Description
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QUASISTAT is a program package that computes both static and post-seismic displacements and strains from an imposed line source. It is a variation of the STATIC1D code baed on Pollitz (1996), which computes static displacements and strains. QUASISTAT uses the `Direct Green's Function' method (e.g., Friederich and Dalkolmo, 1995) for seismic wave propagation on a 1D spherical model, adapted for the quasi-static case. It solves both the non-gravitational and non-gravitational cases; the former uses an approximation that includes g-terms but not G-terms, referred to as the Cowling approximation in section 8.8.6 of Dahlen and Tromp (1998). QUASISTAT has been verified by the VISCO1D code (Pollitz, 1997) in 2007, which uses the viscoelastic normal mode method. VISCO1D requires the identification of the modes, which is practical only for models involving a few homogeneous layers. QUASISTAT has no such limitation and is hence a strong alternative to VISCO1D.

There are four main programs:

(1) QSTAT0 computes spheroidal modtion and toroidal motion Green's functions for seismic moment tensor sources using the Pollitz (1996) prescription. That prescription has been modified to use the method of second order minors, following Friederich and Dalkolmo (1995), to achieve very stable integration of the equations of static equilibrium in the spheroidal motion case. It computes the response at a set of sample Laplace transform parameters, and viscoelasticity is implemented for a Maxwell or Burgers body using the correspondence principle. All spherical harmonic degrees from degree 0 to a specified maximum degree are used. Response functions from a single source depth at a single observation depth are calculated.

(2) QSTAT1 computes static and post-seismic displacements and strains for input (line) dislocation sources. For given source depth and observation depth (that were specified in the input to QSTAT0), QSTAT1 reads in the Green's functions computed by QSTAT0 and convolves them with the input source information in the Laplace transform domain. A numerical inverse Laplace transform is used to derive both static deformation and time-dependent postseismic deformation. QSTAT1 outputs the displacements and strains at a set of input observation points (specified with their latitude and longitude) at time 0 (static displacements) and a set of 10 additional post-seismic times that depends upon a time interval that is input into QSTAT1.

(3) QSTAT0A is an extended version of QSTAT0 which calculates response functions at a set of source depths and one observation depth that is used to implement a finite fault.

(4) QSTAT1A is an extended version of QSTAT1 which implements input finite faults.

Compiling
===
Change directory to MAINPROG.

```
> make all
```

Example 1
===
Change directory to EXAMPLES.

go.xEXAMPLE1 evaluates post-thrusting displacements and strains in the NON-GRAVITATIONAL case. It performs two steps:

(1) QSTAT0 computes the Green's functions for sources at 23.58 km depth and observation depth of 0.0 km.
A maximum spherical harmonic degree of 2700 is specified.
The lines involved in this step are as follows --

```
qstat0 << ! >  /dev/null
# Maximum spherical harmonic degree
2700
# source depth (km)
23.58
# observation depth (km)
0.0
# gravitational acceleration at earth's surface (m/s^2) (0 for non-
gravitational case)
0.
!
```

The input file `earth.model' read in by QSTAT0 has the following lines --

```
  40  6371.000
 5350.000 5400.000    2.800    5.000    3.000 0.100000E+02
 5400.000 5450.000    2.800    5.000    3.000 0.100000E+02
 5450.000 5500.000    2.800    5.000    3.000 0.100000E+02
 5500.000 5550.000    2.800    5.000    3.000 0.100000E+02
 5550.000 5600.000    2.800    5.000    3.000 0.100000E+02
 5600.000 5650.000    2.800    5.000    3.000 0.100000E+02
 5650.000 5700.000    2.800    5.000    3.000 0.100000E+02
```

```
 5700.000 5750.000    2.800    5.000    3.000 0.100000E+02
 5750.000 5800.000    2.800    5.000    3.000 0.100000E+02
 5800.000 5850.000    2.800    5.000    3.000 0.100000E+02
 5850.000 5900.000    2.800    5.000    3.000 0.100000E+02
 5900.000 5950.000    2.800    5.000    3.000 0.100000E+02
 5950.000 5975.600    2.800    5.000    3.000 0.100000E+02
 5975.600 6001.200    2.800    5.000    3.000 0.100000E+02
 6001.200 6026.900    2.800    5.000    3.000 0.100000E+02
 6026.900 6052.500    2.800    5.000    3.000 0.100000E+02
 6052.500 6078.100    2.800    5.000    3.000 0.100000E+02
 6078.100 6103.800    2.800    5.000    3.000 0.100000E+02
 6103.800 6129.400    2.800    5.000    3.000 0.100000E+02
 6129.400 6155.000    2.800    5.000    3.000 0.100000E+02
 6155.000 6180.600    2.800    5.000    3.000 0.100000E+02
 6180.600 6206.300    2.800    5.000    3.000 0.100000E+02
 6206.300 6231.900    2.800    5.000    3.000 0.100000E+02
 6231.900 6257.500    2.800    5.000    3.000 0.100000E+02
 6257.500 6283.100    2.800    5.000    3.000 0.100000E+02
 6283.100 6308.800    2.800    5.000    3.000 0.100000E+02
 6308.800 6321.000    2.800    5.000    3.000 0.100000E+02
 6321.000 6334.400    2.800    5.000    3.000 0.100000E+02
 6334.400 6338.000    2.800    5.000    3.000 0.100000E+02
 6338.000 6341.000    2.800    5.000    3.000 0.100000E+02
 6341.000 6346.000    2.800    5.000    3.000 0.100000E+12
 6346.000 6355.000    2.800    5.000    3.000 0.100000E+12
 6355.000 6357.000    2.800    5.000    3.000 0.100000E+12
 6357.000 6359.000    2.800    5.000    3.000 0.100000E+12
 6359.000 6361.000    2.800    5.000    3.000 0.100000E+12
 6361.000 6363.000    2.800    5.000    3.000 0.100000E+12
 6363.000 6365.000    2.800    5.000    3.000 0.100000E+12
 6365.000 6367.000    2.800    5.000    3.000 0.100000E+12
 6367.000 6369.000    2.800    5.000    3.000 0.100000E+12
 6369.000 6371.000    2.800    5.000    3.000 0.100000E+12
```

There are 40 layers with a starting radius of 5355 km, below which a homogeneous sphere with the same material properties as this deepest layer is assumed. (In fact, the first 29 layers could be removed and computations would be unaltered because the material properties do not change below radius 6341.000) The radius of the earth is specified at 6371 km.

```
 6321.000 6334.400    2.800    5.000    3.000 0.100000E+02
```

[bottom radius of layer=6321.0 km, top radius of layer=6334.4 km, density=
2.800 g-cm-3, bulk modulus=5.0×10^10 Pa, shear modulus=3.0×10^10 Pa, viscosity=(0.100000E+02) × 10^18 = 10^19 Pa s]

In theis model there are only Maxwell viscoelastic layers (deeper than 6341 km radius) or elastic layers (shallower than 6341 km radius).

(2) QSTAT1 computes the response at 101 latitude,longitude pairs

representing a profile bisecting the fault, at
the observation depth specified on the input to QSTAT0 (0.0 km),
to dip slip on a 200 km long fault striking 0 deg., dipping 30-degree,
with its moment collapsed onto a line source at the depth specified on
the input to QSTAT0 (23.58 km).
The lines involved in this step are as follows --

```
qstat1 << ! > /dev/null
# year of earthquake, year obs.#1, year obs.#2 (yrs), viscosity
multiplier
0. 0. 5.452 1.
# finite-length fault with # segments
1
# lat,lon(deg.),length(km),strike(deg.),dip(deg.),rake(deg.),total
moment (10^20 N m) for each segment
0.899361 0. 200. 0. 30. 90. 7.20000e-5
# number of observation points, followed by their latitude,longitude
101
   0.00000000     -0.809425294
   0.00000000      0.777048230
   ... [skipping 95 lines]
   ...
   0.00000000      0.793236732
   0.00000000      0.809425294
!
```

The output of this step is contained in 'qstat1.out'. The first lines
of this file are --

```
xtxx,xtxy,xtxz,xtyy,xtyz,xtzz
     time1     time2  displ_E      displ_W      displ_Z      e_EE
e_EN         e_EZ         e_NN         e_NZ         e_ZZ
     years     years  cm           cm           cm
microstrain  microstrain  microstrain  microstrain  microstrain
microstrain
----------------------------------------------------------------------
--------------------------------------------------------------------
     0.000     0.000  0.16283E-03  0.15176E-07 -0.13310E-04
0.55685E-05  0.10112E-08  0.45519E-18 -0.18150E-05  0.16650E-19
-0.12512E-05
     0.000     0.818  0.97882E-05 -0.17132E-06 -0.32007E-05
0.31727E-06  0.75518E-10 -0.13126E-18 -0.19515E-06 -0.45714E-20
-0.40708E-07
     0.000     1.364  0.16111E-04 -0.26296E-06 -0.53285E-05
0.50502E-06  0.12290E-09 -0.20034E-18 -0.32250E-06 -0.69708E-20
-0.60837E-07
     0.000     2.276  0.26308E-04 -0.38226E-06 -0.88591E-05
0.77953E-06  0.19693E-09 -0.28849E-18 -0.52967E-06 -0.10018E-19
-0.83286E-07
     0.000     3.796  0.42452E-04 -0.50899E-06 -0.14697E-04
0.11435E-05  0.30798E-09 -0.37800E-18 -0.86101E-06 -0.13068E-19
```

```
-0.94176E-07
     0.000     6.332  0.67356E-04 -0.59184E-06 -0.24290E-04
0.15383E-05  0.46385E-09 -0.42814E-18 -0.13761E-05 -0.14640E-19
-0.54058E-07
     0.000    10.562  0.10440E-03 -0.57495E-06 -0.39885E-04
0.17550E-05  0.65903E-09 -0.40309E-18 -0.21399E-05 -0.13379E-19
0.12829E-06
     0.000    17.619  0.15645E-03 -0.50264E-06 -0.64735E-04
0.12599E-05  0.84982E-09 -0.36391E-18 -0.31877E-05 -0.11385E-19
0.64261E-06
     0.000    29.390  0.22206E-03 -0.55647E-06 -0.10283E-03
-0.11435E-05  0.90657E-09 -0.48054E-18 -0.44592E-05 -0.15108E-19
0.18676E-05
     0.000    49.026  0.28959E-03 -0.73446E-06 -0.15715E-03
-0.75293E-05  0.58243E-09 -0.71581E-18 -0.57517E-05 -0.24739E-19
0.44270E-05
     0.000    81.780  0.33865E-03 -0.71334E-06 -0.22480E-03
-0.19601E-04 -0.34342E-09 -0.74242E-18 -0.68022E-05 -0.29454E-19
0.88009E-05
     ... [an additional 11 x 100 lines for the next 100 observation
points]
----------------------------------------------------------------------
--------------------------------------------------------------------
```

Here E=local due East; N=local due North; Z=local Up.
For each observation point, there are 11 output lines; the above lines are for just the first point.
The first line (time1=time2=0.000) corresponds to the static displacement. This is a long-wavelength estimate,
using spherical harmonic degrees from degree 0 to degree 2000, but sufficient for the present example. The next 10 lines are the cumulative postseismic displacement from time time1=0.000 to time2. time2 is specified in the source code to loop over 10 times ranging from 0 to 15*[year obs.#2], which was specified in the input to QSTAT1. year obs.#2 in the input file was chosen so that one of the time points is 10.562 years, which happens to be the Maxwell relaxation time = asthenosphere viscosity / rigidity in this model.

Comparison of Direct Green's Function static and postseismic displacements with analytic results
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-

We first compare the Direct Green's Function horizontal (displ_E) and vertical (displ_Z) static displacement with that predicted by the Okada formulas, using the source and 1D viscoelastic structure described above.
The two agree very closely (Figure 1), and sphericity effects, which are present in the Direct Green's Function approach but not the Okada approach, do not play a role at this short spatial scale.

At 1tau=10.562 years, we compare the Direct Green's Function horizontal (displ_E) and vertical (displ_Z) cumulative postseismic displacement with that predicted by the viscoelastic mode sum (VISCO1D solution). As shown in Figure 2, the two agree well, and small differences reflect the approximate nature of the inverse Laplace transform employed by QSTAT1. A similar comparison at 7.74tau=81.370 years is shown in Figure 3

Figures 4 and 5 show similar comparisons for the case of a 45 degree dipping fault.

Example 2

===

go.xEXAMPLE2 performs the same computation as in Example 1 but for the GRAVITATIONAL case. We perform again two steps:

(1) QSTAT0 computes the Green's functions for sources at 23.58 km depth and observation depth of 0.0 km.
A maximum spherical harmonic degree of 2700 is specified.
The lines involved in this step are as follows --

```
qstat0 << ! >  /dev/null
# Maximum spherical harmonic degree
2700
# source depth (km)
23.58
# observation depth (km)
0.0
# gravitational acceleration at earth's surface (m/s^2) (0 for non-
gravitational case)
9.8
!
```

This differs from step 1 of the NON-GRAVITATIONAL case only in the appearance of 9.8 m/s^2 for the value of g in the final input line.

Step 2 is the same as in Example 1:

(2) QSTAT1 computes the response at 101 latitude,longitude pairs representing a profile bisecting the fault, at
the observation depth specified on the input to QSTAT0 (0.0 km),
to dip slip on a 200 km long fault striking 0 deg., dipping 30-degree, with its moment collapsed onto a line source at the depth specified on the input to QSTAT0 (23.58 km).

Example 3

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go.xEXAMPLE3 calculates post-thrusting displacement for a 60 degree-dipping finite fault.

(1) QSTAT0A computes the Green's functions for sources at 16 different depths (16 being specified by parameter node in the source code) ranging from 29 to 15 km. A maximum spherical harmonic degree of 1500 is specified.
The lines involved in this step are as follows --

```
qstat0A << ! > /dev/null
# Maximum spherical harmonic degree
1500
# Fault plane max,min depths (km)
29.00 15.00
# observation depth (km)
0.0
# gravitational acceleration at earth's surface (m/s^2) (0 for non-
gravitational case)
0.
!
```

The earth model, which has been copied from 'earth.modelREF' has an elastic thickness of 30 km and a Maxwellian viscosity of 10^19 Pa s from 30 to 230 km depth.

(2) QSTAT1A computes the response at 3900 latitude,longitude pairs covering a wide area surrounding the finite fault, at the observation depth specified in the input to QSTAT0A (0.0 km),
to dip slip on a 100 km long fault striking 0 deg., dipping 60-degree, with lower and upper edge depths of 29 and 15 km, respectively. This source geometry is embodied in the input lines

```
# lat,lon(deg.),length(km),strike(deg.),dip(deg.),rake(deg.),slip (cm)
for each segment
-2.72516 -2.95000 100. 0. 60. 90. 100.
```

The lower and upper edge depths were specified in the input to QSTAT0A and are not repeated in the input to QSTAT1A.

Note that in the output file qstat1.outEXAMPLE3, the original input time of 114.089 years appears as the fifth time within each set of 10 postseismic times per observation point.

Example 4
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go.xEXAMPLE4 calculates post-strike-slip displacement for a 90 degree-dipping finite fault, and it employs a Burgers body rheology in a 200-km thick layer below the elastic plate.

(1) QSTAT0A computes the Green's functions for sources at 16 different depths (16 being specified by parameter node in the source code) ranging from 29 to 15 km. A maximum spherical harmonic degree of 1500 is specified.
The lines involved in this step are as follows --

```
qstat0A << ! > /dev/null
# Maximum spherical harmonic degree
1500
# Fault plane max,min depths (km)
29.00 15.00
# observation depth (km)
0.0
# gravitational acceleration at earth's surface (m/s^2) (0 for non-
gravitational case)
0.
!
```

The earth model, which has been copied from 'earth.modelREF-BURG' has an elastic thickness of 30 km and a Maxwellian and Kelvin viscosities of 10^19 Pa s and 10^18 Pa s, respectively, from 30 to 230 km depth.

(2) QSTAT1A computes the response at 3900 latitude,longitude pairs covering a wide area surrounding the finite fault, at the observation depth specified in the input to QSTAT0A (0.0 km),
to strike slip on a 100 km long fault striking 45 deg., dipping 90-degree, with lower and upper edge depths of 29 and 15 km, respectively. This source geometry is embodied in the input lines

```
# lat,lon(deg.),length(km),strike(deg.),dip(deg.),rake(deg.),slip (cm)
for each segment
-2.72516 -2.72516 100. 45. 90. 180. 100.
```

The lower and upper edge depths were specified in the input to QSTAT0A and are not repeated in the input to QSTAT1A.

Comparison of Direct Green's Function postseismic displacements with analytic results

At 1tau=10.562 years, we compare in Figure 6 the Direct Green's Function horizontal (displ_E) and vertical (displ_Z) cumulative postseismic displacement with that predicted by the viscoelastic mode sum (VISCO1D solution. The two methods both produce slightly smaller displacements than in the corresponding non-gravitational case of Figure 2. A similar comparison at 7.74tau=81.370 years is shown in Figure 7. Comparing these results with those of Figure 3, we see that gravity at time 7.74tau substantially modifies the vertical displacements, reducing them by about 10% in the gravitational case.

The preceding comparisons are all for line sources and on linear profiles. Comparisons of postseismic displacements from the finite-fault Examples 3 and 4 of QUASISTAT with corresponding results of Visco1d over a broad area surrounding the source are shown in Figures 8 and 9, respectively.

References

Dahlen, F. A. and Tromp, J. (1998). *Theoretical Global Seismology.* Princeton University Press, Princeton, N.J.

Friederich, W. and Dalkolmo, J. (1995). Complete synthetic seismograms for a spherically symmetric earth by a numerical computation of the GreenÕs function in the frequency domain. *Geophys. J. Int.*, 122:537–550.

Okada, Y. (1985). Surface deformation due to shear and tensile faults in a half-space. *Bull. Seism. Soc. Am.*, 75:1135-1154.

Pollitz, F. F. (1996). Coseismic deformation from earthquake faulting on a layered spherical earth. *Geophys. J. Int.*, 125:1–14.

Pollitz, F. F. (1997). Gravitational viscoelastic postseismic relaxation on a layered spherical earth. *J. Geophys. Res.*, 102:17921–17941.

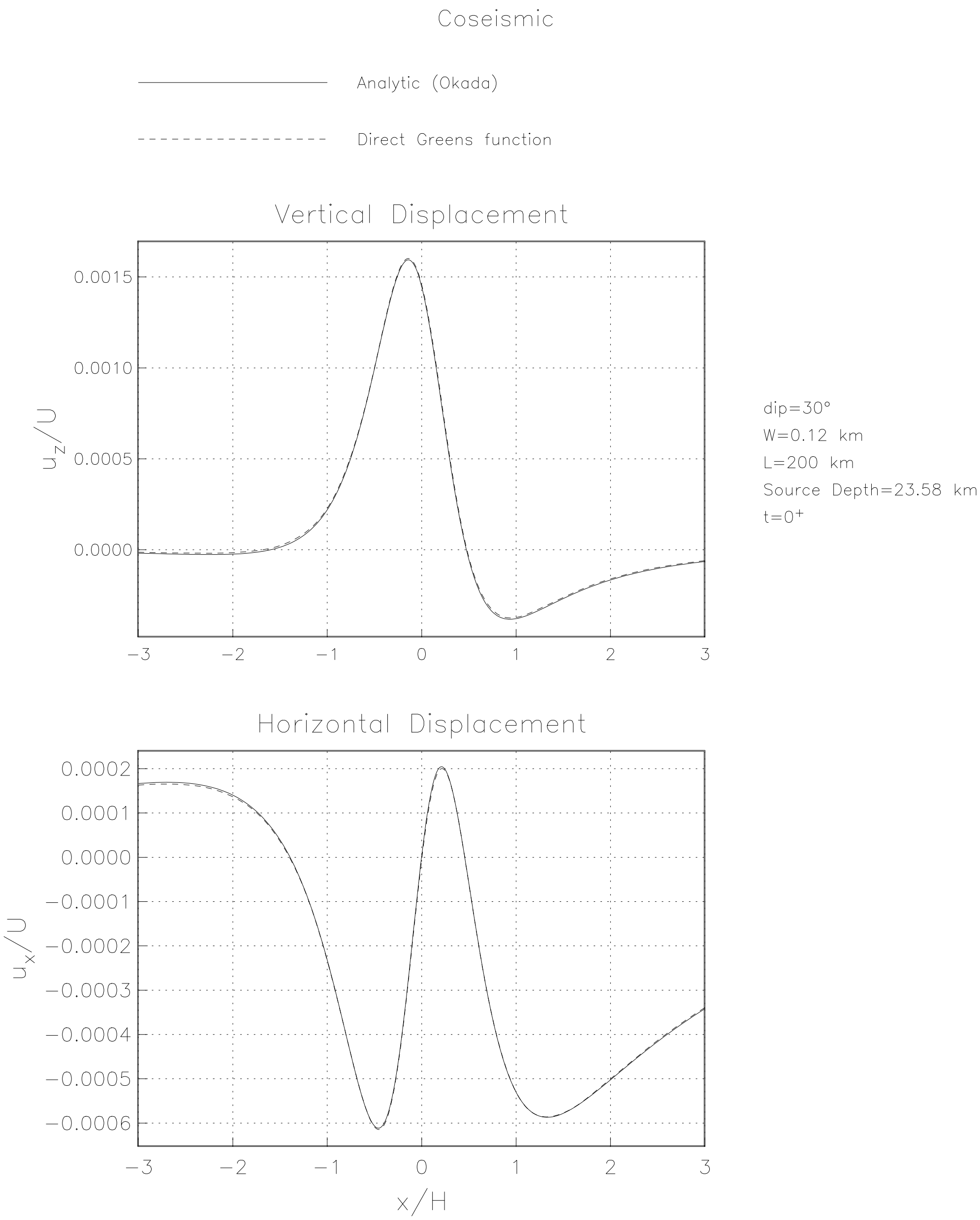

Figure 1: Result of Example 1. Comparison of non-gravitational horizontal and vertical static displacement predicted by the Direct Green's Function method (on a homogeneous sphere) and Okada (1985) formulas (on a homogeneous halfspace) on a profile bisecting a fault with the indicated parameters. Horizontal distance on the x-axis is scaled by the elastic plate thickness $H = 30$ km. Displacements are normalized by the coseismic slip U on the fault.

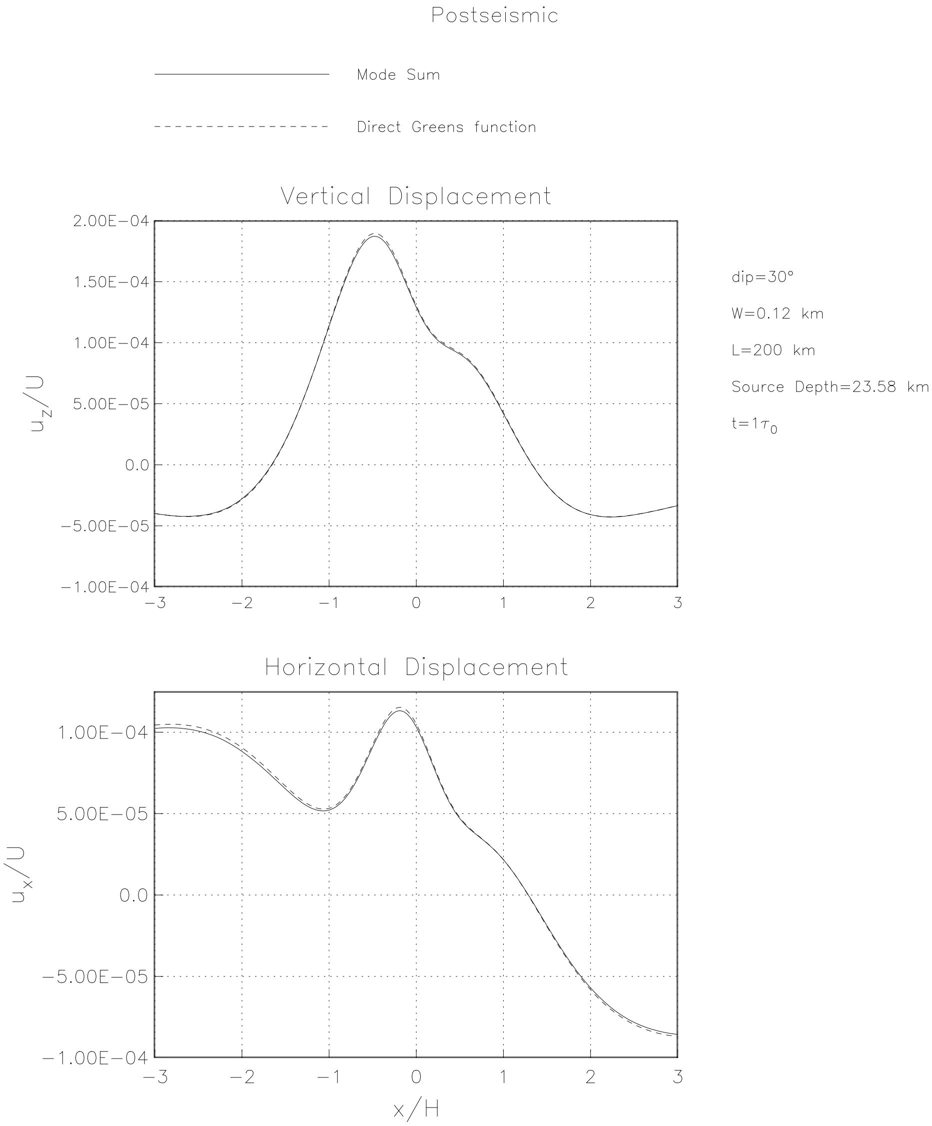

Figure 2: Result of Example 1. Comparison of non-gravitational horizontal and vertical postseismic displacement predicted by the Direct Green's Function method and viscoelastic normal mode method (Pollitz, 1997) on a profile bisecting a fault with the indicated parameters. Horizontal distance on the x-axis is scaled by the elastic plate thickness $H = 30$ km. Displacements are normalized by the coseismic slip U on the fault.

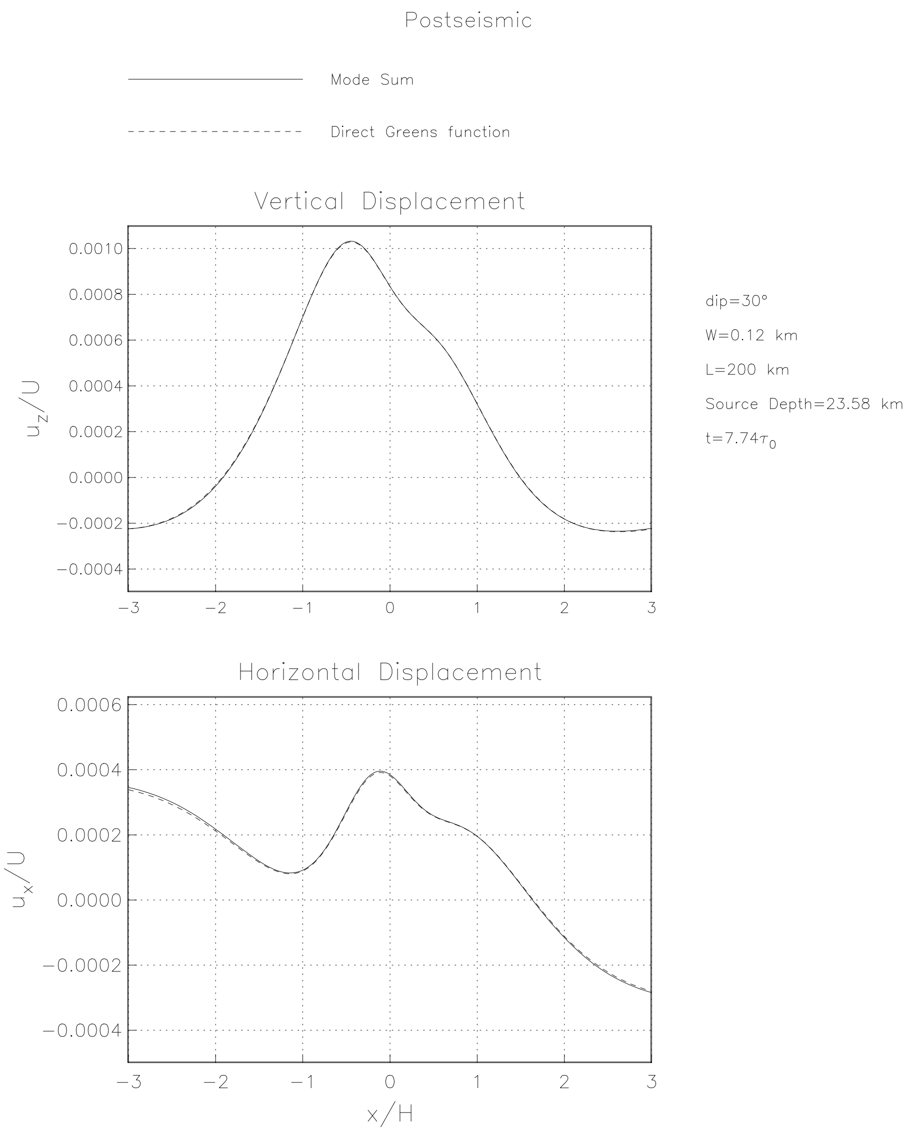

Figure 3: Result of Example 1. Comparison of non-gravitational horizontal and vertical postseismic displacement predicted by the Direct Green's Function method and viscoelastic normal mode method (Pollitz, 1997) on a profile bisecting a fault with the indicated parameters. Horizontal distance on the x-axis is scaled by the elastic plate thickness $H = 30$ km. Displacements are normalized by the coseismic slip U on the fault.

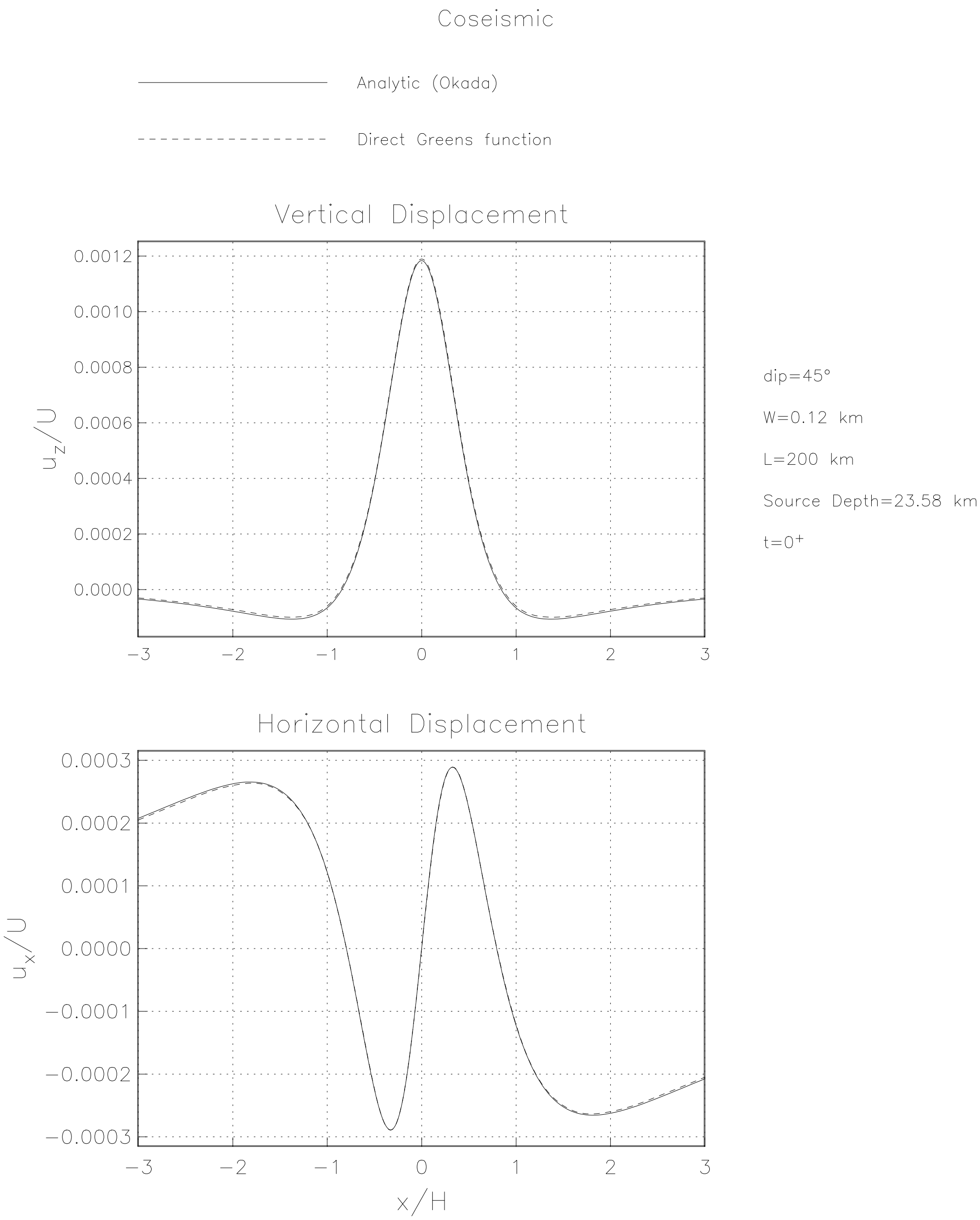

Figure 4: Variation on Example 1 for a 45°-dipping thrust fault. Comparison of non-gravitational horizontal and vertical static displacement predicted by the Direct Green's Function method (on a homogeneous sphere) and Okada (1985) formulas (on a homogeneous halfspace) on a profile bisecting a fault with the indicated parameters. Horizontal distance on the x-axis is scaled by the elastic plate thickness $H = 30$ km. Displacements are normalized by the coseismic slip U on the fault.

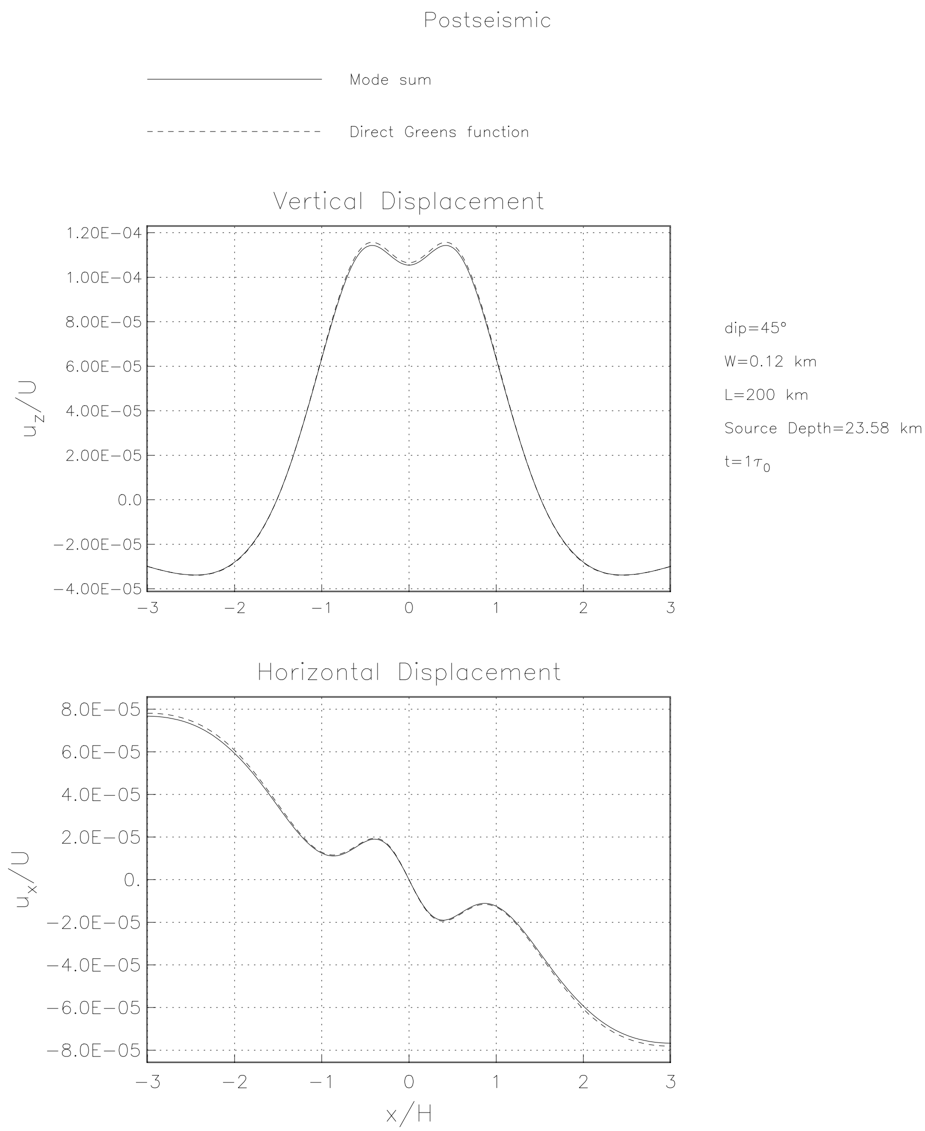

Figure 5: Variation on Example 1 for a 45°-dipping thrust fault. Comparison of non-gravitational horizontal and vertical postseismic displacement predicted by the Direct Green's Function method and viscoelastic normal mode method (Pollitz, 1997) on a profile bisecting a fault with the indicated parameters. Horizontal distance on the x-axis is scaled by the elastic plate thickness $H = 30$ km. Displacements are normalized by the coseismic slip U on the fault.

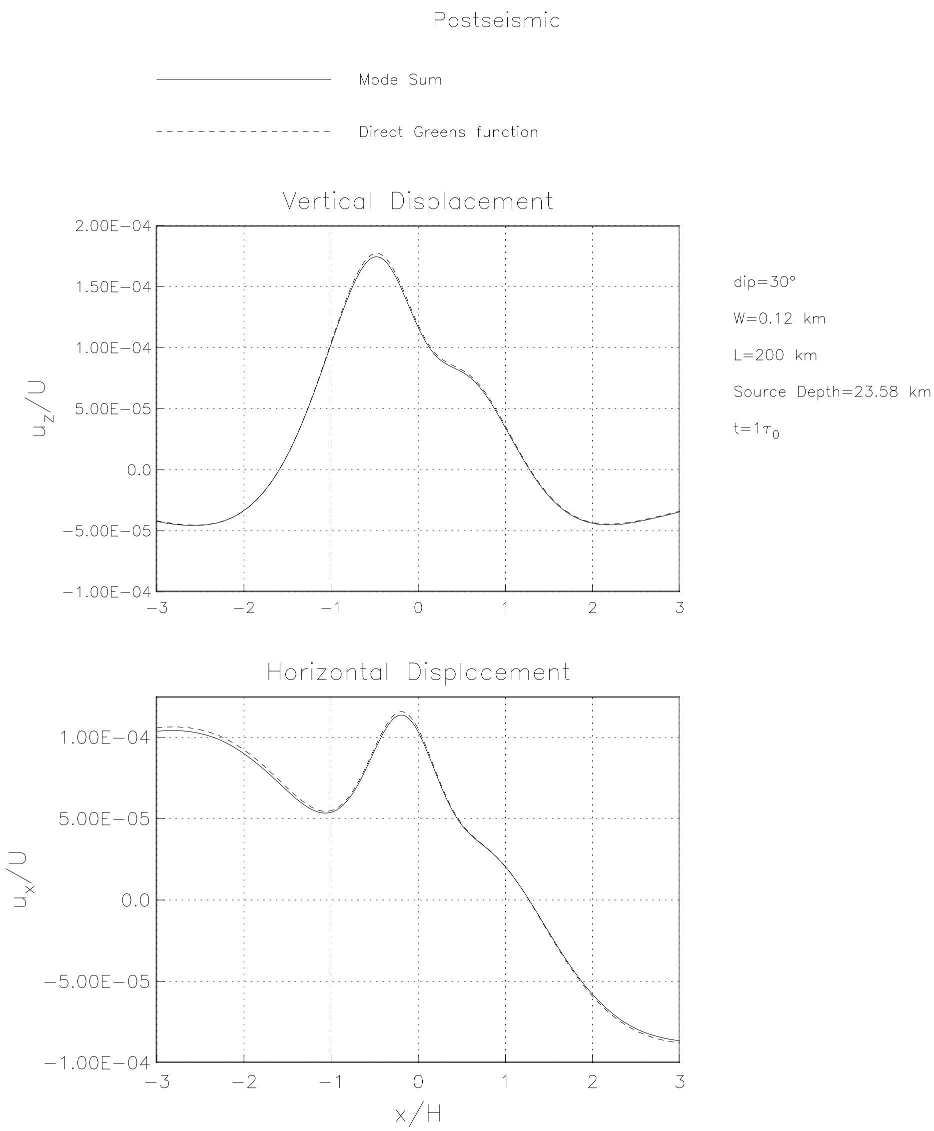

Figure 6: Result of Example 2. Comparison of gravitational horizontal and vertical postseismic displacement predicted by the Direct Green's Function method and viscoelastic normal mode method (Pollitz, 1997) on a profile bisecting a fault with the indicated parameters. Horizontal distance on the x-axis is scaled by the elastic plate thickness $H = 30$ km. Displacements are normalized by the coseismic slip U on the fault.

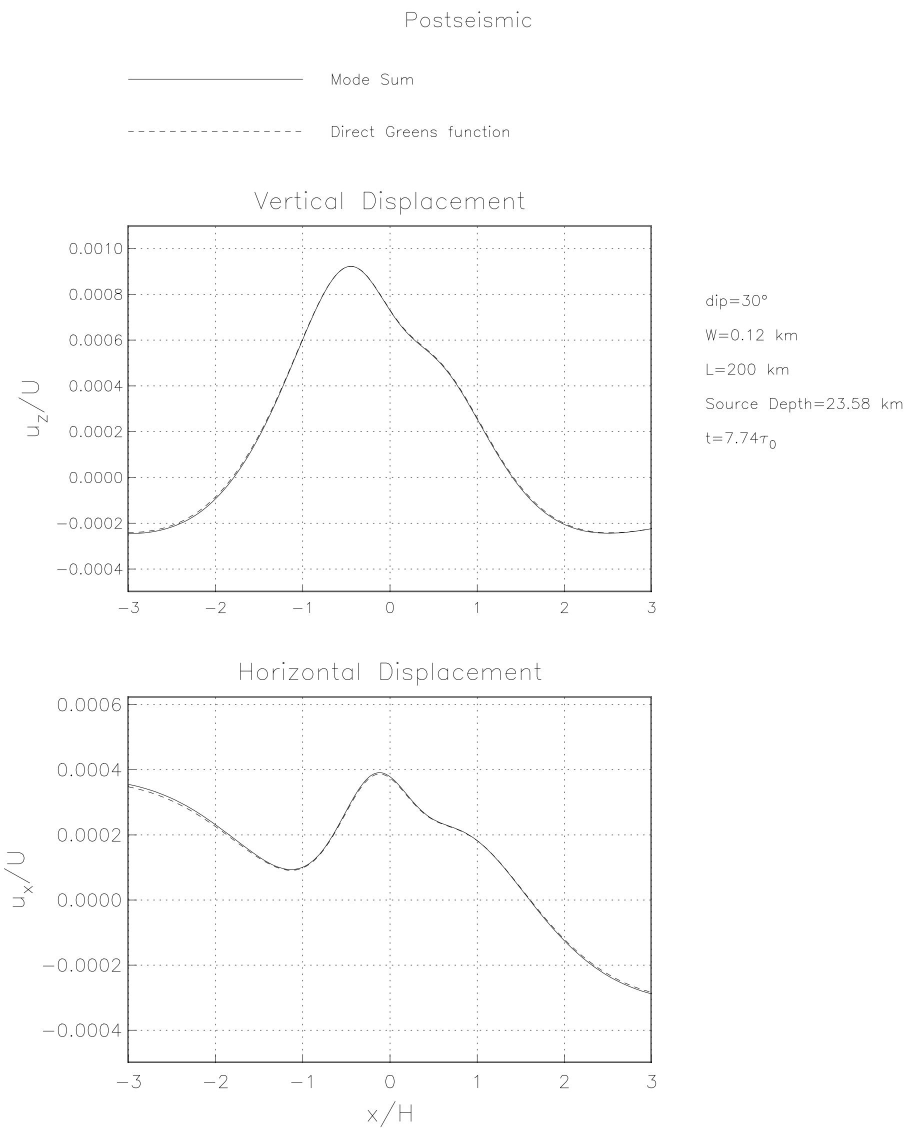

Figure 7: Result of Example 2. Comparison of gravitational horizontal and vertical postseismic displacement predicted by the Direct Green's Function method and viscoelastic normal mode method (Pollitz, 1997) on a profile bisecting a fault with the indicated parameters. Horizontal distance on the x-axis is scaled by the elastic plate thickness $H = 30$ km. Displacements are normalized by the coseismic slip U on the fault.

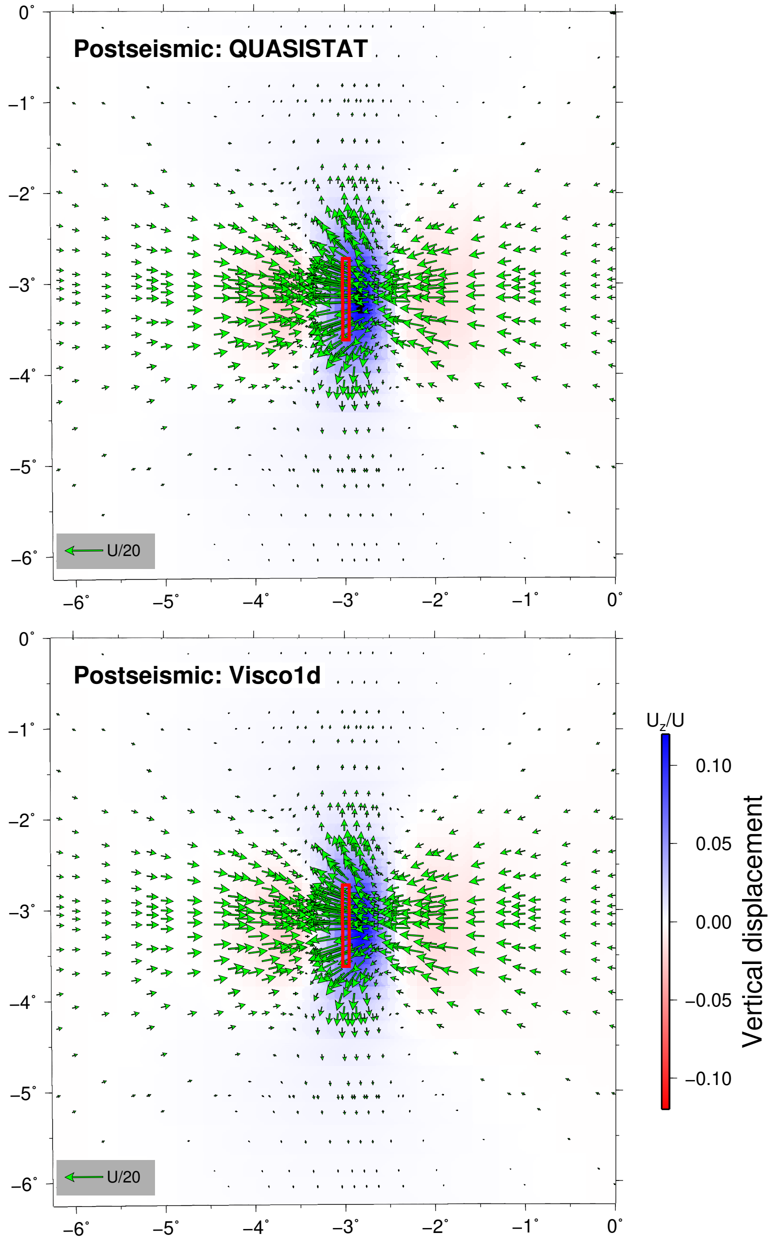

Figure 8: Result of Example 3. Comparison of non-gravitational horizontal and vertical postseismic displacement predicted by the Direct Green's Function method (QUASISTAT) and viscoelastic normal mode method (Visco1d) on an area surrounding a 60°-dipping thrust fault. Cumulative displacements are evaluated at $t = 114$ years after a slip event with slip U.

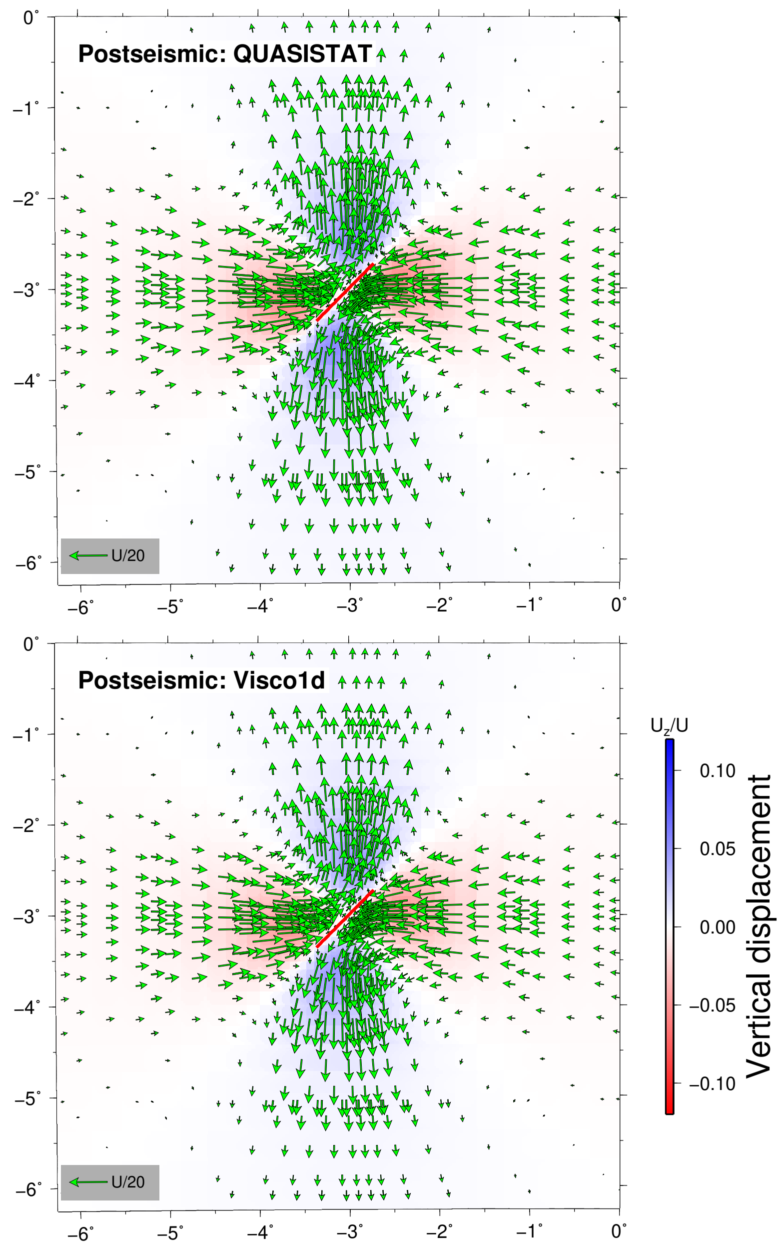

Figure 9: Result of Example 4. Comparison of non-gravitational horizontal and vertical postseismic displacement predicted by the Direct Green's Function method (QUASISTAT) and viscoelastic normal mode method (Visco1d) on an area surrounding a 90°-dipping strike-slip fault. Cumulative displacements are evaluated at $t = 114$ years after a slip event with slip U.