Australian Earthquake Engineering Society 2010 Conference, Perth, Western Australia

Contrast in Seismic Wave Propagation and Ground Motion Models between Cratonic and Other Regions of Australia

Paul Somerville[1,2] and Sidao Ni[3]

1. Principal Seismologist, URS Corporation, Pasadena, California, USA. Email: paul_somerville@urscorp.com

2. Deputy Director, Risk Frontiers, Macquarie University, North Ryde, NSW, Australia. Email: paul.somerville@mq.edu.au

3. Project Seismologist, URS Corporation, Pasadena, California, USA. Email: sidao_ni@urscorp.com

Abstract

Somerville et al. (2009) developed models for the prediction of ground motion response spectra in Australia for rock site conditions (V_s30 of 865 m/sec). Models were developed for two distinct regions: Cratonic (based on data and simulations for the Yilgarn craton), and Non-Cratonic (based on data and simulations for southeastern Australia, including the Paleozoic Lachlan Fold Belt). For both the Lachlan Fold Belt and Yilgarn regions, we used comparison of synthetic seismograms with the recorded seismograms of small earthquakes to explore the seismic wave propagation characteristics of the two regions, and to test and modify regional crustal velocity models. In the Yilgarn craton, both recorded and synthetic seismograms from shallow earthquakes contain large Rg waves whose amplitudes dominate the velocity seismograms. This is in strong contrast with southeastern Australia, in which the peak velocities are dominated by S waves (body waves), as is usually the case. Somerville et al. (2009) generated suites of broadband ground motion time histories using these crustal structure models, and used them to generate ground motion prediction models for each region. The Somerville et al. (2009) Cratonic ground motion model is quite similar to the model developed using Yilgarn Craton data by Liang et al. (2008), and less similar to the models for stable regions of eastern North America by Toro et al (1997) and Atkinson and Boore (2006). The very large ground motions predicted by the Cratonic model at periods of 1 second and longer are due to surface waves that are generated by shallow faulting and trapped in a shallow layer (1 km thick) of lower velocity rock; such waves are prominently recorded in the Yilgarn craton. The Non-cratonic ground motion model is more similar to models for tectonically active regions such as Boore and Atkinson (2008) than the Toro et al. (1997) model for tectonically stable eastern North America, mainly due to the higher value of kappa used in the non-cratonic model than in Toro et al. (1997). We used kappa values of 0.006 and 0.04 respectively in the Cratonic and Non-cratonic models.

Key Words: Seismic wave propagation, earthquake ground motions.

INTRODUCTION

Clark et al. (2010) divided Australia into several different tectonic domains. The focus of this paper is on their domain D1: Precambrian Craton, in which the 2007 Katanning earthquake occurred, and their domain D4: Phanerozoic Accretionary, a non-cratonic domain in which the 2003 Moss Vale earthquake occurred.

YILGARN CRATON: THE 2007 Mw 4.7 KATANNING EARTHQUAKE

A magnitude Mw 4.7 earthquake occurred 30km south of Katanning, Western Australia at 7:58am Australian Western Standard Time (AWST) on October, 9th, 2007 (Geoscience Australia; Dawson et al., 2008). It is easy to tell that the earthquake was very shallow because of the strong recorded Love and Rg waves (Figure 1), as typically short period Rg waves are only excited by events shallower than 3km (Saikia, 1992).

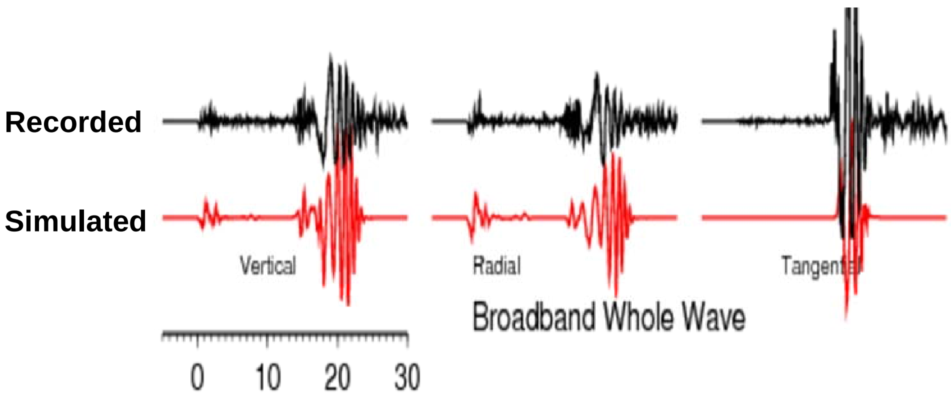

Figure 1. Recorded (top) and synthetic (bottom) seismograms of the Katanning earthquake, showing successive arrival of the P wave, the S wave, and the Rg wave, which has the largest amplitude and is highly dispersed.

We used surface wave dispersion (0.5s-5s) of the Rg waves to constrain the shallow structure of this region. A 1 km thick low velocity zone (V_s 3.15km/s) overlying crystalline basement (Vs ~3.5km/s) is required to explain the strongly dispersed R_g wave. By modeling the details of receiver functions, we found that the mid-crustal discontinuity is shallower than indicated in previous studies, i.e., at a depth of 12-15km instead of 20-25km. Also, the Moho needs to be fairly sharp to satisfy both seismic refraction and receiver function data.

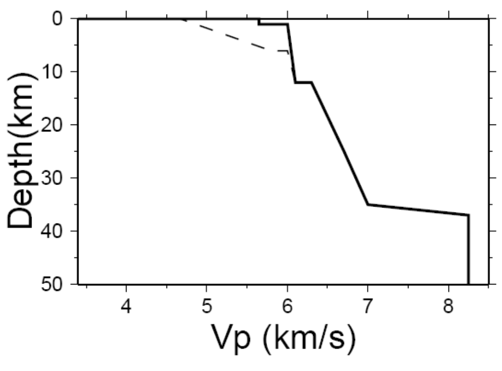

Figure 2. Crustal structure model for Yilgarn Craton (solid) and Perth Basin (dashed).

We used this crustal structure model to model the recorded waveforms of the Katanning earthquake. We employ the Cut and Paste (CAP) method (Zhu and Helmberger, 1996) of resolving the source mechanism and depth of this earthquake from broadband waveforms recorded by stations MUN, NWAO and BLDU. The focal depth was well resolved because the Pnl waveform is sensitive to focal depth, and the amplitude ratio between the surface wave and the Pnl wave (the long period wave train preceding the S wave) provides good constraints on focal depth (Wallace and Helmberger, 1982). From this inversion, the Katanning event was found to have moment magnitude of 4.7, a depth of 2 km, and a thrust mechanism. The short period synthetic seismograms are in fairly good agreement with the data, as shown in Figure 1. In particular, the synthetic seismograms contain large Rg waves whose amplitudes dominate the velocity seismograms. This is in contrast with the usual situation, which we find in southeastern Australia as described below, in which the peak velocities are dominated by S waves (body waves).

LACHLAN FOLD BELT: THE 2003 M_w 3.8 MOSS VALE EARTHQUAKE

On December 11, 2003, an M_L 4.2 earthquake occurred near Moss Vale, about 100 kilometers south of Sydney. It was felt in Bowral, Canberra, and as far north as Katoomba and the north shore of Sydney. The Geoscope broadband seismic station CAN recorded this event with very good quality for periods shorter than 2s (Figure 3). In the 0.5-2s band, the body wave part consists of several recognizable phases. The first few arrivals are expected to be Pn, Pg and PmP given the epicentral distance of 159 km. At this distance, the strong signal about 3 second after the first arrival is easily identified as sPmP, the wave leaving the source as an S wave, reflected from the free surface as a P wave and reflected post-critically by the Moho. sPmP is also called a depth phase because its arrival is very sensitive to focal depth, and is thus very valuable in determining source depth.

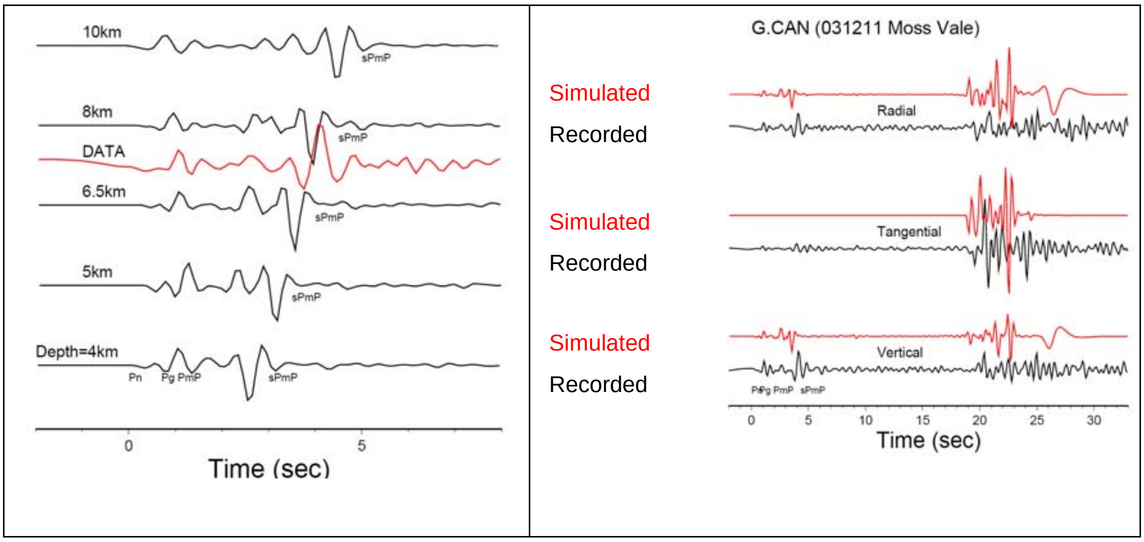

Figure 3. Left: Identification of the depth phase sPmP in the Moss Vale earthquake using synthetic seismograms for a range of focal depths. Right: Comparison of recorded and simulated seismograms of the Moss Vale earthquake.

To confirm that the strong signal is sPmP, we constructed reflectivity seismograms for different depths using the Lachlan Fold Belt crustal structure model shown in Figure 4. The P velocity model is based on seismic refraction (Collins et al., 2003) and the S velocity model is based on the P velocity model assuming a Vp/Vs ratio (1.75) determined from teleseismic receiver function analysis. Synthetic and observed vertical components are shown on the left side of Figure 3, where sPmP shows clear move-out with depth. By comparing synthetics and data, we demonstrate that the earthquake occurred at a depth between 6.5 and 8 km. With focal depth resolved, we analyze the focal mechanism and magnitude by trial and error fitting and find that an M_w 3.8 earthquake with a thrust mechanism containing a strike slip component (strike 200/dip 80/rake 60) can explain the short period body wave phases (right side of Figure 3) and longer period surface waves.

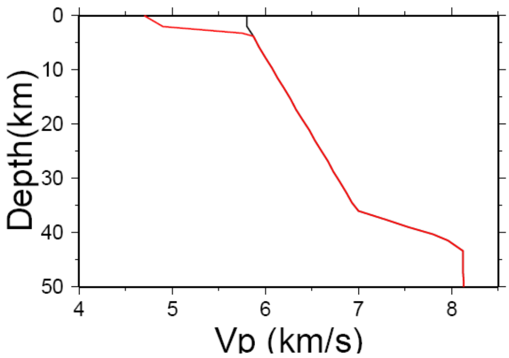

Figure 4. Crustal structure of the Lachlan Fold Belt (black) and Sydney Basin (red).

COMPARISON OF GROUND MOTION MODELS

Ground motion models for the Cratonic and Non-cratonic regions of Australia were developed by Somerville et al. (2009). As shown in Figure 5, the Cratonic model predicts larger peak accelerations than the Non-cratonic model. This is as we would expect, because we used a much lower kappa value in the Cratonic model. In contrast, the ground motion model of Gaull et al. (1990) shows the opposite trend – smaller peak acceleration in Western Australia than in Southeast Australia.

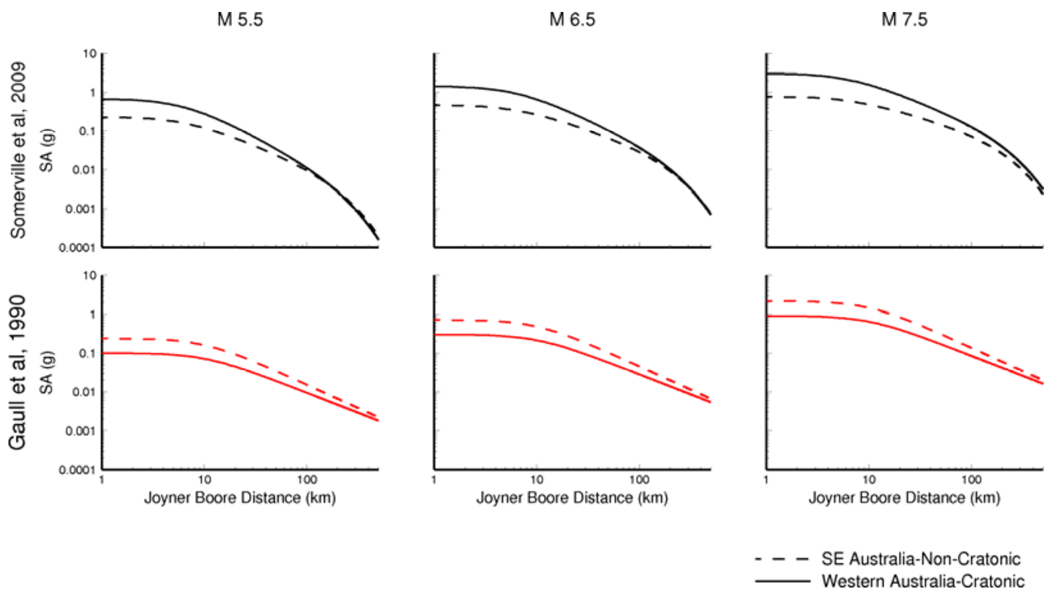

Figure 5. Comparison of the Somerville et al. (2009) Non-cratonic and Cratonic ground motion prediction models for peak acceleration (top) with the Gaul et al. (1990) SE Australia and Western Australia models (bottom).

The predictions of the Gaull et al. (1990) and Somerville et al. (2009) ground motion models for peak acceleration are compared in Figure 6. The predictions are fairly similar in Southeastern Australia, but quite different in Western Australia at distances less than 100 km. In Figures 5 and 6, the Gaull et al. (1990) model for Western Australia does not distinguish between cratonic (e.g. Yilgarn Craton) and non-cratonic (e.g. Perth) regions, but Somerville et al. (2009) do make that distinction, and place the region west of the Darling Fault (including Perth) in the Non-cratonic category, as described further below.

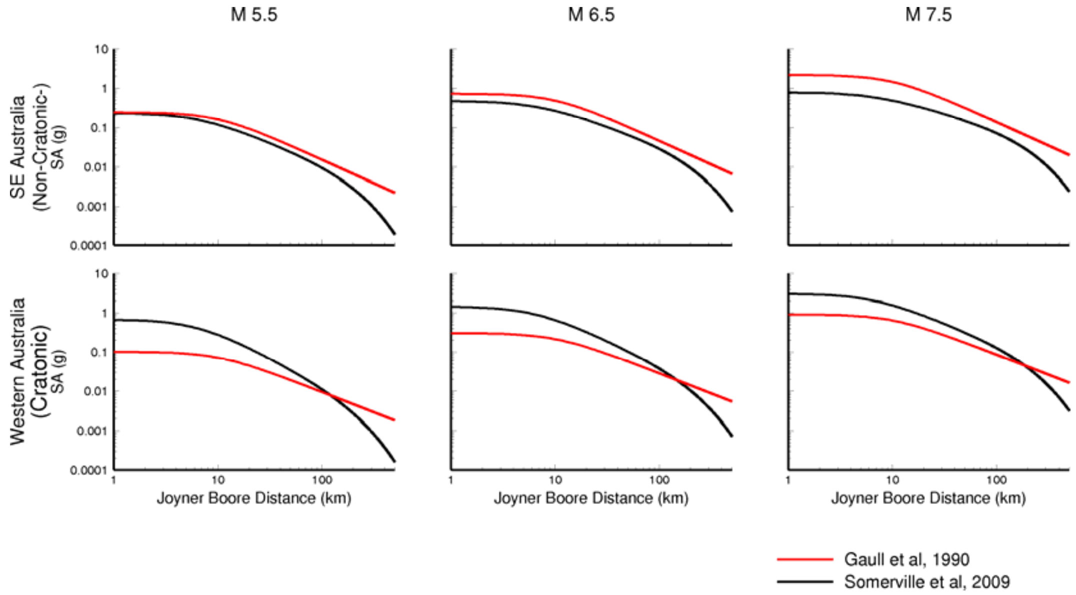

Figure 6. Comparison of the Gaull et al. (1990) ground motion prediction model for peak acceleration in Southeast Australia with the Somerville et al. (2009) Non-cratonic model (top) and the Gaull et al. (1990) ground motion prediction model for Western Australia with the Somerville et al. (2009) Cratonic model (bottom).

The response spectra predicted by various ground motion models are compared in Figure 7. The Somerville et al. (2009) cratonic ground motion model is quite similar to the model developed using Yilgarn Craton data by Liang et al. (2008) model, and less similar to the models for stable regions of eastern North America by Toro et al (1997) and Atkinson and Boore (2006), as shown on the left side of Figure 7. The very large ground motions predicted by the cratonic model at periods of 1 second and longer are due to surface waves that are generated by shallow faulting and trapped in a shallow layer (1 km thick) of lower velocity rock; such waves are prominently recorded in the Yilgarn craton. The non-cratonic ground motion model is more similar to models for tectonically active regions such as Boore and Atkinson (2008) than the Toro et al. (1997) model for tectonically stable eastern North America, as shown on the right side of Figure 7, mainly due to the higher value of kappa used in the non-cratonic model than in Toro et al. (1997). We used kappa values of 0.006 and 0.04 respectively with the cratonic and non-cratonic models. This difference in kappa is the main cause of the differences in predicted ground motion levels at short periods between the two regions. This is consistent with the finding by Risk Engineering Inc. (2001, Figure 4.10), using a stochastic ground motion simulation model, that except for the effects of differences in kappa, the ground motions for eastern North America and western North America are similar for a given reference site condition.

The regions in which the Cratonic and Non-cratonic models of Somerville et al. (2009) are applicable remain to be established, but to first order, we expect that the Cratonic model is applicable to all of the D1 – Precambrian Craton regions of Australia (Clark et al., 2010), and that the Non-cratonic model is applicable to all other regions of Australia, including the part of Western Australia (including Perth) that lies west of the Darling fault.

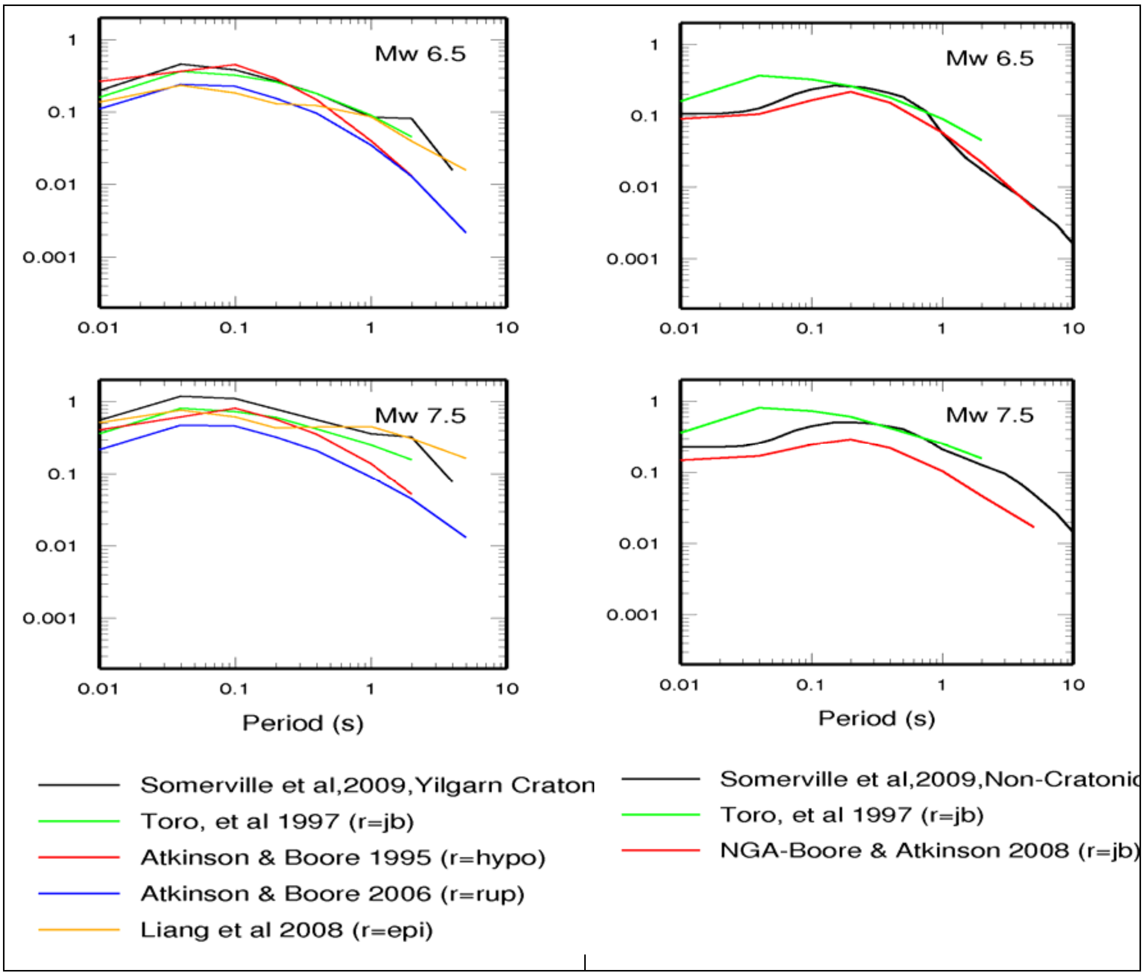

Figure 7. Comparison of cratonic model response spectrum (black line, left) and non-cratonic model response spectrum (black line, right) with other ground motion models for magnitude 6.5 and 7.5 earthquakes at a distance of 30 km. The vertical axis shows response spectral acceleration in g's as a function of period on the horizontal axis.

ACKNOWLEDGMENTS

This paper describes work done by URS under contract to Geoscience Australia. The authors would like to acknowledge the many contributions of Trevor Allen to this study, including the estimates of kappa that he provided, and the review comments of Gary Gibson. The ground motion data shown in Figure 2 come from a database of Australian strong ground motions that was assembled in a collaborative effort between Geoscience Australia, Environmental Systems and Services (ES&S), and the Australian National Committee on Large Dams (ANCOLD), with a large proportion of the strong motion data being supplied by ES&S. This strong motion data base

forms the principal data source available for the development of ground motion prediction models in Australia.

REFERENCES

Atkinson, G.M. and Boore, D.M. (2006). Earthquake ground-motion prediction equations for eastern North America. *Bull. Seism. Soc. Am.*, 96, 2181-2205.

Atkinson. G.M and D.M. Boore (1996). New ground motion relations for eastern North America. *Bull. Seism. Soc. Am*. 85, 17-30.

Boore, David M., and Gail M. Atkinson (2008). Ground motion prediction equations for the average horizontal component of PGA, PGV and 5% damped PSA at spectral periods between 0.01s and 10.0s. *Earthquake Spectra* 24, 99-138.

Clark, D., A. McPherson and C. Collins (2010). Australia's seismogenic neotectonic record: a case for heterogeneous intraplate deformation. *Geoscience Australia Record* 2010/xxx, 95pp.

Collins C, R. Kayen, B. Carkin, T. Allen, P. Cummins and A. McPherson (2006). Shear Wave Velocity measurement at Australian Ground Motion Seismometer Sites by the Spectral Analysis of Surface Waves (SASW) Method, GA report 10008.

Collins, C.D.N., B.J. Drummond, and M.G. Nicoll (2003). Crustal structure thickness patterns in the Australian continent. *Geol. Soc. Australia Spec. Pub*. 22, 121-128.

Dawson, J., P. Cummins, P. Tregoning, and M. Leonard (2008), Shallow intraplate earthquakes in Western Australia observed by Interferometric Synthetic Aperture Radar, *J. Geophys. Res.*, 113, B11408, doi:10.1029/2008JB005807.

Gaull, B.A., Michael-Leiba M. and Rynn J.M.W. 1990. Probabilistic earthquake risk maps of Australia. *Australian Journal of Earth Sciences* **37**, 169-187.

Liang, J. Z., Hao, H., Gaull, B. A. and Sinadinovski, C. (2008). Estimation of Strong Ground Motions in Southwest Western Australia with a Combined Green's Function and Stochastic Approach, *Journal of Earthquake Engineering*, 12:3,382 – 405.

Risk Engineering, Inc. (2001). Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-consistent Ground Motion Spectra Guidelines. *NUREG/CR-6728*.

Saikia, C. K. (1992). Numerical study of quarry generated *Rg* as a discriminant for earthquakes and explosions: modeling of *Rg* in Southwestern New England, *J. Geophys. Res.*, 97, 11057-11072.

Somerville, P., R.W. Graves, N.F. Collins, S.G. Song, and S. Ni (2009a). Ground motion models for Australian earthquakes. Report to Geoscience Australia, 29 June 2009.

Somerville, P.G., R.W. Graves, N.F. Collins, S.G. Song, S. Ni and P. Cummins (2009b). Source and ground motion models of Australian earthquakes. Proceedings of the 2009 Annual Conference of the Australian Earthquake Engineering Society, Newcastle, December 11-13.

Somerville, P.G., N. Collins, N. Abrahamson, R. Graves and C. Saikia (2001). Earthquake source scaling and ground motion attenuation relations for the central and eastern United States. Final Report to the U.S. Geological Survey, Contract No. 99HQGR0098.

Toro, G.R., N.A. Abrahamson, and J.F. Schneider (1997). Model of strong ground motions from earthquakes in central and eastern North America: best estimates and uncertainties. *Seismological Research Letters*, 68(1), 41-57.

Wallace,T.C.and D.V. Helmberger (1982). Determining source parameters of moderate-size earthquakes from regional waveforms. *Physics of the Earth and Planetary Interiors* 30, 185-196.

Zhu, L. and D.V. Helmberger (1996). Advancement in source estimation techniques using broadband regional seismograms. *Bull. Seism. Soc. Am.* 86; p. 1634-1641.