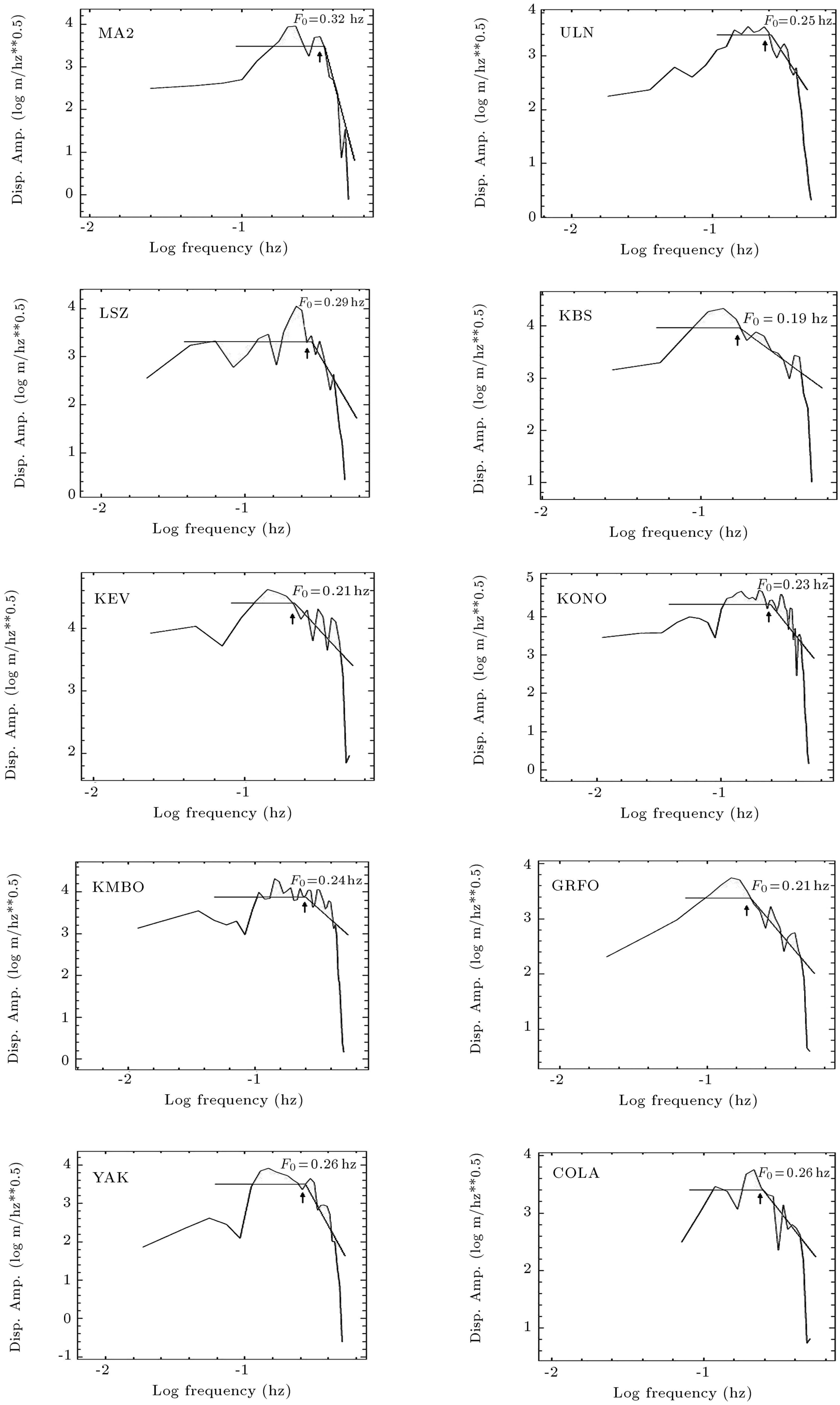

Figure 3. *P* wave recorded in Ma2 station and calculated displacement spectra.

Table 2. Average source parameters calculated by using methods described by Archuleta et al. [18].

Average Corner Frequency (F_0)	Average Source Radius (r)	Average Seismic Moment (M_O)
0.24 HZ	9281 m	14.92×10^{19} N-M

regional stress field, which, presumably, is the cause of the earthquake. Although a stress drop does not represent absolute levels of stress, it does indicate how much or how little stress is being released in an earthquake. The stress drop of this event is calculated as being 87 $\times 10^6$ N/m^2.

DISCUSSION AND CONCLUSION

The source parameters seismic moment and source dimension, as estimated from teleseismic body wave spectra, were interpreted following the Brune model [3]. Scatter in the seismic moment values is caused by such factors as site condition and errors in the radiation pattern corrections. The stress drop of an earthquake must represent the minimum tectonic stress required to cause the event, as well as a minimum estimate of material strength near the rupture surface. The proximity of low and high stress drop events indicates inhomogeneities in the stress or in the material properties within a rupture zone.

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REFERENCES

1. Kanamori, H. and Stewart, G.S. "Seismological aspects of the Guatemala earthquake", *J. Geophys. Res.*, **83**, pp 3427-3434 (1978).
2. Das, S. and Aki, K. "Fault plane with barriers: A versatile earthquake model", *J. Geophys. Res.*, **82**, pp 5658-5670 (1977).
3. Brune, J.N. "Tectonic stress and the spectra of seismic shear waves from earthquakes", *J. Geophys. Res.*, **75**, pp 4997-5009 (1970).
4. Brune, J.N. "Correction", *J. Geophys. Res.*, **76**, p 5002 (1971).
5. Natale, G.D., Madriaga, R., Scarpa, R. and Zollo, A. "Source parameter analysis from strong motion records of the Friuli earthquake sequence (1976-1977)", *Bull. Seism. Soc. Am.*, **77**(4), pp 1127-1146 (1987).
6. Choy, G. and Kind, R. "Rupture complexity of a moderate- sized (m_b 6.0) earthquake: Broadband body-wave analysis of the north Yemen earthquake of December 13th, 1982", *Bull. Seism. Soc. Am.*, **77**(1), pp 28-46 (1987).
7. Wyss, M., Hanks, T.C. and Liebermann, R.C. "Comparison of P-wave spectra of underground explosions and earthquakes", *J. Geophys. Res.*, **76**, pp 2715-2729 (1971).
8. Keilis-Borok, V.I. "Investigation of the mechanism of earthquakes", *Sov. Res. Geophys. (English Tarns.)*, **4**, p 29 (1960).
9. Aki, K. "Scaling law of seismic spectrum", *J. Geophys. Res.*, **72**, pp 1217-1232 (1967).
10. Dahlen, F.A. "On the ratio of P-wave to S-wave corner frequencies for shallow earthquake sources", *Bull. Seism. Soc. Am.*, **54**, pp 1811-1841 (1974).
11. Burridge, R. "The effect of sonic rupture velocity on the ratio of S to P corner frequencies", *Bull. Seism. Soc. Am.*, **65**, pp 667-676 (1975).
12. Molnar, P., Tucker, B.E. and Brune J.N. "Corner frequencies of P and S waves and models of earthquake sources", *Bull. Seism. Soc. Am.*, **63**, pp 2091-2104 (1973).
13. Aki, K. "Analysis of the seismic coda of local earthquake as scattered waves", *J. Geophys. Res.*, **74**, pp 615-631 (1969).
14. Aki, K. and Chouet, B. "Origin of coda waves: Source, attenuation and scattering effects", *J. Geophys. Res.*, **80**, pp 3322-3342 (1975).
15. Bolt, B.A. and Herraiz, M. "Simplified estimation of seismic moment from seismograms", *Bull. Seism. Soc. Am.*, **73**(3), pp 735-748 (1983).
16. Riznichenko, Y.V. *Problems of Seismology*, pp 3-27, Springer Verlag, Moscow (1992).
17. Hanks, T. and Wyss, M. "The use of body wave spectra in the determination of seismic source parameters", *Bull. Seism. Soc. Am.*, **62**(2), pp 561-589 (1972).
18. Archuleta, R., Cranswick, E., Muller, C. and Spudich, P. "Source parameters of the 1980 Mammoth Lake", *Califoria Earthquake Sequence, J. Geophys. Res.*, **87**, pp 4595-4607 (1982).
19. Scholtz, C.H., Aviles, C.A. and Wessnousky, S.G. "Scaling differences between large interplate and intraplate earthquakes", *Bull. Seism. Soc. Am.*, **76**, pp 65-70 (1986).