San Bernardino Region 3D Velocity Model

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Investigations

The San Bernardino region of southern California is situated on a wedge shaped sedimentary basin bounded to the north by the San Andreas fault and to the south by the San Jacinto fault. Both of these active faults are capable of generating Mw 7+ earthquakes, stressing the need for timely assessment of the ground shaking hazard for future earthquakes. Sediment accumulations are relatively thin in the northern portion of the basin, and then steadily increase in thickness toward the south. The maximum sediment thickness is about 1.8 km just north of the San Jacinto fault, with an abrupt step-up and shallowing of the basement surface along the San Jacinto fault. Observations of long period ground motions on a dense array of strong motion stations for both large (Mw 7.2 Hector Mine) and small (Mw 4.6 Big Bear Lake) earthquakes show significant amplification and extended durations of shaking at sites within the basin. Preliminary 3D models of the basin structure have been developed using constraints from potential field data and seismic reflection profiles. These models work well at matching the observed waveforms at periods of about 3 seconds and longer. In order to provide ground motion estimates for more practical (engineering) purposes, the resolution limit of these models needs to be extended down to periods near 1 second. Not only does this present a formidable computational task, but perhaps more importantly, it requires accurate knowledge of source processes and 3D velocity structure on a very detailed level. Unfortunately, direct measurements of shear velocity in the basin sediments are not available. Our modeling suggests that near surface shear velocities of about 300 to 400 m/s are required to match the observed waveforms down to periods near 1 second. Additionally, the effects of anelastic attenuation become increasingly important in these softer materials, and must be included in the calculations. Finally, we note that although the use of small events for validation studies is attractive, these events are not always "simple". The Big Bear Lake sequence indicates that the structure outside of the basin contains complexities (e.g.,site response, mid-crustal reflectors) that significantly affect the waveforms around periods of 1 second. These structural complexities must be properly accounted for in the background velocity models in order to adequately understand the response of the basin sediments.

Results

The Mw 4.6 Big Bear Lake earthquake occurred on 02/10/01 at a depth of 8.5 km just north of the San Bernardino region of southern California. The mechanism of the event is primarily strike-slip as determined by regional waveform inversion (see www.trinet.org/shake). Ground motions were recorded at nearly 30 stations in and around the San Bernardino basin region. These stations are part of the TriNet system and are operated jointly by CSMIP, USGS and Caltech. Figure 1 shows the distribution of the stations and the event epicenter. There is a large concentration of stations within the San Bernardino basin, which lies in the wedge shaped region between the San Andreas and San Jacinto faults.

The profiles in Figure 2 display the recorded ground velocities rotated to tangential and radial components relative to the epicenter. These motions have been low pass filtered at 1 Hz. The ordering of the stations in these profiles is roughly with increasing epicentral distance. The stations in the middle of the profiles are located within the basin (indicated by the red brackets). Clearly, the basin sites show amplified motions and extended durations of shaking relative to the sites outside of the basin. In addition, for many of the basin sites the largest motions occur later in the records after the direct arrivals. These ground motion characteristics are indicative of basin response effects such as the generation of basin surface waves. Our goal is to model these data to better understand the nature of the basin response and then to use this knowledge to estimate its effect on ground motions for future events in this region (e.g., San Andreas or San Jacinto ruptures).

Complexity of Non-Basin Motions

The use of small events for basin validation studies is attractive because the source process can usually be regarded as "simple" in the frequency range where the modeling is targeted (typically $f < 1$ Hz). Unfortunately, as the modeling is pushed toward shorter periods, the details of the velocity structure outside of the basin region begins to become important, as well. This is illustrated in Figure 3 which displays ground velocity time histories recorded at two TerraScope sites outside of the San Bernardino basin. Motions for two events are shown: those in black are for the Mw 4.6 Big Bear Lake event and those in red are for a Mw 3.2 aftershock which occurred very close to the mainshock. The motions for the smaller event have been scaled by a factor of 200 to account for the difference in moment. Both sets of motions have been low pass filtered at 1 Hz.

The similarity in the amplitudes and waveforms for the two events is remarkable. Since these events differ by over two units in magnitude, this suggests that the complexities seen in the waveforms are due to path and site effects. In the absence of path and site complexities, we would expect the motions at these stations to be characterized by simple pulses of motion related to the direct P and S waves. However, the motions exhibit significant arrivals following the main pulses and lasting in duration for 5 to 10 seconds. Granted, the complexity of these motions is not nearly as strong as seen at the basin sites where the large amplitude later arrivals can last in duration for 50 seconds or more. Nonetheless, the complexity at these non-basin sites is indicative of the characteristics of the wave field as it propagates into the basin region. We suspect that the response at these stations may be effected by topography, local site conditions (e.g., svd is in a zone of very complex geology adjacent to the San Andreas fault), or small basin type structures (e.g., bbr is in a small valley containing Big Bear Lake). In our modeling, we have not attempted to match all of the details of the response at these non basin sites, but rather to capture the main characteristics of the motion as it propagates into the basin region. Ultimately, a more complete realization of the motions at all of the sites will require very detailed knowledge of the subsurface geology and seismic velocity structure.

3D Basin Structure

In a recent study, Graves and Wald (2002) have examined the ground motion response and 3D velocity structure of the San Bernardino basin region. That study used ground motion recordings from the Mw 7.2 Hector Mine earthquake to test three models of the basin geometry. It was shown that the Hector Mine data were fit best using a gently southwestward dipping basement interface that reaches its maximum depth just north of the San Jacinto fault. Due to computational limitations and the long period nature of the Hector Mine source, the basin modeling in that study had little resolution below about 3 - 4 seconds period.

In the current study, we extend this earlier work by using data from the Big Bear Lake earthquake to refine the velocity structure and push the modeling threshold to shorter periods. We start with the basin geometry given by the gravity model of Anderson et al. (2000). This is referred to as Model A in Graves and Wald (2002) and the structure is displayed in a perspective view in Figure 4. The previous study used a minimum shear velocity of 600 m/s in the basin. In order to model the shorter period data, we reduce this to 400 m/s. Additionally, we have added a gradient in the near surface of the media outside the basin which lowers the surface velocity to 700 m/s. This is consistent with a class B site type. The panels in Figure 5 show shear velocity cross sections through the basin structure.

Section A-A' crosses through the deepest portion of the basin (about 1.8 km), which occurs just northeast of the San Jacinto fault zone. The basin has an ubrupt step-up along this fault structure with the sediments reducing in thickness to about 300 m south of the fault. Section B-B' runs along a more northerly azimuth along which the sediments reach a maximum thickness of only about 600 m.

Figure 6 displays vertical velocity and density profiles taken at the locations of 4 stations within the basin region. Station 5331 is just north of the basin, station 5337 is located in the northern basin and stations 5339 and 5329 are located in the deep central portion of the basin. Currently, there is little direct information regarding the velocity structure of the deep basin. The values we use are based on our previous modeling work with the Hector Mine data, and they have been subsequently adjusted using a trial-and-error procedure in an attmept to improve the fit to the ground motion data. Attenuation is modeled using Qs = 100 * Vs where Vs is given in km/s.

Ground Motion Simulations

Ground motions are simulated using the finite difference method of Graves (1996). In order to reduce the model storage requirements, we use the grid stretching algorithm of Pitarka (1998). The minimum grid spacing is 100 m horizontally and 50 m vertically which gives a frequency resolution of 0.8 Hz in the lowest velocity regions of the model. The grid spacing is increased outside and beneath the low velocity materials in a manner that preserves the above frequency resolution limit. The Big Bear Lake earthquake is modeled as a point source having a moment of 8.0×10^{22} dyne-cm (Mw 4.57). The mechanism is strike=208○, dip=77○ and rake=10○, and the source function is a cosine bell with a width of 0.6 sec.

Figures 7 and 8 display the observed and simulated ground velocities for the Big Bear Lake earthquake. In these figures, tangential and radial components are compared for most of the stations in and around the San Bernardino basin. The sites within the basin are indicated by the brackets. In Figure 7, the motions are filtered at T > 3 sec, and in Figure 8, the motions are filtered at T > 1 sec. The locations of the sites are shown in the map at far left.

At T > 3 sec (Figure 7), the simulation provides a good match to the amplitudes and waveforms of the observed motions at almost all of the stations. This includes the strong amplification that is seen at the basin sites. The simulation tends to underpredict the duration of the largest motions on the tangential component at the basin sites, although the main cycles of motion are modeled well. The only station which is fit poorly in this passband is sbpx.

At T > 1 sec (Figure 8), the match between the synthetics and data is not as good. For most stations, the timing of the main arrivals is matched well, and the amplitude of the first few cycles of motion is also matched reasonably well. However, the simulation underpredicts the duration of shaking at most of the basin sites, and it does not reproduce many of the large amplitude late arriving phases observed at these sites.

To examine the frequency characteristics of the basin modeling in more detail, Figure 9 plots observed and simulated motions filtered in three pass bands. The sites shown in the figure are located just north of the basin (svd), in the northern basin (5373) and in the deep central basin (5328).

Again, at the longer periods (T > 3 sec), the match between the simulated and observed motions is good. Going to a somewhat shorter period band (T > 2 sec), we see that the fit begins to worsen. This is true not only at the basin sites, but also at the non-basin site, svd. Although the first few cycles of motion tend to be matched with reasonable accuracy, the fit deteriorates with time into the record. This same trend continues to the shortest period band (T > 1 sec). In addition, the simulation tends to underpredict the peak amplitudes and the shaking durations more severely at the shorter periods.

These results suggest that 1) the current model works reasonably well at simulating the ground motions at periods of 3 sec and longer, 2) extending the model to shorter periods represents a non-trivial task (i.e., it is more complex than simply reducing the minimum velocity threshold in the numerical calculation) and requires detailed knowledge of the subsurface structure and seismic velocities at short length scales (100 m) and 3) as we attempt to model shorter period motions, structural complexity at non-basin sites becomes increasingly important and its effects on the wave field must be considered as it propagates into the basin.

References

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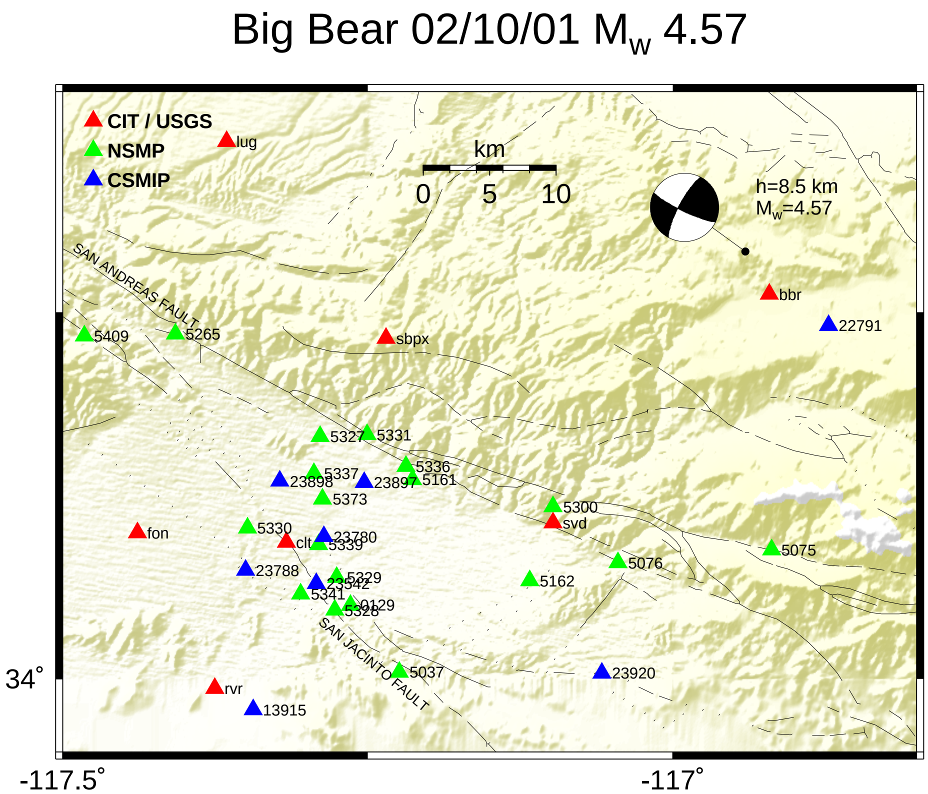
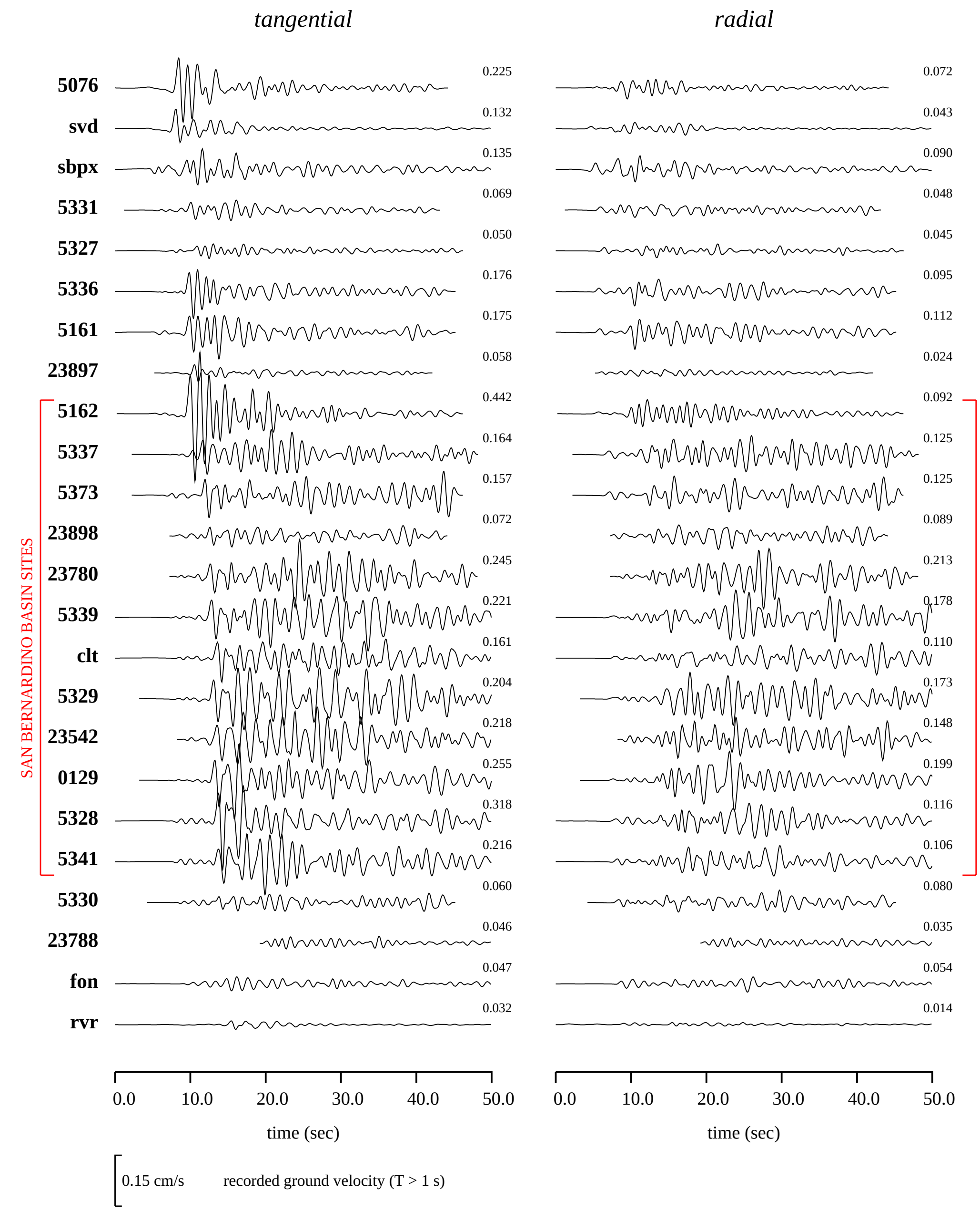

Big Bear 02/10/01 M_w 4.57
CIT / USGS
NSMP
CSMIP
km
0
5
10
h=8.5 km
M_w=4.57
SAN ANDREAS FAULT
SAN JACINTO FAULT
lug
bbr
22791
sbpx
5409
5265
5327
5331
5336
5161
23898
5337
23897
5373
5300
svd
fon
5330
clt
23780
5339
5075
5076
23788
5329
23542
5341
5162
0129
5328
5037
23920
rvr
13915
34°
-117.5°
-117°

Figure 1:



tangential
radial
5076
svd
sbpx
5331
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5336
5161
23897
5162
5337
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23898
23780
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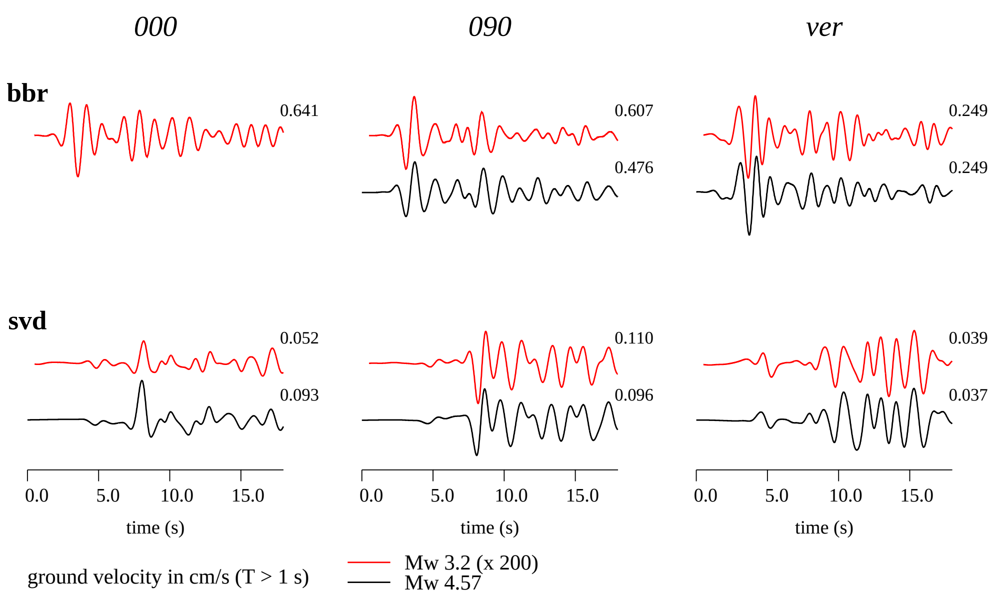
clt
5329
23542
0129
5328
5341
5330
23788
fon
rvr
SAN BERNARDINO BASIN SITES
time (sec)
0.15 cm/s
recorded ground velocity (T > 1 s)

Figure 2:



000
090
ver
bbr
0.641
0.607
0.476
0.249
0.249
svd
0.052
0.093
0.110
0.096
0.039
0.037
0.0
5.0
10.0
15.0
time (s)
ground velocity in cm/s (T > 1 s)
Mw 3.2 (x 200)
Mw 4.57

Figure 3:

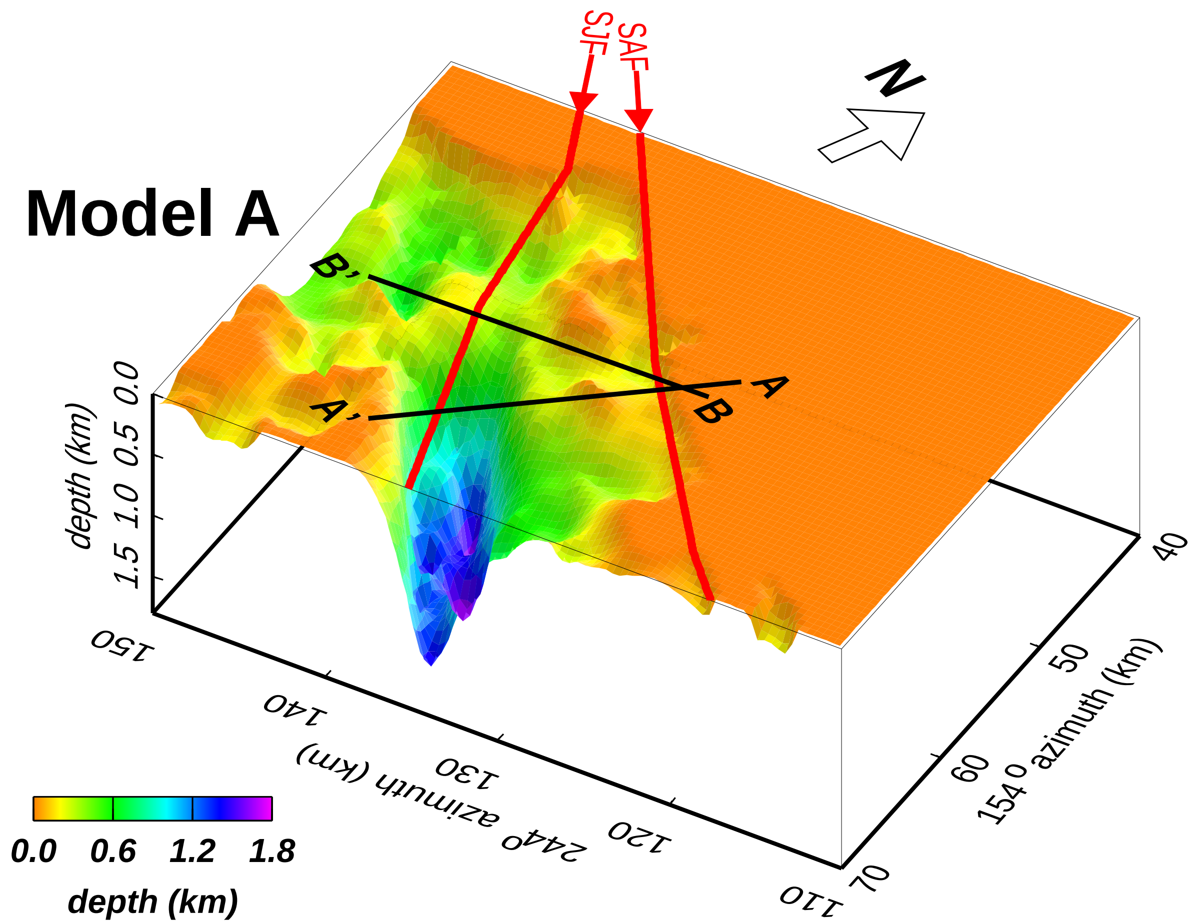
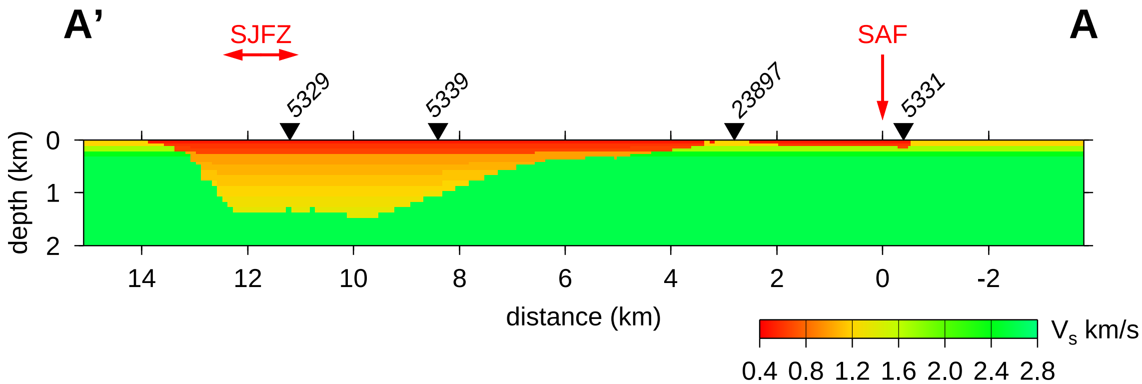
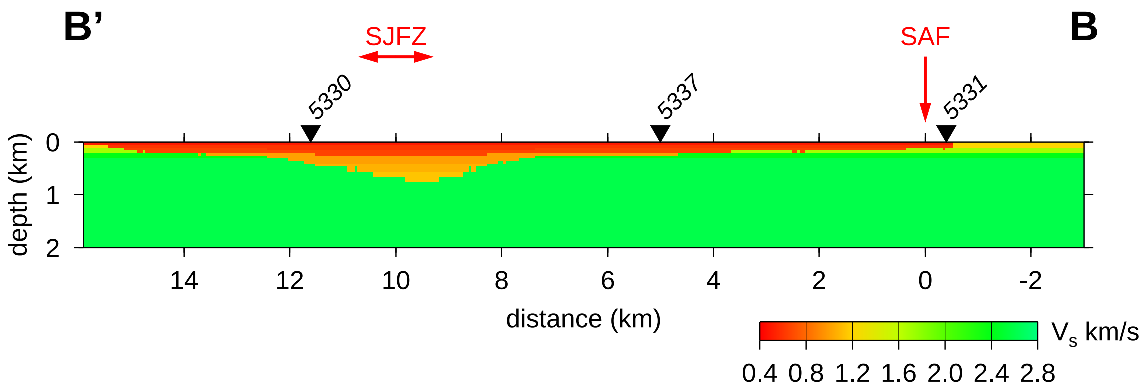

Model A
SJF
SAF
N
B'
A
A'
B
depth (km)
0.0
0.5
1.0
1.5
150
140
130
120
110
244° azimuth (km)
40
50
60
70
154° azimuth (km)
0.0
0.6
1.2
1.8
depth (km)

Figure 4:



A'
SJFZ
SAF
A
5329
5339
23897
5331
depth (km)
0
1
2
14
12
10
8
6
4
2
0
-2
distance (km)
Vs km/s
0.4 0.8 1.2 1.6 2.0 2.4 2.8



B'
SJFZ
SAF
B
5330
5337
5331
depth (km)
0
1
2
14
12
10
8
6
4
2
0
-2
distance (km)
Vs km/s
0.4 0.8 1.2 1.6 2.0 2.4 2.8

Figure 5:

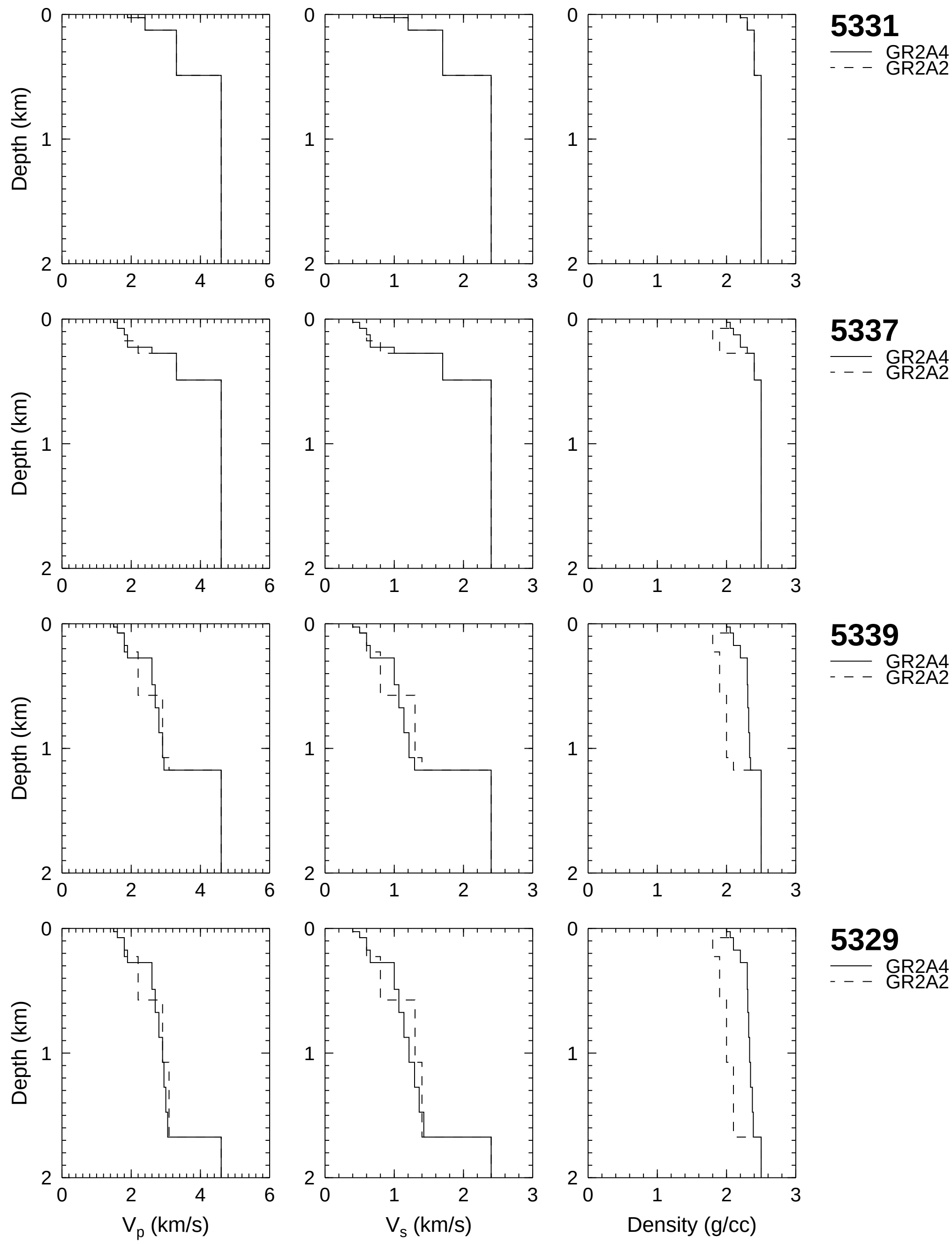
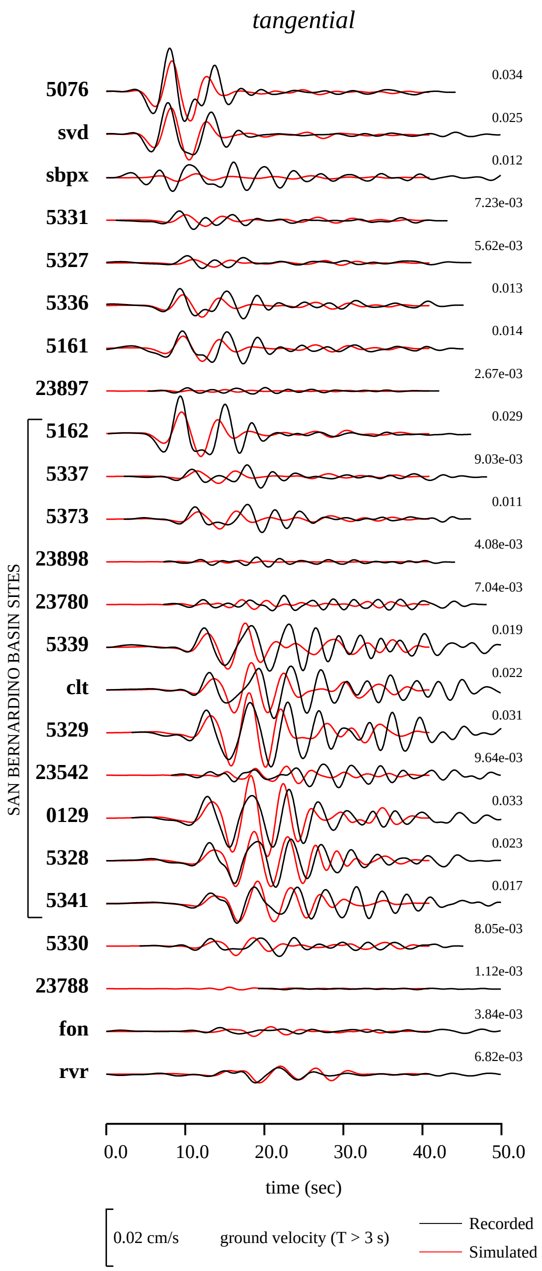

5331
GR2A4
GR2A2
5337
GR2A4
GR2A2
5339
GR2A4
GR2A2
5329
GR2A4
GR2A2
Depth (km)
Vp (km/s)
Vs (km/s)
Density (g/cc)

Figure 6:



tangential
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23780
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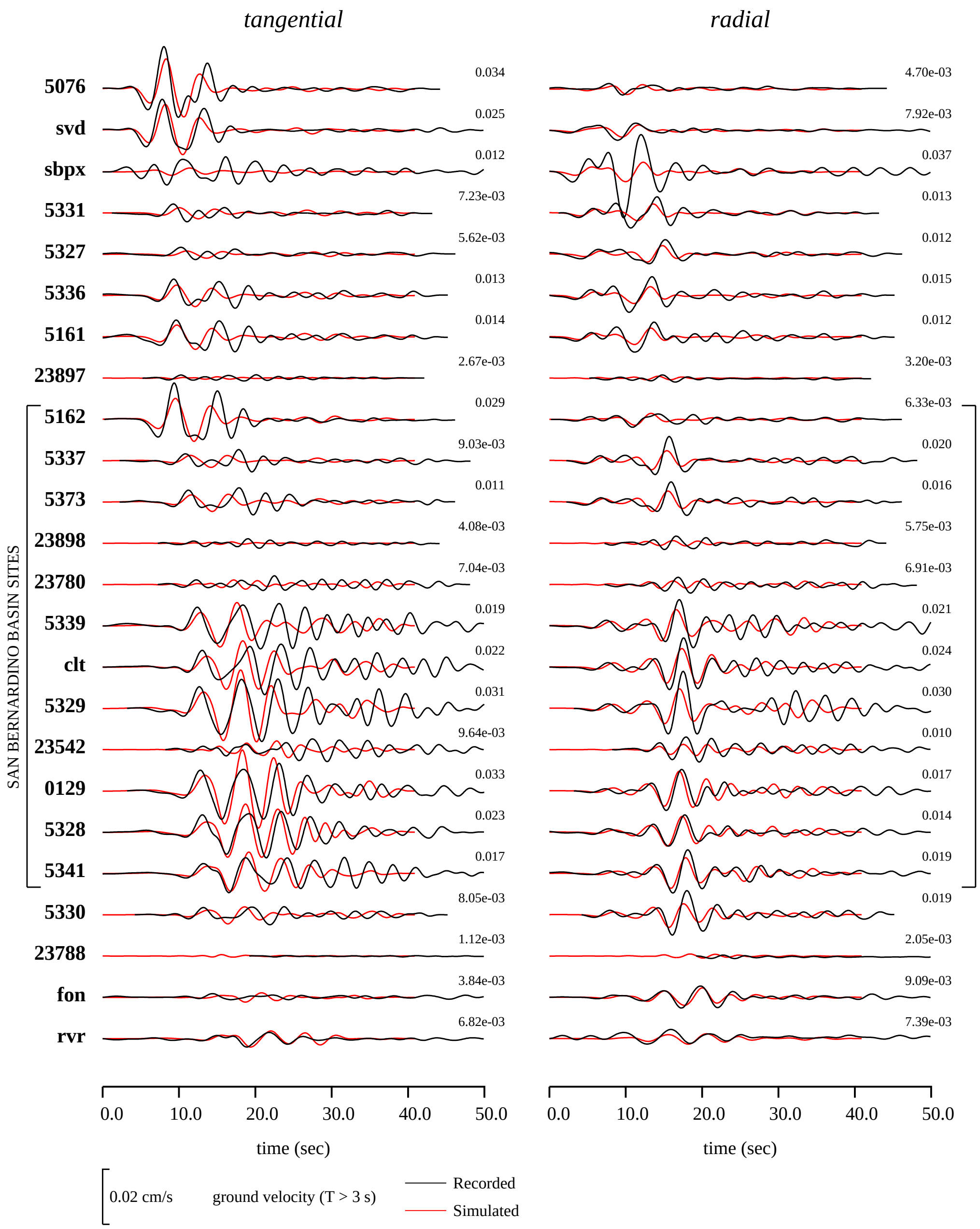
clt
5329
23542
0129
5328
5341
5330
23788
fon
rvr
SAN BERNARDINO BASIN SITES
0.034
0.025
0.012
7.23e-03
5.62e-03
0.013
0.014
2.67e-03
0.029
9.03e-03
0.011
4.08e-03
7.04e-03
0.019
0.022
0.031
9.64e-03
0.033
0.023
0.017
8.05e-03
1.12e-03
3.84e-03
6.82e-03
4.70e-03
7.92e-03
0.037
0.013
0.012
0.015
0.012
3.20e-03
6.33e-03
0.020
0.016
5.75e-03
6.91e-03
0.021
0.024
0.030
0.010
0.017
0.014
0.019
0.019
2.05e-03
9.09e-03
7.39e-03
0.0
10.0
20.0
30.0
40.0
50.0
time (sec)
0.02 cm/s
ground velocity (T > 3 s)
Recorded
Simulated

Figure 7:


tangential
radial
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23780
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clt
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rvr
SAN BERNARDINO BASIN SITES
0.034
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0.012
7.23e-03
5.62e-03
0.013
0.014
2.67e-03
0.029
9.03e-03
0.011
4.08e-03
7.04e-03
0.019
0.022
0.031
9.64e-03
0.033
0.023
0.017
8.05e-03
1.12e-03
3.84e-03
6.82e-03
4.70e-03
7.92e-03
0.037
0.013
0.012
0.015
0.012
3.20e-03
6.33e-03
0.020
0.016
5.75e-03
6.91e-03
0.021
0.024
0.030
0.010
0.017
0.014
0.019
0.019
2.05e-03
9.09e-03
7.39e-03
0.0
10.0
20.0
30.0
40.0
50.0
time (sec)
0.02 cm/s
ground velocity (T > 3 s)
Recorded
Simulated

Figure 8:


T > 3 sec
T > 2 sec
T > 1 sec
svd
tan
rad
ver
0.025
0.023
7.92e-03
5.92e-03
6.64e-03
6.13e-03
0.057
0.044
0.012
9.10e-03
0.018
0.011
0.132
0.165
0.043
0.043
0.037
0.033
5373
0.011
8.06e-03
0.016
0.011
9.73e-03
7.14e-03
0.032
0.017
0.037
0.018
0.019
0.012
0.157
0.064
0.125
0.058
0.038
0.028
5328
0.021
0.026
0.014
0.013
8.55e-03
5.37e-03
0.072
0.063
0.047
0.027
0.020
0.017
0.318
0.207
0.116
0.063
0.073
0.087
0.0
10.0
20.0
30.0
40.0
50.0
time (s)
ground velocity in cm/s
Recorded
Simulated

Figure 9:

Non-technical Summary

Due to its large population base, extensive built environment and close proximity to active faults, the region in and around the San Bernardino basin represents one the highest levels of seismic risk in southern California. This basin is formed by the intersection of the San Andreas and San Jacinto faults, both of which are capable of generating large magnitude earthquakes, stressing the need for timely assessment of the ground shaking hazard for future scenario earthquakes. Ground motion estimation is further complicated by the highly variable nature of the subsurface geology. Existing observations from both large and small earthquakes demonstrate that ground shaking levels are greatly enhanced at sites situated on top of the basin sediments. Our goal in this project is to use sophisticated computer simulation techniques to analyze these data and to develop a more comprehensive understanding of the ground shaking expected in this region from future large earthquakes.

Reports

Graves, R. W. (2002). The seismic response of the San Bernardino basin region, *Eos. Trans. AGU*, **83**(47), Fall Meet. Suppl., Abstract S21A-0968.