Moment-tensor analysis using regional data: Application to the 25 March, 1993, Scotts Mills, Oregon, earthquake

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Abstract. In this paper we outline a procedure we use for routine moment-tensor analysis of regional data from broadband seismic stations in northwestern North America and apply it to the moment magnitude 5.5, March, 1993, Scotts Mills, Oregon, earthquake. The results compare favorably with those obtained from telesismic data. We found that the earthquake occurred at a depth of 13-15 km and had a mechanism with approximately equal amounts of reverse and right-lateral strike-slip components. The estimated stress drop of 40 bar is average on a world-wide basis, supporting the view that the rather large damage was caused primarily by poor construction and not by exceptional properties of the source. The Scotts Mills earthquake is most likely related to the Mt. Angel Fault. This fault is a part of the Gales Creek-Mt. Angel structural lineament (GCMAL) extending about 150 km across the Willamette Valley. At present data are not sufficient to estimate the likelihood of an earthquake involving the entire GCMAL, but given its length an earthquake of magnitude 7 is conceivable. The results of this study, together with investigations of other earthquakes, suggest that sparse broadband networks can be used efficiently for determining source parameters of earthquakes of magnitude greater than 4.0 in regions with infrequent seismicity.

Introduction

The Scotts Mills earthquake of March 25 (Mw = 5.5) was the first of several unusually strong earthquakes that rocked Oregon in 1993. It occurred about 35 km east of the state capital, Salem, on the east side of the Willamette Valley, in the foothills of the Cascade mountains. For its magnitude it caused an unusually large amount of damage [Madin et al., 1993]. The second set of Mw = 6.0 earthquakes occurred near the town of Klamath Falls in the southern part of the state in September. The analysis of the Klamath Falls earthquakes is presented in a companion paper by Braunmiller et al. [1994b]. The regional stations used in this study are shown in Figure 1. The Scotts Mills earthquake is presented in a companion paper by Braunmiller et al. [1994b]. For its location in a subduction zone, indicate that the earthquake potential in this region cannot be ignored.

Because the event was well recorded by the regional short-period network, as well as some teleseismic stations, we are able to compare the results based on sparse regional broadband data with those derived from other observations.

Regional Data and Inversion Procedure

The regional stations used in this study are shown in Figure 1. At the time of the Scotts Mills event, there were 8 broadband stations operating within a radius of 800 km from the epicenter. We used data from 7 of them: COR (operated by the Incorporated Institutions for Seismology and the Oregon State University), ARC, WDC, MIN (Univ. of California at Berkeley), and PGC and WALA (Canadian National Seismograph Network). Although station LON has a broadband sensor, its records were saturated due to the low-dynamic range of the recorder. Instead, we were able to use data from the digital long-period seismometer which also records at that site. Station HAO (U.S. Geological Survey) is a digital strong-motion accelerograph located in Portland, 56 km from the epicenter. It recorded surprisingly good low-frequency data suitable for our analysis.

The inversion for the moment tensor and source time function involves modeling of the entire 3-component seismograms. The source parametrization and inversion procedure follow closely those used by Nábělek [1984] for the analysis of telesismic body waves. For a horizontally layered medium, displacement as a function of time t observed at a station at a distance A and azimuth φ from the earthquake epicenter can be expressed as

$$u_{PSV}(\phi, \Delta t) = \left( u^{PSV2} (\Delta, h, t) \left[ 1/2 (m_{yy} + m_{xx}) - m_{zz} \cos^2 \phi + m_{xz} \sin^2 \phi \right] + u_{PSV1} (\Delta, h, t) \left[ m_{yz} \sin \phi + m_{zx} \cos \phi \right] + u_{PSV0} (\Delta, h, t) \cdot m_{zz} \cdot \Omega(t) \right)$$

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Figure 1. (Background) Map of station distribution used in the regional wave analysis. (Foreground) Seismicity (mb>1.5, 1990-1993, WRSN data) in the area of the Scotts Mills earthquake. Mainshock is indicated by the star. The mapped trace of the Mt. Angel fault is indicated. Topography, 75-m contour interval.
where \( u^{SV} \) signifies displacement (vertical and radial components) resulting from the P-SV coupled seismic waves, and \( u^{SH} \) signifies displacement (transverse component) due to SH coupled waves. \( m_{ij} \) are the source moment tensor components. \( \Omega(t) \) is the far-field source time function.

Following Nábělek [1984], we parameterize the source time function as

\[
\Omega(t) = \sum a_k T_{2x}(t-\tau(k-1)), \quad k = 1, 2, ..., n;
\]

where \( T_{2x} \) is a series of \( n \) isosceles-triangle functions of a unit area, duration \( 2x \), and overlapped by \( \tau \), and \( a_k \) are the corresponding amplitude weights (required to sum to 1). The resulting time function has amplitudes specified at an equal time interval \( \tau \), with the intervening samples interpolated by the trapezoidal rule. By varying \( \tau \) and \( n \) we can control the time resolution and the total duration of the source time function.

If we know the crustal structure, we can calculate the excitation functions and determine the best fitting (we use the least-squares inversion) moment tensor and source time function. The depth can be determined by observing the fits for a suite of trial depths. We calculate the excitation functions using the method discrete wavenumber summation of Bouchon [1982] for the crustal model shown Table 1. This model was derived from a refraction study in western Oregon and Washington [Trhu et al., 1994], adjusting the Poisson's ratio so that major phases match the arrival times at distant stations. Using the same crustal model for the entire region limits the frequency band for which the theoretical seismograms can adequately describe the observed data. We used 0.1-0.01 Hz frequency band for the nearest three stations, and 0.05-0.01 Hz band for the others. In these frequency bands seismograms are dominated by guided waves in the crust (Pnl, Rayleigh, Love) and wide-angle reflections.

The moment tensor was constrained to be purely deviatoric. In order to give roughly equal weight to all stations, we used the same number of samples (200) from each seismogram (the near stations were sampled at a rate of 2 sps and the distant stations at 1 sps) and the amplitudes of the seismograms were corrected to a reference distance assuming cylindrical geometrical spreading. Even after correcting for the geometrical spreading, because of the difference in pass-bands, the power of the signal at the near stations was higher than at the distant stations; we corrected for this discrepancy by down-weighting the near stations by 40%.

In order to counter-act some of the phase misalignment due to deviations from the assumed crustal model and errors in the origin time and epicentral location, we realigned the observed and synthetic seismograms to maximize the correlation. The maximum shift was 3 s. Because we required all 3-components at a given station to shift together, this process did not remove misalignments caused by Love/Rayleigh wave anisotropy.

### Table 1. Crustal layer parameters used for calculation of synthetic seismograms

<table>
<thead>
<tr>
<th>Thickness, km</th>
<th>Vp, km/s</th>
<th>Vs, km/s</th>
<th>Density, g/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>4.00</td>
<td>2.25</td>
<td>2.14</td>
</tr>
<tr>
<td>5.0</td>
<td>5.50</td>
<td>3.09</td>
<td>2.56</td>
</tr>
<tr>
<td>3.0</td>
<td>6.35</td>
<td>3.56</td>
<td>2.80</td>
</tr>
<tr>
<td>3.0</td>
<td>6.67</td>
<td>3.74</td>
<td>2.89</td>
</tr>
<tr>
<td>5.0</td>
<td>6.75</td>
<td>3.79</td>
<td>2.91</td>
</tr>
<tr>
<td>4.0</td>
<td>6.93</td>
<td>3.89</td>
<td>2.96</td>
</tr>
<tr>
<td>9.0</td>
<td>7.16</td>
<td>4.02</td>
<td>3.02</td>
</tr>
<tr>
<td>6.0</td>
<td>6.50</td>
<td>3.65</td>
<td>2.84</td>
</tr>
<tr>
<td>half-space</td>
<td>8.10</td>
<td>4.35</td>
<td>3.29</td>
</tr>
</tbody>
</table>

### Table 2. Source parameters of the Scotts Mills earthquake determined in this study

<table>
<thead>
<tr>
<th>Data</th>
<th>Strike, deg</th>
<th>Dip, deg</th>
<th>Rake, deg</th>
<th>Depth, km</th>
<th>Mo, Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional</td>
<td>302</td>
<td>51</td>
<td>145</td>
<td>12-13</td>
<td>2.5x10¹⁷</td>
</tr>
<tr>
<td>Teleseismic</td>
<td>297</td>
<td>48</td>
<td>138</td>
<td>14.3</td>
<td>2.4x10¹⁷</td>
</tr>
</tbody>
</table>

Results of the Regional Wave Analysis

Figure 2 shows the observed and theoretical seismograms for the best-fit model. The data show large variations in the amplitudes of the three components from station to station reflecting the radiation pattern of the source mechanism (moment tensor). Table 2 lists the results. Data are generally well matched; the misfit is understandably larger for the distant stations. It appears that some of the mismatch, in particular at WALA, can be attributed to L/R anisotropy.

Figure 3 (top) shows the variance reduction as a function of source depth. The minimum is found for 12 and 13 km. If we assume 10% variance increase being significant, the uncertainty extends from about 11 to 15 km. The figure shows that the estimated moment tensor varies as a function of the assumed source depth from predominantly thrust mechanisms at a shallow depth to predominantly strike-slip mechanisms for the lower of the calculated depths. The northeast-dipping plane of the focal mechanism is relatively stable (its dip increases slightly with depth) while the southeast-dipping plane progressively changes the dip direction from southerly to easterly. As the depth increases, the estimated seismic moment increases. For the best fitting depth, the mechanism is mid-way between thrust and strike-slip, and the seismic moment is 2.4x10¹⁷ Nm (Mo = 5.5). Near the best-fitting depth the solution is 90% double-couple.

Duration: 2.0 s
Fault radius: 3.0 km; Av. slip: 22 cm; Av. stress drop: 40 bar
Figure 3. (Top) Variance (normalized by data power) vs. assumed depth of the source. The fault plane solutions (beach balls), the seismic moment in units of $10^{17}$ Nm (first number), and the percentage of the double-couple component of the moment tensor (second number) estimated for each depth are also shown. (Bottom) Variance vs. deviation from the best-fit estimate of strike, dip, and rake for a source at a 13 km depth.

Figure 3 (bottom) shows the resolution of the focal mechanism assuming a northeast-dipping fault plane and a source depth of 13 km. The best resolved parameter is the strike of the fault plane, while the rake of the slip angle is the least resolved. For a 10% variance increase, the bounds are -4° to +4° for strike, -7° to +4° for dip, and -7° to +9° for rake, relative to the best-fit estimates.

Using long-period data the source time function cannot be well resolved. All we can say is that the duration is shorter than 3 s.

Telesismic Bodywave Analysis

The results of the regional wave analysis are checked against those obtained from telesismic body waves. Typically such analysis is performed using broadband P and SH waves in the 30-90° epicentral distance range (e.g., Nábělek, 1984). For the Scotts Mills earthquake only a few good quality broadband body waves are available, nevertheless, after bandpass filtering in the 0.02-0.05 Hz band (notch in the Earth's ambient noise spectrum) we were able to obtain good azimuthal distribution of P and SH waveforms to constrain the mechanism and seismic moment (Figure 4, Table 2). The results are in very good agreement with the regional wave analysis. The low-frequency body waves could not resolve the source depth, but fortunately two stations in Asia (TLY and YSS) produced good quality broadband P waves with distinct P and sP arrivals (pP is nodal). These could be used to determine the source depth precisely (Figure 5), in good agreement with the depth estimate from the regional waves. The pulse widths at these two stations indicate a source duration of ~2 s.

Source Duration From Empirical Green Function and Stress Drop

The telesismic estimate of source duration for a medium magnitude earthquake is significantly affected by the uncertainty in the Earth attenuation. A better estimate can be obtained from close-in stations using seismograms from suitable aftershocks as the empirical Green functions calibrating the propagation paths (e.g., Mori and Frankel, 1990). Station HA0 would be a logical choice for such analysis. Unfortunately, the only aftershock which triggered this station showed very little coherence with the mainshock indicating a very different mechanism and source depth, and therefore could not be used. We use the aftershock of June 8, 1993 ($m_b=3.7$) which produced coherent records at COR, 74 km from the epicenter. Because COR was nodal for vertical and radial components, the analysis was carried out only on the transverse component. The estimated source time function (Figure 6) has a duration of 1.8 s. Accounting for some underestimate due to the finite duration of the aftershock, the mainshock duration was probably about 2.0 s. Assuming a circular crack model (Madariaga, 1976) with equal rupture and healing velocities of 3 km/s (0.8 vs) we can estimate the fault radius to be about 3.0 km. Together with the seismic moment of $2.5 \times 10^{17}$ Nm, this implies an average slip on the fault of 22 cm and a stress drop of 40 bar.

Summary and Discussion

The results of the regional and telesismic analyses of the Scotts Mills earthquake are remarkably consistent (Table 2). They indicate a mechanism with approximately equal amounts of reverse and right-lateral strike-slip components on a fault with a strike of about 300° and a dip of 50°. The centroid depth is 13-15
Figure 6. Broadband displacement seismogram (trans. comp., 20 sps, solid line) for the mainshock recorded at COR. The source time function (below) was found by deconvolving the mainshock waveform with a waveform from an aftershock (dashed line).

km and the moment magnitude 5.5. Except for the somewhat smaller dip, the parameters found here are also in excellent agreement with those reported by Thomas et al. [1993] based on the first-motion analysis of regional short-period seismograms from the Washington Regional Seismic Network (WRSN) (strike = 304°, dip = 58°, rake = 138°; focal depth = 15 km). Using data from the WRSN and temporary local stations they found that aftershocks extended from about 8 to 13 km. A subset of these events apparently lies on a NWW striking plane with a dip of 55° to 60° to the northeast. A preliminary examination of data recorded by temporary broadband stations deployed in the epicentral area after the mainshock by the Oregon State University (OSU) shows a wide variation of mechanisms of the aftershocks, indicating that the aftershocks cannot be interpreted in terms of a single fault plane.

The estimated stress drop of 40 bar for the mainshock is average on a world-wide basis, supporting the view that the rather large damage was caused primarily by poor construction of the pre-1950 structures [Bonneville et al., 1993; Dewey et al., 1994], and not by exceptional properties of the source.

The Scotts Mills earthquake is most likely related to the Mt. Angel Fault (MAF), which has been mapped at the surface west of the epicenter (Figure 1). The strike of the MAF at its southern mapped end is identical to that of the mainshock mechanism. The exact relationship, however, is not certain. Given the estimated dip, centroid depth and epicenter of the mainshock, the projected structural lineament (GCMAL) extending across the Willamette Valley lies on a WNW striking plane with a dip of 55° to 60° to the northeast. A preliminary examination of data recorded by temporary broadband stations deployed in the epicentral area after the mainshock by the Oregon State University (OSU) shows a wide variation of mechanisms of the aftershocks, indicating that the aftershocks cannot be interpreted in terms of a single fault plane.

The Mt. Angel Fault is a part of the Gales Creek - Mt. Angel structural lineament (GCMAL) extending across the Willamette Valley [Beezeno et al., 1985]. The MAF structure has been mapped using water well and industry seismic reflection data by Werner et al. [1992]. The offsets of sedimentary horizons indicate a post Miocene age. In 1990 a series of small earthquakes (M<sub>S</sub> 2.5) occurred south of Woodburn at the northwest end of the mapped fault (Figure 1). The events occurred at a depth of 15 km and had a strike-slip mechanism consistent with the orientation of the MAF there, indicating active deformation and seismic potential of the fault [Werner et al., 1992]. At present we do not have sufficient data to estimate the likelihood of an earthquake involving the entire GCMAL, but given the length of the structure (about 150 km) and the seismogenic thickness of the crust (15 km) an earthquake of magnitude 7 is conceivable.

In conclusion, our study shows that a relatively simple analysis of data from sparse regional broadband stations can yield quite precise estimates of source parameters. In the northwestern United States and western Canada, where there are 30 broadband seismic stations operating at this time, this technique can be routinely applied to events of magnitude greater than 4. The OSU routine moment-tensor determinations for this region are now included in the Quarterly Network Reports of the WRSN compiled by the Univ. of Washington. In special circumstances, when the earthquake occurs within 100 - 150 km from several stations, higher frequency data can be included in the analysis and the magnitude threshold is lower. For example, Braunmiller et al. [1994b] were able to apply this technique to aftershocks of the Klamath Falls earthquake that had a magnitude as low as 3.5. Further improvements in the precision of the parameter estimates and application to smaller events would require a denser station coverage and better calibration of the wave propagation paths.

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References


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