# Timpson, Texas Earthquakes of May, 2012

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## Introduction

The earthquake sequence that occurred near Timpton, Texas in 2012 was significant in that earthquakes are rare inTexas, and yet the larges thad an Mw > 4.5. A paper by Frohlich et al (2014). Because of its association with injection wells, it is the subject of further study.

The Saint Louis University Regional Moment Tensors gave two different contradictory solutions for the events of May 10 and May 17 (www.eas.slu.edu/eqc/eqc_mt/MECH.NA) (Figure 1). The events for comparison are:

http://www.eas.slu.edu/eqc/eqc_mt/MECH.NA/20120510151539/index.html
http://www.eas.slu.edu/eqc/eqc_mt/MECH.NA/20120517081201/index.html

and the source parameters are

| Date Time | Lat | Lon | H | Mw | Stk | Dip | Rake | Ref | Model | Authority |
|---|---|---|---|---|---|---|---|---|---|---|
| 20120510_151539 | 31.90 | -94.42 | 10 | 4.00 | 240 | 90 | 40 | WEB | WUS | SLU |
| 20120517_081201 | 31.90 | -94.33 | 4.0 | 4.83 | 150 | 50 | 0 | WEB | WUS | SLU |

20120510151539 20120517081201

Fig. 1. Original mechanisms published by SLU. The nodal plane orientations are similar, but the sense of motion is reversed for the two solutions.

There are several reasons for the difference in the solutions.

First the distribution of broadband stations was not optimal for source inversion (Figure 2). A good azimuthal coverage would be preferred.

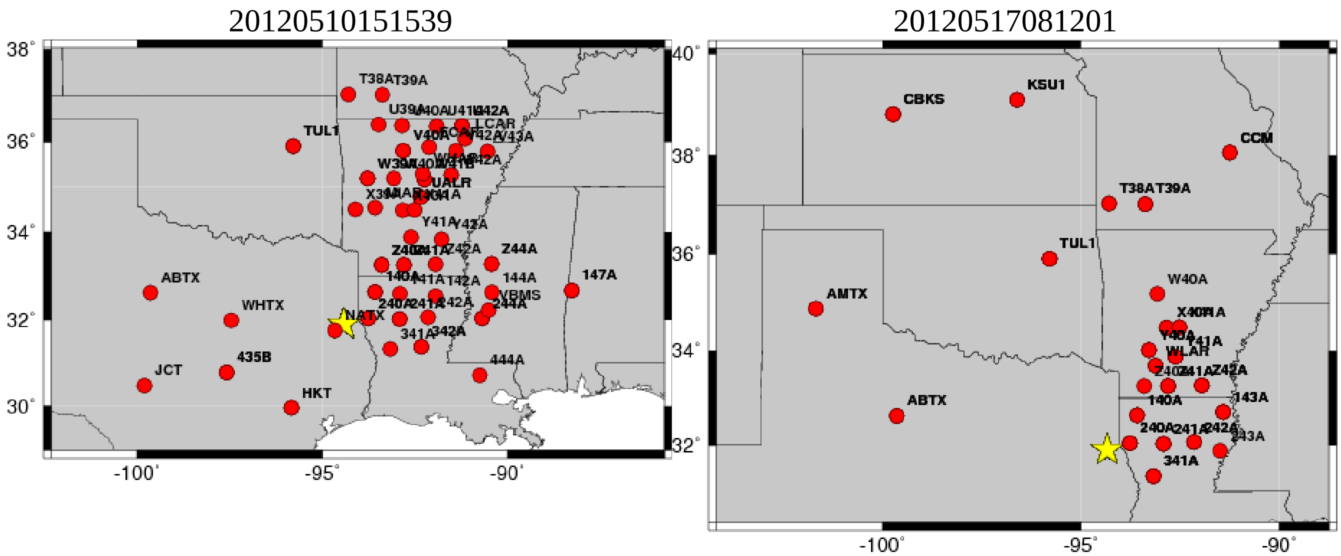


Fig. 2. Distribution of broadband stations used for source inversion.

Second, the velocity model and frequency band used must be able to fit the observed data unambiguously. The SLU solutions used the WUS model which has low velocities near the surface. However, the observed signals had significant, slow dispersed surface waves in the 0.02 – 0.10 Hz band, and thus lower frequencies had to be used. For the 2012/05/10 earthquake, the 0.02 – 0.07 band was used, while the 0.01 – 0.025 Hz band was used for the 2012/05/17 earthquake. Lower frequencies could not be used for the first event because of the lower signal-to-noise because of its smaller size. Higher frequencies were not used because of the dispersion – a incorrect model could lead to an interchange of the P- and T-axes.

## Review of the solution:

On June 22, 2016, I received the following email that prompted me to review these earthquakes:

> Hi Professor Herrmann,
>
> I am a graduate student at Stanford interested in stress and seismicity in Texas. I'm working with Mark Zoback to create a new Stress Map of Texas, and SLU's moment tensors are a very helpful source of information.
>
> One area of interest is Timpson, Texas, where Cliff Frohlich and others have suggested that earthquakes may have been triggered by wastewater injection. There are two SLU moment tensors for 2012 earthquakes in that area and they both show steeply-dipping nodal planes that strike NE and NW (dates: 2012-5-10 and 2012-5-17). Interestingly, the nodal planes have identical orientations between the two moment tensors, but the tensional/compressional quadrants of the two moment tensors are 90º apart (see the table and figure below). This seems unusual because I'd expect the P-axes of two nearby strike-slip mechanisms to trend in at least the same general direction, not orthogonal to one another. It's also surprising that the planes in the two moment tensors are identical.
>
> Is it possible that there is an error with the reporting of one of these two moment tensors? I'd just like to

make sure that there isn't a problem with one of them before going forward with any analyses.

Thank you,

To address the issue, a velocity model must be developed for this region of the Gulf Coast, and the inversion must use stations for which that model is appropriate. A way to accomplish this is to replace the upper 3 km of the WUS model (Herrmann et al 2011) with the 3km upper crust model of Frohlich et al (2014) model, and then to patch both onto AK135 to provide a realistic upper mantle. To test such a model, we look at current tomography results for the Central and Eastern US at http://www.eas.slu.edu/eqc/eqc_research/NATOMO/ This site permits a download of the latest SLU surface wave tomography inversions for Love and Rayleigh wave phase and group velocities. In addition the phase velocity results of Ekström (2013) for continental US and Ekström (2011) global propagation are provided. The comparison is shown in Figure 3.

The frames of this figure present the Love and Rayleigh (columns) wave group, U, and phase, c, dispersion (rows). The SLU tomography results for the Central and Eastern US (CEUS) on a 25 km x 25 km grid are given by the blue dots, the SLU NA tomography on a 100 km x 100 km grid are given by the red dots. The Ekström (2013) phase velocities from USArray stations are given by the yellow dots, and the Ekström (2011) global dispersion at longer periods is shown by the green dots. These are the data sets used to invert for a new velocity model for the region.

Since we have noted problems with the Ekström (2011) Love wave dispersion at periods less than 40 sec, these values are not used. In addition we only use the recent CEUS tomography results. Finally the Ekström (2013) phase velocities are used.

To start the inversion using **surf96** (Herrmann, 2013) we used the patched model constructed above, noted in the figure as TTXin. The result of the inversion is the TTX model. Since the inversion did not permit much change in the upper 3 km, and since the waveform match for source inversion will use periods greater than 10 sec, we are not concerned about the difference in the Rayleigh wave group velocities in the 5 – 20 second period range. The important point is that the velocity model fits observed dispersion significantly better than the WUS model previously used for the source modeling.

As a side note about waveform inversion, an adequate velocity model is one that matches the group velocity dispersion curve in the range of frequencies used for the inversion.

The inversion used an iterative damped least-squares technique with a constraint that the velocity model be smooth. Figure 4 shows the upper 50 km of the models considered. The WUS, TTXi and final TTX models are compared. Note that the inversion constraints mostly preserved the upper 3 km of the model given by Frohlich et al (2014).

The model was truncated at a depth of 220.5 km for the computation of the Green's functions for source inversion in the 0 – 500 km distance range. To model the waveforms, the model could have been truncated at 50 km and the computations completed faster. However, if one suffers if trying to complete things quickly. So the results of use a better local velocity model are shown in Figure 5.

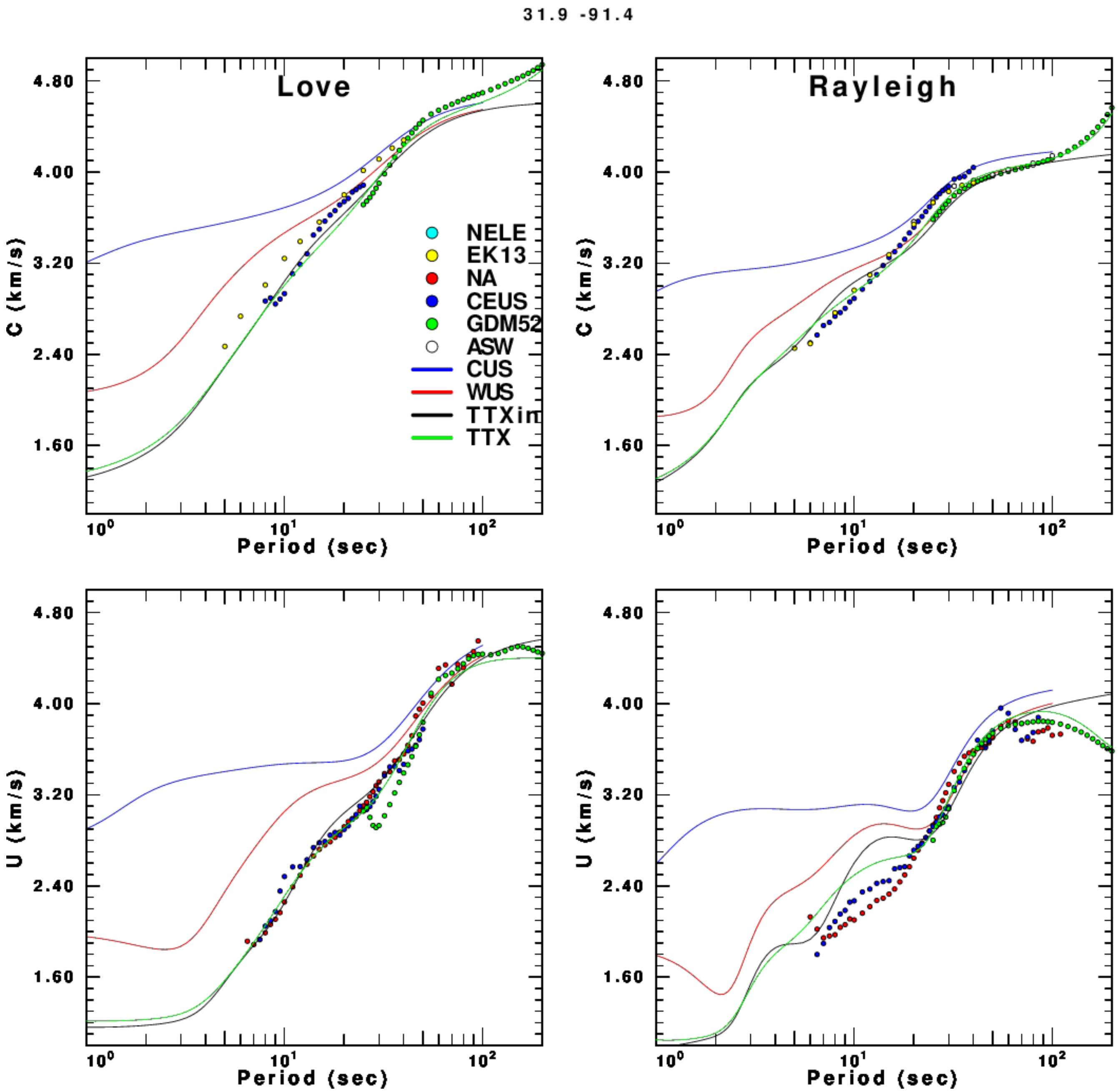


Fig. 3. Comparison between observed and predicted dispersion for the coordinates of the Timpson, TX earthquakes.

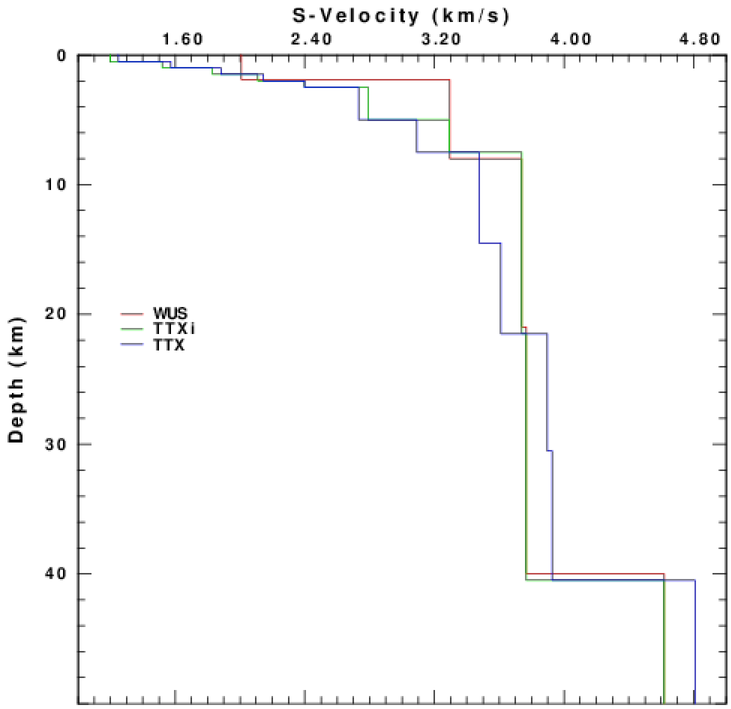


Fig. 4. Velocity model comparison

## Waveform inversion

Inversion for the best shear dislocation was performed using **wvfgrd96** and the procedure given in Herrmann et al (2011). Using the 0.02 – 0.05 Hz frequency band, the goodness of fit at each selected source depth are given in Table 1 and the mechanisms corresponding to the best fit are plotted in Figure 5.

Table 1. Revised solution goodness of fit with depth

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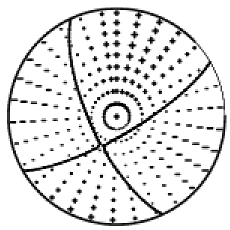
| | H | STK | DIP | RAKE | MW | FIR |
|---|---|---|---|---|---|---|
| WVFGRD96 | 1.0 | 150 | 85 | 5 | 3.51 | 0.4176 |
| WVFGRD96 | 2.0 | 150 | 90 | 10 | 3.65 | 0.5597 |
| WVFGRD96 | 3.0 | 155 | 70 | 15 | 3.73 | 0.6079 |
| WVFGRD96 | 4.0 | 155 | 70 | 15 | 3.77 | 0.6096 |
| WVFGRD96 | 5.0 | 150 | 50 | -5 | 3.84 | 0.5903 |
| WVFGRD96 | 6.0 | 150 | 50 | -5 | 3.86 | 0.5636 |
| WVFGRD96 | 7.0 | 150 | 45 | -5 | 3.88 | 0.5321 |
| WVFGRD96 | 8.0 | 150 | 40 | 0 | 3.93 | 0.5001 |
| WVFGRD96 | 9.0 | 330 | 40 | 0 | 3.94 | 0.4713 |
| WVFGRD96 | 10.0 | 330 | 40 | 0 | 3.95 | 0.4471 |
| WVFGRD96 | 11.0 | 330 | 45 | -5 | 3.95 | 0.4240 |
| WVFGRD96 | 12.0 | 330 | 45 | -5 | 3.96 | 0.4027 |
| WVFGRD96 | 13.0 | 330 | 50 | -5 | 3.95 | 0.3831 |

20120517081201

| | H | STK | DIP | RAKE | MW | FIT |
|---|---|---|---|---|---|---|
| WVFGRD96 | 1.0 | 150 | 80 | 5 | 4.48 | 0.3494 |
| WVFGRD96 | 2.0 | 330 | 90 | 0 | 4.62 | 0.4873 |
| WVFGRD96 | 3.0 | 150 | 70 | 0 | 4.70 | 0.5492 |
| WVFGRD96 | 4.0 | 150 | 60 | 0 | 4.76 | 0.5701 |
| WVFGRD96 | 5.0 | 150 | 60 | 0 | 4.81 | 0.5719 |
| WVFGRD96 | 6.0 | 150 | 65 | 0 | 4.83 | 0.5586 |
| WVFGRD96 | 7.0 | 150 | 60 | 0 | 4.86 | 0.5378 |
| WVFGRD96 | 8.0 | 150 | 55 | 0 | 4.89 | 0.5134 |
| WVFGRD96 | 9.0 | 150 | 55 | 0 | 4.90 | 0.4877 |
| WVFGRD96 | 10.0 | 150 | 60 | 0 | 4.91 | 0.4631 |
| WVFGRD96 | 11.0 | 330 | 90 | 20 | 4.90 | 0.4412 |
| WVFGRD96 | 12.0 | 150 | 90 | -15 | 4.91 | 0.4235 |
| WVFGRD96 | 13.0 | 330 | 90 | 15 | 4.92 | 0.4063 |

20120510151539



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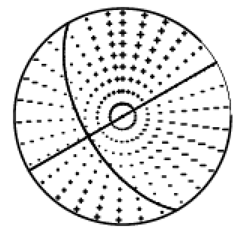

Fig. 5. Revised mechanisms published by SLU using the local TTX velocity model.

The revised source parameters are

| Date Time | Lat | Lon | H | Mw | Stk | Dip | Rake | Ref | Model | Authority |
|---|---|---|---|---|---|---|---|---|---|---|
| 20120510_151539 | 31.90 | -94.42 | 4 | 3.77 | 155 | 70 | 15 | WEB | TTX | SLU |
| 20120517_081201 | 31.90 | -94.33 | 5 | 4.81 | 150 | 60 | 0 | WEB | TTX | SLU |

## Discussion

The obvious point of this exercise is that regional moment tensor inversion is possible only if the velocity model is appropriate for the source region and the paths to the stations. The structure of the Gulf Coast is *terra incognita* for earthquake studies because of the lack of earthquakes there. Fortunately we have this sequence an also the results of a very laborious effort of defining local surface wave dispersion. The dispersion is important for crustal earthquakes because the fundamental mode surface wave if the most significant feature of the the seismograms to be inverted.

Viewing the revised web pages, you will see that the delay plot may indicate significant mislocation in from the assumed NEIC coordinates. However those are based on an assumption of a Love wave velocity of 3.5 km/s in the rand of frequencies modeled. The structure here is much slower and thus the conversion of time shifts for waveforms matching gives offsets too large. So this is not a problem.

The new model gives depths of 4 to 5 km for these two earthquakes. The aftershock relocations of Frohlich et al (2014) give a range of 2 to 5 km, which is an independent evaluation of our results.

One of the new nodal planes dip 60 to 70 degrees to the southwest which is similar to the dip see in Figure 6A of the Frohlich (2014) paper.

## References

Ekström, G. (2011). A global model of Love and Rayleigh surface wave dispersion and anisotropy, 25-

250 s, Geophy. J. Int., doi:10.1111/j.1365-246X.2011.05225.x

Ekström, G. (203). Love and Rayleigh phase-velocity maps, 5-40 s, of the western and central USA from USArray data, Earth Planet. Sci. Lett. http://dx.doi.org/10.1016/j.epsl.2013.11.022

Frohlich, C., W. Ellsworth, W. A. Brown, M. Brunt, J. Luetgert, T. MacDonald, and S. Walter (2014), The 17 May 2012 M4.8 earthquake near Timpson, East Texas: An event possibly triggered by fluid injection, J. Geophys. Res. Solid Earth, 119, 581–593, doi:10.1002/2013JB010755.

Herrmann, R. B., H. Benz, and C. J. Ammon (2011). Monitoring the earthquake process in North America, *Bull. Seism. Soc. Am. 1***01**, *2609-2625*, doi:10.1785/0120110095 .

Herrmann, R. B. (2013) Computer programs in seismology: An evolving tool for instruction and research, *Seism. Res. Lettr.* 84, 1081-1088, doi:10.1785/0220110096

Appendix – Models

ts03 model: Supplemental materials in Frohlich et al (2014)

**Table ts03.txt. Velocity model used for location in this study.**

| layer | P-velocity (km/sec) | S-velocity (km/sec) | thickness (km) | depth (km) |
|---|---|---|---|---|
| 1 | 2.82 | 1.20 | 3.5 | 0-0.5 |
| 2 | 3.30 | 1.52 | 0.5 | 0.5-1.0 |
| 3 | 3.79 | 1.82 | 0.5 | 1.0-1.5 |
| 4 | 4.28 | 2.11 | 0.5 | 1.5-2.0 |
| 5 | 4.76 | 2.40 | 0.5 | 2.0-2.5 |
| 6 | 5.11 | 2.79 | 0.5 | 2.5-3.0 |
| 7 | 5.12 | 2.93 | -- | 3.0+ |

Note there is a discrepancy in the listed thickness of the first layer. We interpret that value to be 0.5 km for compatibility with the depth range:

Final model derived in this study: TTX.mod

```
MODEL.01
Model after   100 iterations
ISOTROPIC
KGS
SPHERICAL EARTH
1-D
CONSTANT VELOCITY
LINE08
LINE09
LINE10
LINE11
      H(KM)   VP(KM/S)   VS(KM/S) RHO(GM/CC)     QP         QS       ETAP       ETAS      FREFP      FREFS
     0.5000     2.9356     1.2494     2.3774   0.00       0.00       0.00       0.00       1.00       1.00
     0.5000     3.4156     1.5736     2.2162   0.00       0.00       0.00       0.00       1.00       1.00
     0.5000     3.9006     1.8839     2.3017   0.00       0.00       0.00       0.00       1.00       1.00
     0.5000     4.3529     2.1458     2.3691   0.00       0.00       0.00       0.00       1.00       1.00
     0.5000     4.7573     2.3986     2.4463   0.00       0.00       0.00       0.00       1.00       1.00
     2.5000     5.0056     2.7330     2.5010  0.349E-02  0.784E-02   0.00       0.00       1.00       1.00
     2.5000     5.3456     3.0909     2.5694  0.349E-02  0.784E-02   0.00       0.00       1.00       1.00
     7.0000     5.8288     3.4764     2.6661  0.212E-02  0.476E-02   0.00       0.00       1.00       1.00
     7.0000     6.0550     3.6108     2.7162  0.212E-02  0.476E-02   0.00       0.00       1.00       1.00
     9.0000     6.6270     3.8965     2.8826  0.111E-02  0.249E-02   0.00       0.00       1.00       1.00
    10.0000     6.6822     3.9286     2.8977  0.111E-02  0.249E-02   0.00       0.00       1.00       1.00
    10.0000     8.2235     4.8094     3.3903  0.164E-10  0.370E-10   0.00       0.00       1.00       1.00
    15.0000     8.0856     4.7281     3.3407  0.164E-10  0.370E-10   0.00       0.00       1.00       1.00
    25.0000     7.9367     4.6420     3.2885  0.164E-10  0.370E-10   0.00       0.00       1.00       1.00
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 30.0000 | 7.9215 | 4.6319 | 3.2833 | 0.164E-10 | 0.370E-10 | 0.00 | 0.00 | 1.00 | 1.00 |
| 45.0000 | 8.1864 | 4.5458 | 3.3771 | 0.855E-02 | 0.131E-01 | 0.00 | 0.00 | 1.00 | 1.00 |
| 45.0000 | 8.3076 | 4.5524 | 3.4205 | 0.820E-02 | 0.128E-01 | 0.00 | 0.00 | 1.00 | 1.00 |
| 50.0000 | 8.3425 | 4.5380 | 3.4331 | 0.469E-02 | 0.741E-02 | 0.00 | 0.00 | 1.00 | 1.00 |
| 50.0000 | 8.3738 | 4.5444 | 3.4446 | 0.459E-02 | 0.725E-02 | 0.00 | 0.00 | 1.00 | 1.00 |
| 50.0000 | 8.4646 | 4.5820 | 3.4775 | 0.446E-02 | 0.709E-02 | 0.00 | 0.00 | 1.00 | 1.00 |
| 50.0000 | 8.6510 | 4.6719 | 3.5416 | 0.433E-02 | 0.690E-02 | 0.00 | 0.00 | 1.00 | 1.00 |

This is in the Model format of Computer Programs in Seismology (Herrmann, 2013). The colums are layer thickness, P- and S-velocity and density, followed by in Qp and Qs.