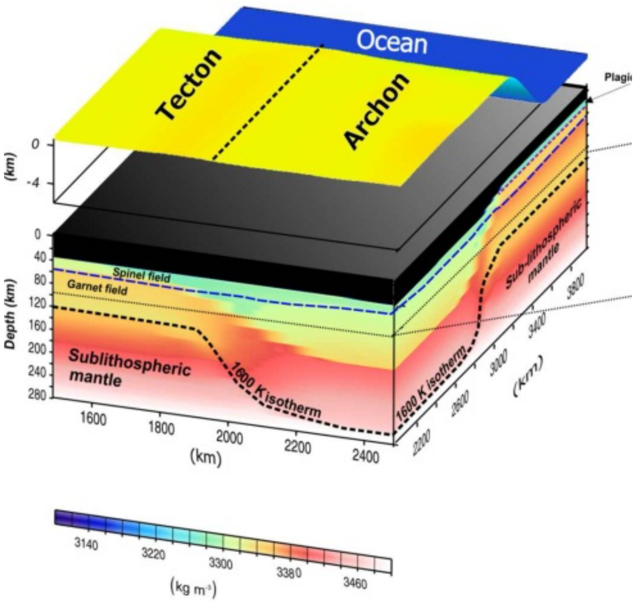
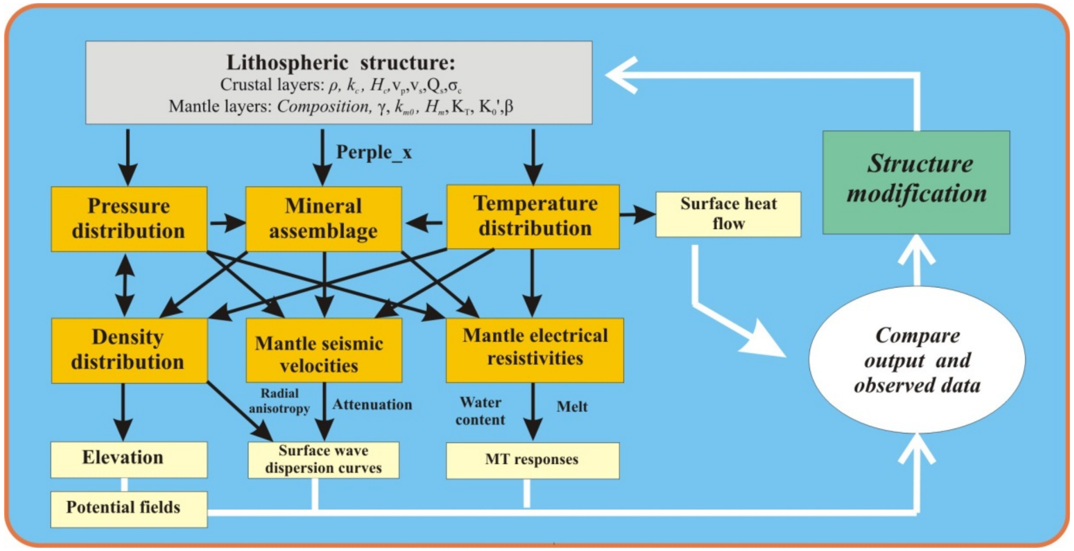
Integrated geophysical-petrological thermochemical modelling of the lithosphere





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Perple_X forward modelling

Perplex_LitMod→ simplified ver of petrological software Perple_X (https://www.perplex.ethz.ch/)

Perple_**X** is a collection of Fortran77 programs for calculating phase diagrams, manipulating thermodynamic data, and modeling equilibrium phase fractionation and reactive transport.

Written and maintained by J.A.D. Connolly

Perple_X forward modelling

Perplex_LitMod requires several input files, the most relevant here are:
Stx08ver.dat →Thermodynamically self-consistent data base for the upper mantle (Xu et al., 2008)

Solution_model.dat→solid solution model

Perple_X requires input temperature, Pressure and bulk composition (wt% major oxides) and output the stable mineral assemblage and associated bulk rock geophysical properties.

```
>>Perplex_LitMod
 Input T (C), P (GPa)...?
900 3
 Input bulk composition (wt%) Al2O3,FeO,MgO,CaO
3.1 8.05 39 2.5
```

Perple_X forward modelling

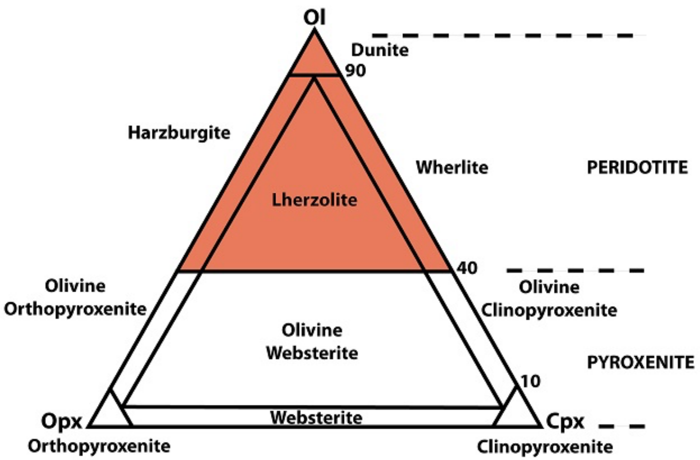
```
>>Perplex_LitMod
 Input T (C), P (GPa)...?
900 3
 Input bulk composition (wt%) Al2O3,FeO,MgO,CaO
3 8 38 2.5

Bulk rock properties Density (kg/m3)   3360.0861038042376
 Vp (km/s)   8.0137759407203770
Vs (km/s)   4.5890076372711954
Mineral assemblage Total number of stable phases:           4
Mineral phase: O(stx8)        Volumetric fraction:    42.741977568465622
Mineral phase: Opx(stx8)       Volumetric fraction:    39.319342830154390
Mineral phase: Cpx(stx8)       Volumetric fraction:    7.2590347316147028
Mineral phase: Gt(stx8)       Volumetric fraction:    10.679644869765283
 ///////////////////////////////////////
```

Perple_X forward modelling

Compute the density, Vp and Vs values corresponding to temperatures T= 600 Cº and 1400 ºC, Pressure P= 3 and 8 GPa for the compositions lherzolite and harzburgite in the table.

- What is the effect of temperature and pressure variations on the predicted rock properties for a given composition?
- What is the effect of changing composition for given T and P conditions?
- What happens with rho and Vp, Vs if you enrich in FeO a harzburgitic rock?



Oxides	Lherzolite	Harzburgite	Dunite	Pyroxenite	PUM [2] McDonough and Sun 1995
SiO_2	44.5	45.7	40.5	50.1	45
Al_2O_3	3.5	1	0.01	15.2	4.5
FeO	8	6.4	7.5	7.8	8.1
MgO	39.8	45.5	49.7	16.7	37.8
CaO	3.1	0.6	0.25	7.5	3.6

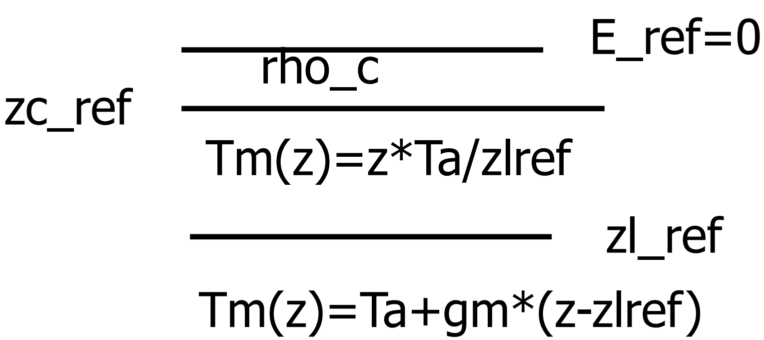
Perple_X forward modelling

Let’s construct a reference lithospheric column with Perple_X

*Consider a column with surface topography E=0, crustal thickness z_cref=30 km and lithospheric thickness z_lref=100 km. Assume a crustal average density rho_c=2830 kg/m3.

*For the lithospheric geotherm, consider a linear conductive gradient Tm(z)=z*Ta/zl for z< zlref, with the temperature at the base of the lithosphere Ta=1300 ºC; in the sublithosphere z>zl the geotherm is adiabatic: Tm(z)=Ta+gm*(z-zl), with gm=0.45 C/km.

*The lithostatic pressure is P= rho_c *g*z_cref + rho_m*g*(z- z_cref) (g=9.8 m/s2)



Perple_X forward modelling

*Consider a **lherzolitic mantle composition** in the lithosphere (z<zlref) and evaluate the density at different depths: z_cref+dz, z_cref+2*dz,…, 150 km.

*In the first node: T= (z_cref+dz)*Ta/zl= , P=rho_c *g*z_cref + rho_m*g*dz. Notice that you need to initially assume a value for rho_m (e.g., 3300 kg/m3). Therefore: T=650 ºC (z=50 km), P=1.48 GPa

```
>>Perplex_LitMod

Input T (C), P (GPa)...?
650 1.48
 Input bulk composition (wt%) Al2O3,FeO,MgO,CaO
3.5 8 39.8 3.1
 Bulk rock properties
 Density (kg/m3)   3355.3565784813932
 Vp (km/s)   8.1189632935690401
 Vs (km/s)   4.6676008863708560
 Mineral assemblage
 Total numner of stable phases:           4
 Mineral phase: Cpx(stx8)
  Volumetric fraction:    9.4668458553667794
 Mineral phase: O(stx8)
  Volumetric fraction:    57.798702923138670
 Mineral phase: Opx(stx8)
  Volumetric fraction:    19.042547040765324
 Mineral phase: Gt(stx8)
  Volumetric fraction:    13.691904180729228
```

Oxides	Lherzolite	Harzburgite	Dunite	Pyroxenite	PUM [2] McDonough and Sun 1995
SiO_2	44.5	45.7	40.5	50.1	45
Al_2O_3	3.5	1	0.01	15.2	4.5
FeO	8	6.4	7.5	7.8	8.1
MgO	39.8	45.5	49.7	16.7	37.8
CaO	3.1	0.6	0.25	7.5	3.6

Perple_X forward modelling

* The real density in the first node is 3355.3 kg/m3, so the pressure has to be recalculated: P=rho_c *g*z_cref + rho_m*g*dz=1.49 GPa

>>Perplex_LitMod

```
 Input T (C), P (GPa)...?
650 1.49
 Input bulk composition (wt%) Al2O3,FeO,MgO,CaO
3.5 8 39.8 3.1
 Bulk rock properties
 Density (kg/m3)   3355.6380057011716
 Vp (km/s)   8.1199466061594325
 Vs (km/s)   4.6678814978096561
```

- In this second iteration the difference in the predicted density is <0.4 kg/m3
- We can extend this calculation to the other nodes in depth (i.e. z=70 km, 90 km, 110 km, 130 km and 150 km). P(70km)=P(50 km)+rho_m*dz. Note that the nodes with z>100 km will be subjected to an adiabatic geotherm (Tm(z)=Ta+gm*(z-zl)) and sublithospheric mantle composition (PUM from table).

Perple_X forward modelling

Let's compute isostatic topography/bathymetry

*The pressure at the bottom of the model Pref(150km) can be taken as a reference for isostatic surface elevation estimates.

*Now redo the integration exercise with Perplex for a column with lithospheric thickness z_l=140 km, first with **lherzolite composition**, and then with **harzburgitic composition** in the lithosphere.

$$If\ P_{ref}(150\ km) > P_{column}(150\ km):$$
$$h_{topo} = (P_{ref}(150\ km) - P_{column}(150\ km))/(g * rho\_c)$$

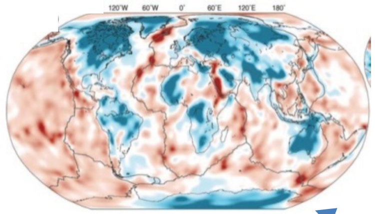
$$If\ P_{ref}(150\ km) < P_{column}(150\ km):$$
$$h_{bathy} = (P_{ref}(150\ km) - P_{column}(150\ km))/(g * (rho_c - rho_w))$$

- ❖ What is the effect of thickening the lithosphere?
- ❖ What is the effect of changing composition?

Oxides	Lherzolite	Harzburgite	Dunite	Pyroxenite	PUM [2]
SiO_2	44.5	45.7	40.5	50.1	45
Al_2O_3	3.5	1	0.01	15.2	4.5
FeO	8	6.4	7.5	7.8	8.1
MgO	39.8	45.5	49.7	16.7	37.8
CaO	3.1	0.6	0.25	7.5	3.6

Lets put Perple_X into a geophysical modelling context

Seismic Velocity models



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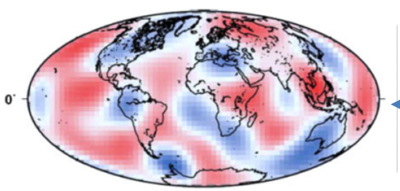
Electrical Conductivity models



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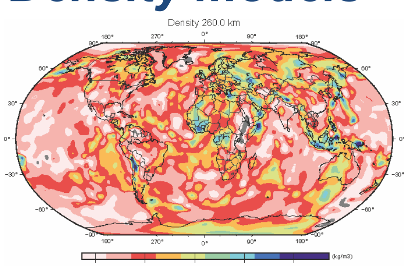
Density models



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$dG = V\,dP - S\,dT + \Sigma_i\,\mu_i\,dX_i$ ***Thermodynamics***

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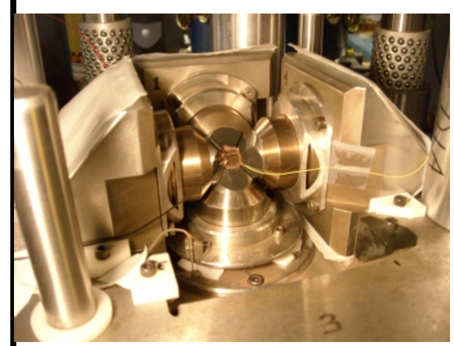
Petrology

+



Mineral physics

Thermal field

- ✓ Mantle thermal conductivity dependent on T, P and C (numerical iteration)

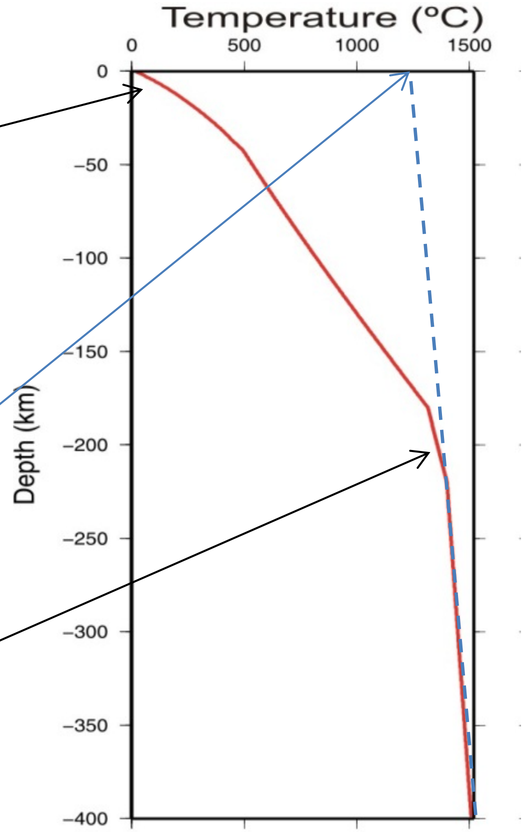
$$k_{(T,P)} = k^{\circ}\left(\frac{298}{T}\right)^{a} \exp\left[-(4\gamma + 1/3)\int_{298}^{T} \alpha(T)dt\right] \times \left(1 + \frac{K_0' P}{K_T}\right) + k_{rad}(T)$$

- ✓ Surface Heat flow (SHF)= Kc*dT/dz

- ✓ Crustal heat production accounts for 20-40% of SHF in continents

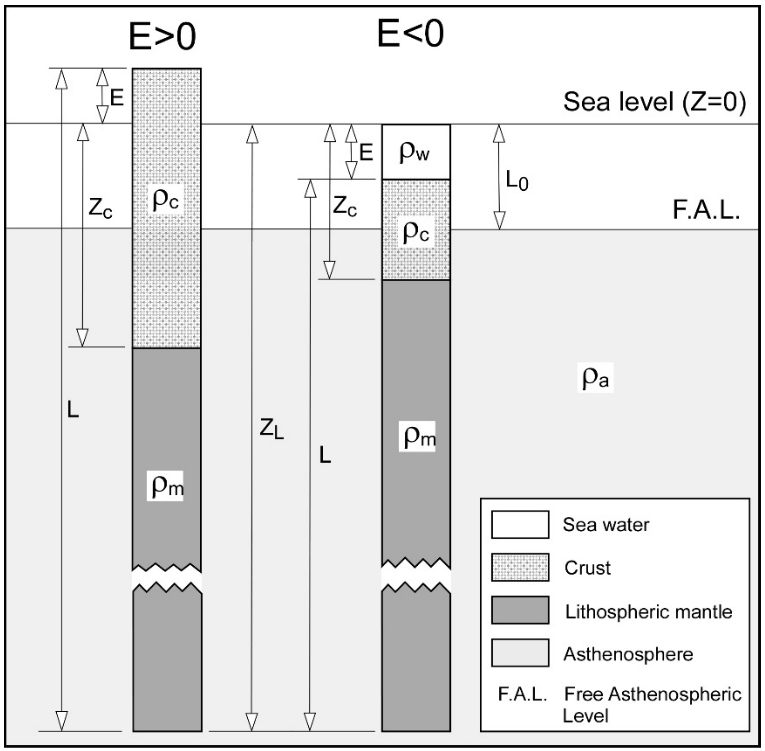
- ✓ Thermal buffer sublithosphere (superadiabatic transition)

- ✓ Sublithospheric geotherm: adiabatic gradient (usually 0.4-0.5 K/km) and potential temperature



Isostasy

✓ ***Lithospheric isostasy: (absolute) elevation as a measure of the bouyancy of the lithosphere***



$$E = \frac{\rho_a - \rho_L}{\rho_a} \cdot L - L_0 \quad (E > 0)$$

$$E = \frac{\rho_a}{\rho_a - \rho_w} \cdot \left(\frac{\rho_a - \rho_L}{\rho_a} \cdot L - L_0 \right) \quad (E < 0)$$

(e.g. Lachenbruch & Morgan 1990)

In terms of the pressure at the bottom of the model:

$$E = L - \frac{P_{bot}}{g\rho_{bot}} - \prod_0$$

$$\prod_0 = z_{bot} - \frac{\rho_{MOR}(z_{bot} - E_{rid}) + \rho_w E_{rid}}{\rho_{bot}}$$

➢ ***Lithospheric mantle able to hold density contrasts over geological time scales…***

Mantle composition

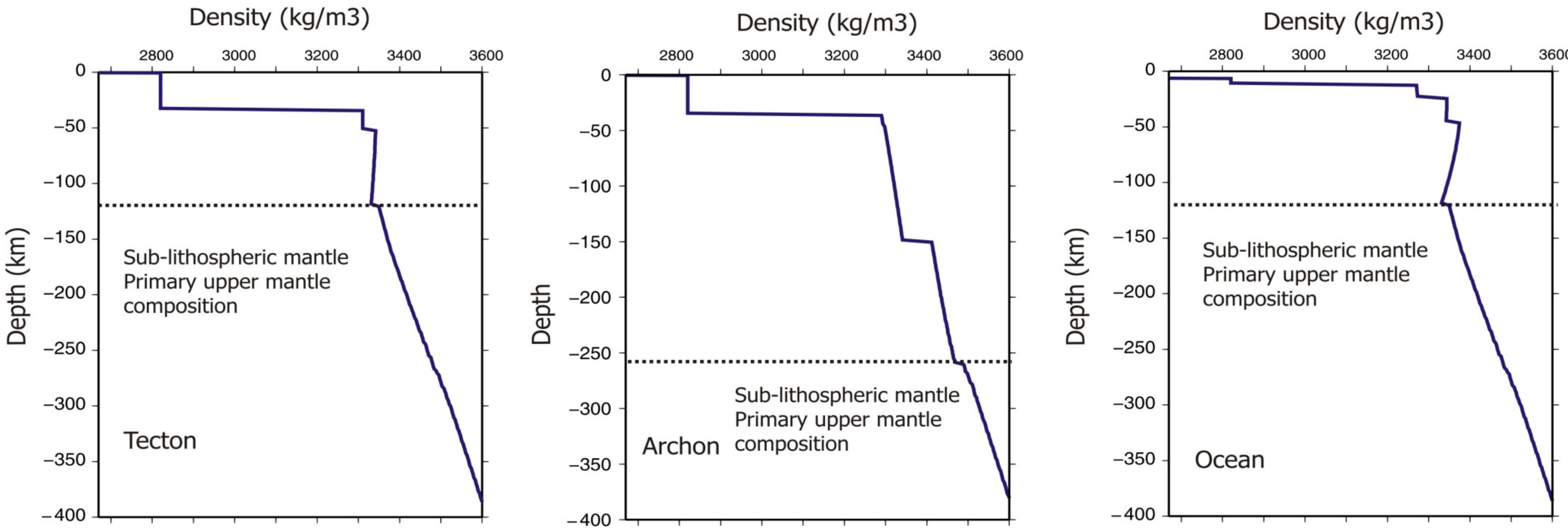
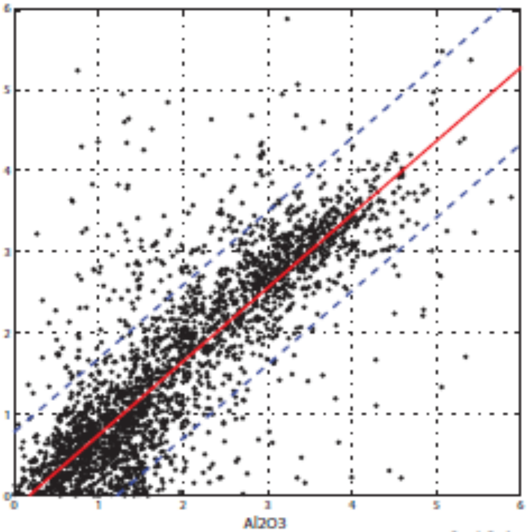


Table 1: Estimates of subcontinental lithospheric mantle compositions from xenoliths suites and peridotite massifs (modified from *Afonso et al., 2008a and Griffin et al, 2008*).

	Aver. Archon Gnt. SCLM*	Aver. Kaapvaal Harzburg.	Aver. Tecton Gnt. SCLM *	PUM J79#	PUM MS# *
SiO_2	45.7	45.9	44.5	45.2	45
TiO_2	0.04	0.05	0.14	0.22	0.2
Al_2O_3	0.99	1.3	3.5	4	4.5
Cr_2O_3	0.28	0.34	0.4	0.46	0.38
FeO	6.4	6.0	8.0	7.8	8.1
MnO	0.11	0.1	0.13	0.13	0.14
MgO	45.5	45.5	39.8	38.3	37.8
CaO	0.59	0.5	3.1	3.5	3.6
Na_2O	0.07	0.07	0.24	0.33	0.36
NiO	0.3	0.28	0.26	0.27	0.25
Mg#	92.7	93.1	89.9	89.7	89.3
Cr/(Cr+Al)	0.16	0.27	0.07	0.07	0.05

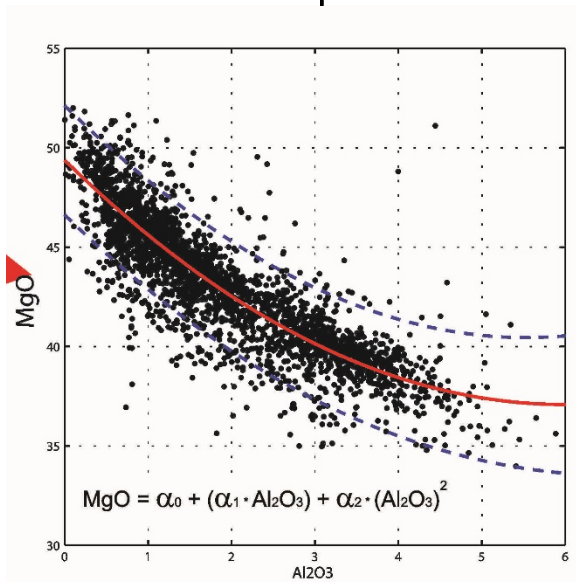
Mantle composition

Major oxides correlations from xenoliths & per. massifs



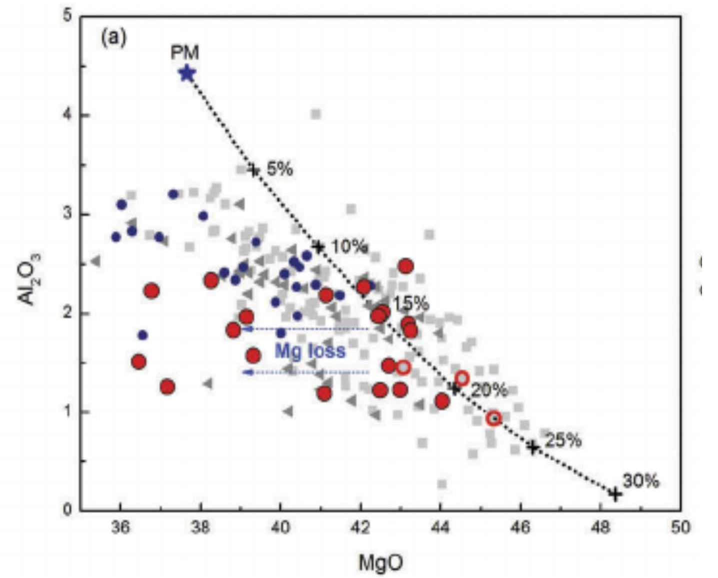
$CaO = \alpha_0 + \alpha_1 * Al_2O_3$ $\alpha_0 = -0.164$

$R^2 = 0.674$ $\alpha_1 = 0.906$



$\alpha_0 = 49.369$ $\alpha_1 = -4.106$ $\alpha_2 = 0.343$

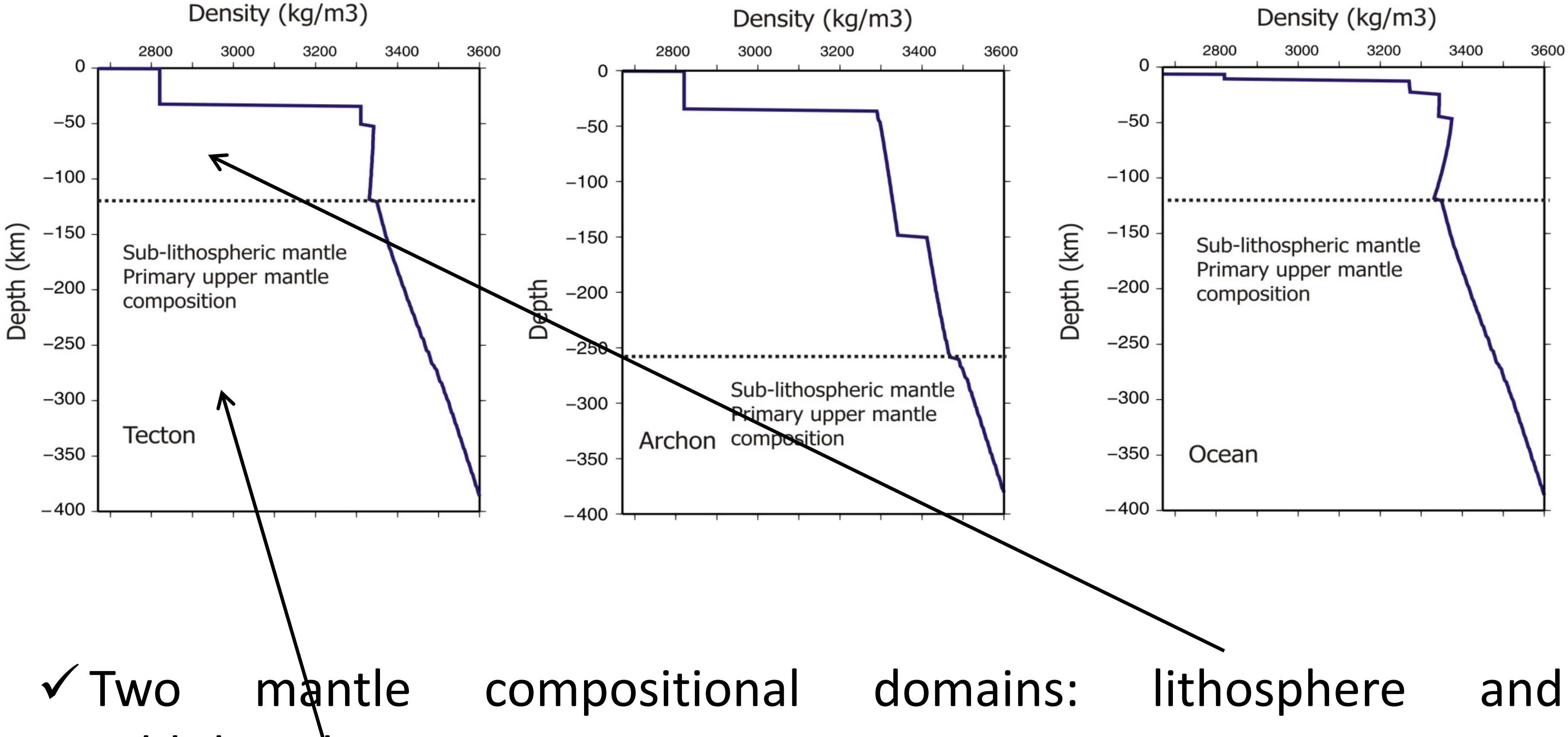
Melting trend



- ✓ Mantle composition described by **Al2O3** and FeO independent variables (CaO and MgO=F(Al2O3))

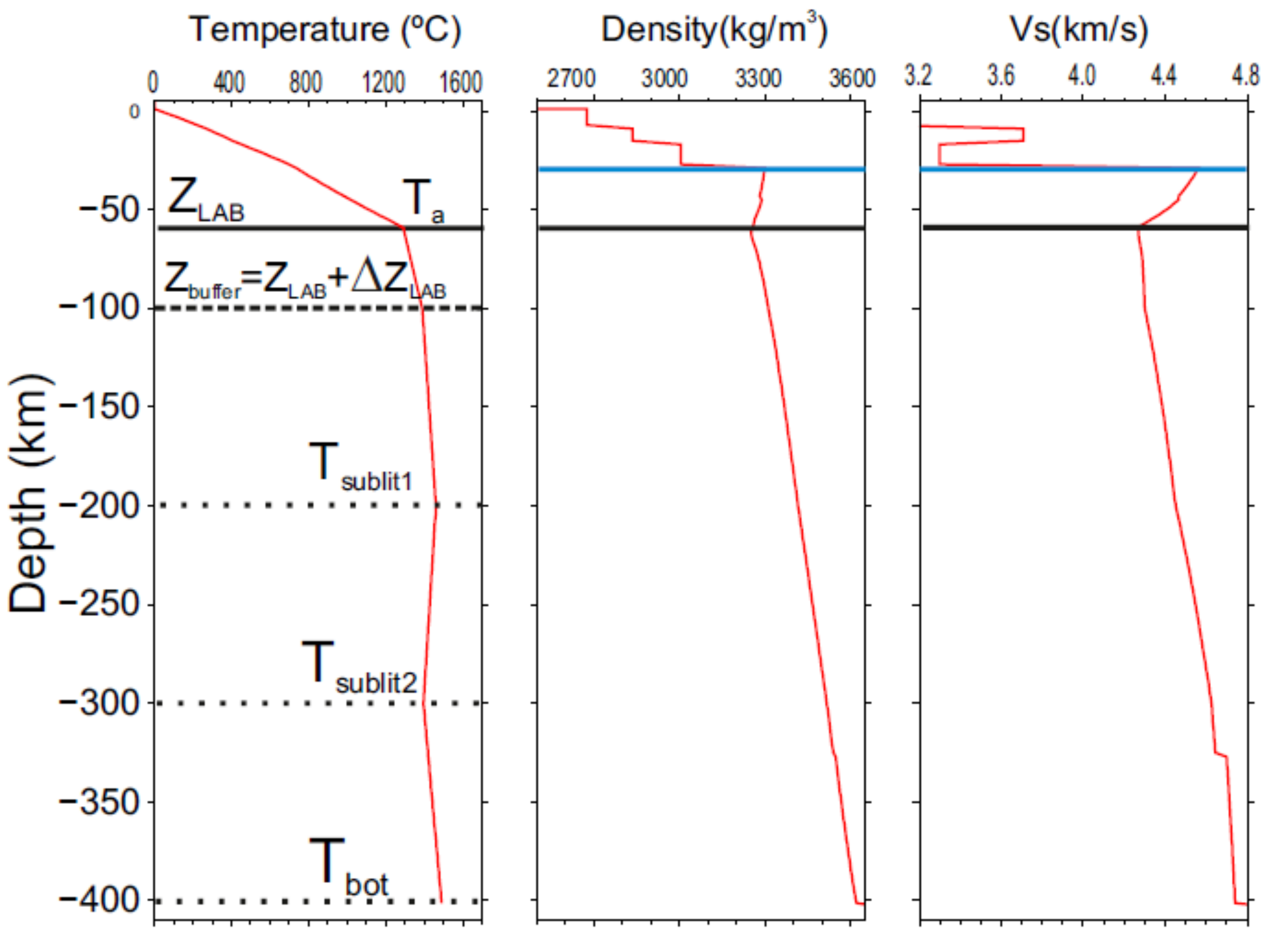
- ✓ Chemical parameterization following melting trend, analogous to pyrolite (Harz+basalt)

Mantle composition



- ✓ Two mantle compositional domains: lithosphere and sublithosphere
- ✓ Chemical parameterization two oxides: Al2O3 and FeO

Mantle density and seismic velocities in WINTERC



✓ Parameters characterizing density and velocities: geotherm and mantle composition (Also attenuation in the case of seismic velocities)

WINTERC forward modelling/inversion

Composition, temperature, pressure within the lithosphere and sub-lithospheric mantle

Thermodynamic calculation for an equilibrium mineral assemblage

PERPLEX (J. Connolly)
LitMod (J. Fullea et al.; J.C. Afonso et al.)

Density, elastic parameters

Calculation of phase velocities for 1-D Earth models

Normal-mode code (e.g., MINEOS)
Attenuation
Radial anisotropy

Surface-wave, topography, surface heat flow observables

Seismic attenuation

Attenuation (anelastic effects) have to be considered. Standard parameterization (e.g. Faul & Jackson) depends on:

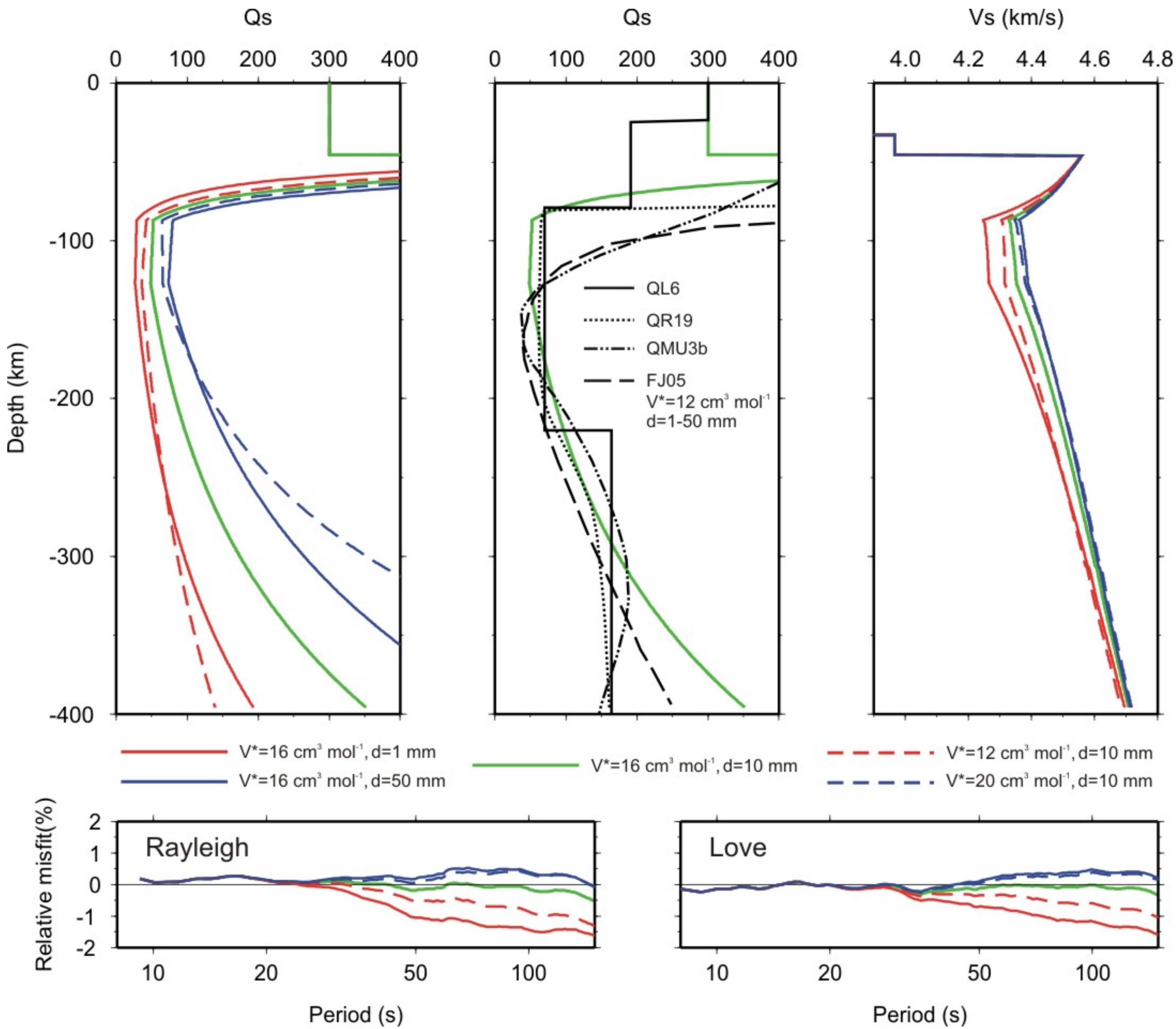
- Temperature and presion
- Grain size and activation volume
- Melt

$$V_P = V_{P0}\left(1 - \left(\frac{2}{9}\right)\cot\left(\frac{\pi\alpha}{2}\right){Q_S}^{-1}\right)$$

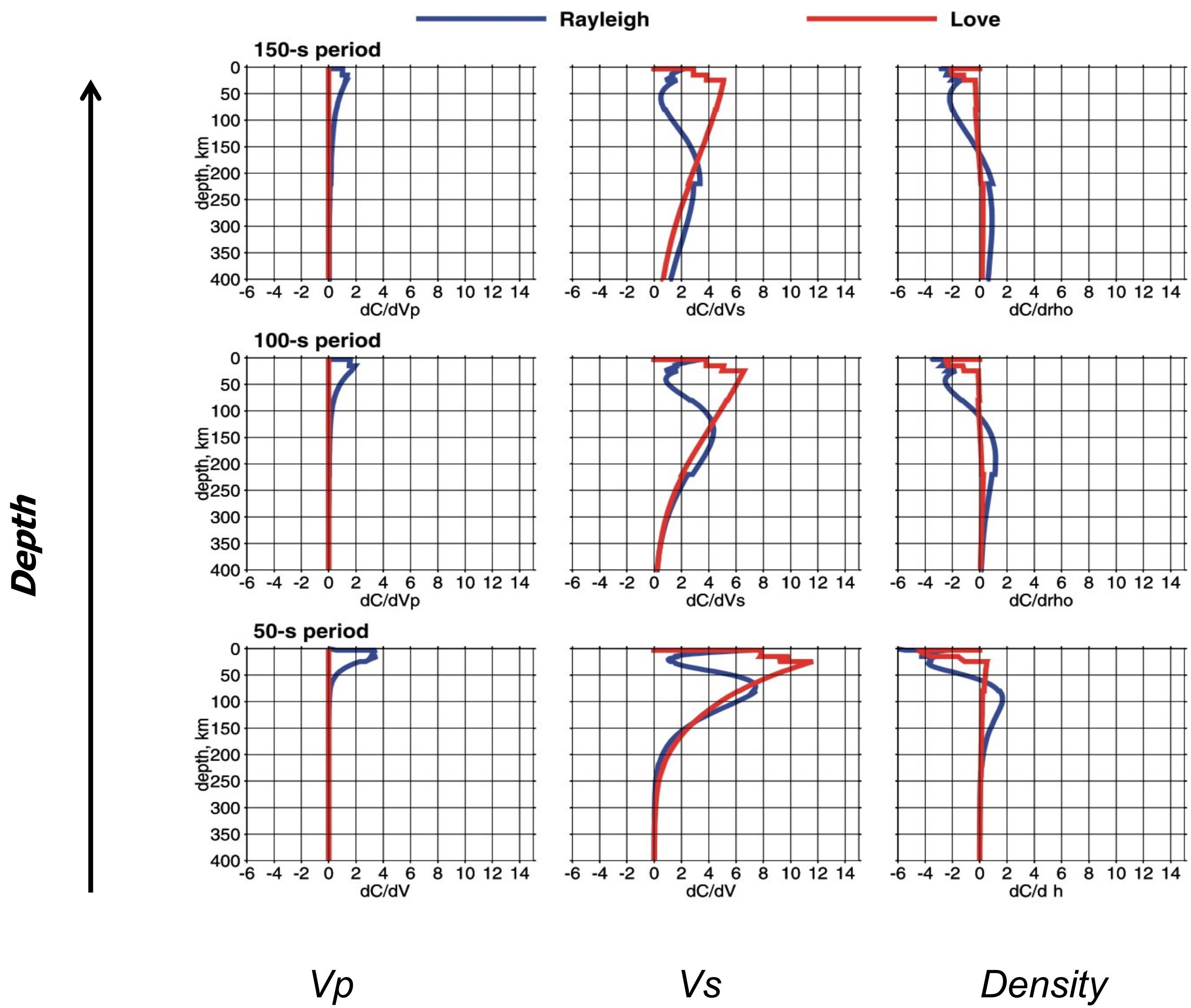
$$V_S = V_{S0}\left(1 - \left(\frac{1}{2}\right)\cot\left(\frac{\pi\alpha}{2}\right){Q_S}^{-1}\right)$$

$${Q_S}^{-1} = A\left[\frac{T_0}{d}\exp\left(\frac{-\left(E + PV^*\right)}{RT}\right)\right]^{\alpha}$$

Seismic attenuation



➢ *Surface-wave sensitivity kernels*



Let’s get to it…

In this course we will see WINTERC: LitMod based 1D forward modelling and stochastic inversion of:

- ✓ Surface elevation (local isostasy)
- ✓ Surface Heat Flow (geotherm)
- ✓ Surface wave dispersion data (Rayleigh and Love curves)

The output model consists of:

- ✓ Crustal structure (Moho depth, density, Vs)
- ✓ Lithospheric structure (LAB deph, lithospheric composition)
- ✓ Sublithospheric structure (temperature, composition)
- ✓ Seismic anisotropy

WINTERC forward modelling

Input files:

- ***WINTERC_var_fwd.info***: input model variables
- ***WINTERC_param_fwd.info***: input parameters

Output files:

- ***TrhovelsComp_fwd.z*** → output 1D column with depth, temperature, density, seismic velocities, mantle composition
- ***out_phase_ray_fwd.dat*** → output Rayleigh phase velocity
- ***out_phase_love_fwd.dat*** → output Love phase velocity
- ***out_E-SHF_fwd.dat*** → output surface elevation and heat flow

Running WINTERC_fwd from a terminal:

*Open a terminal and go to ~/ materials/ WINTERC_3DEARTH-school

*Edit input model file WINTERC_var_fwd.info as needed

(*type: PATH=$PATH: .)

**type: ./WINTERC_fwd*

*Enter input surface elevation, in m. The terminal output should be:

```
 Surface elevation (m)...?
1900
 Reading input variables file WINTERC_var.info
 N_col_mp en read          0
 RADIAL ANISTROPY ON
 Reading input reference variable vector:WINTERC_ref.info
 Reading input parameters file WINTERC_param.info
 E,E_ice   1900.00000000000       1900.00000000000
 RAYLEIGH SURFACE WAVES INVERSION SWITCHED ON
 LOVE SURFACE WAVES INVERSION SWITCHED ON
 NUMBER OF DATA POINTS:        149
 TOTAL NUMBER OF VARIABLES:         35

....
```

```
…

############### PROGRAM WINTERC ##############
#         Parallel Version                  #

***********************************
COLUMN NUMBER:           0
   Crustal densities(kg/m3):   2790.0  2787.0  2820.5
       Crustal iso Vs (m/s):   3241.0  3730.0  3746.0
Depth of crustal layers (km):   9.2 21.3 40.1
 Av crust heat (micro W/m3): 0.90E-06
 d_T transient initial (km): 500.0
Age oceanic lithosphere (Ma):    -40000.26
             LAB depth (km): 146.2
Thermal buffer thickness (km): 25.0
        LAB temperature (C):   1300.0
  Temperature at 200 km (C):   1452.3
  Temperature at 300 km (C):   1487.3
Bottom model temperature (C):   1522.4
    Vs at 410 km disc (m/s):   4890.0
    Vs at 660 km disc (m/s):   5532.0
         Al2O3 (wt%) Litho:  3.35
           FeO (wt%) Litho:  8.10
      Al2O3 (wt%) sub-Litho:  4.41
        FeO (wt%) sub-Litho:  8.05
  Radial anistropy crust(%):      0.0     0.0     0.0
    Radial anistropy mantle, z= 56 km:      0.0
    Radial anistropy mantle, z= 80 km:      0.0
   Radial anistropy mantle, z= 110 km:      0.0
   Radial anistropy mantle, z= 150 km:      0.0
   Radial anistropy mantle, z= 200 km:      0.0
   Radial anistropy mantle, z= 260 km:      0.0
   Radial anistropy mantle, z= 330 km:      0.0
   Radial anistropy mantle, z= 400 km:      0.0
  Radial anistropy mantle,410 km disc:      0.0
  Radial anistropy mantle,660 km disc:      0.0
***********************************
```

Describes the input model as read from file WINTERC_var_fwd.info

....

```
***********************************
 ***********************************
 MATERIAL ASSIGNATION COMPLETED
 THERMAL CALCULATION COMPLETED
 E_calc (m) =    2487.2612032894394
 SHF (mW/m2) =    57.403315101578315
 MODEL ROUGHNESS Vs (%)    0.0
 MODEL ROUGHNESS rho (%)    0.0
```

Terminal output, Isostatic topography (E_calc) and surface heat flow (SHF) plus crustal Vs and density roughness

In addition to the screen output the code produces output files:

- ***TrhovelsComp_fwd.z*** → output 1D column with depth, temperature, density, seismic velocities, mantle composition
- ***out_phase_ray_fwd.dat*** → output Rayleigh phase velocity
- ***out_phase_love_fwd.dat*** → output Love phase velocity
- ***out_E-SHF_fwd.dat*** → output surface elevation and heat flow

Output files:

- ***TrhovelsComp_fwd.z*** →output 1D column with depth, temperature, density, seismic velocities, mantle composition

z (m)	T(C)	rho	Vp	Vs	Al2O3	FeO		
5000.000	0.000	0.000	0.0000	0.0000	-1.00	-1.00	0.00	0.0000
3000.000	0.000	0.000	0.0000	0.0000	-1.00	-1.00	0.00	0.0000
1000.000	0.000	2750.000	6.3000	3.6000	-1.00	-1.00	0.00	0.0000
-1000.000	51.367	2750.000	6.3000	3.6000	-1.00	-1.00	0.00	0.0000
-3000.000	101.097	2750.000	6.3000	3.6000	-1.00	-1.00	0.00	0.0000
-5000.000	149.191	2750.000	6.3000	3.6000	-1.00	-1.00	0.00	0.0000
-7000.000	195.648	2750.000	6.3000	3.6000	-1.00	-1.00	0.00	0.0000
-9000.000	240.470	2750.000	6.3000	3.6000	-1.00	-1.00	0.00	0.0000
-11000.000	280.898	2750.000	6.3000	3.6000	-1.00	-1.00	0.00	0.0000
-13000.000	317.461	2750.000	6.3000	3.6000	-1.00	-1.00	0.00	0.0000
-15000.000	352.583	2750.000	6.3000	3.6000	-1.00	-1.00	0.00	0.0000
-17000.000	386.266	2750.000	6.3000	3.6000	-1.00	-1.00	0.00	0.0000
-19000.000	418.509	2750.000	6.3000	3.6000	-1.00	-1.00	0.00	0.0000
-21000.000	451.990	2750.000	6.5160	3.6000	-1.00	-1.00	0.00	0.0000
-23000.000	486.945	2750.000	6.5160	3.6000	-1.00	-1.00	0.00	0.0000
-25000.000	520.187	2750.000	6.5160	3.6000	-1.00	-1.00	0.00	0.0000
-27000.000	551.713	2750.000	6.5160	3.6000	-1.00	-1.00	0.00	0.0000
-29000.000	581.526	2750.000	6.5160	3.6000	-1.00	-1.00	0.00	0.0000
-31000.000	609.625	2750.000	6.5160	3.6000	-1.00	-1.00	0.00	0.0000
-33000.000	636.009	2750.000	6.5160	3.6000	-1.00	-1.00	0.00	0.0000
-35000.000	660.678	2750.000	6.5160	3.6000	-1.00	-1.00	0.00	0.0000
-37000.000	683.634	2750.000	6.5160	3.6000	-1.00	-1.00	0.00	0.0000
-39000.000	704.875	2750.000	6.5160	3.6000	-1.00	-1.00	0.00	0.0000
-41000.000	721.064	3345.318	8.0215	4.6210	4.35	8.10	0.00	2.0000
-43000.000	734.913	3345.881	8.0208	4.6180	4.35	8.10	0.00	2.0000

….

Output files:

- ***out_phase_ray_fwd.dat*** → output Rayleigh phase velocity

Period (s)	Vph (m/s)	uncertainty (m/s)
20.366000000000000	3481.8532714843750	6.8940001027286053
21.187000000000001	3504.5856933593750	6.9540001036226755
22.041000000000000	3529.4541015625000	6.9940001042187214
22.928999999999998	3556.3740234375000	7.0440001049637795
23.853000000000002	3585.1943359375000	7.1140001060068609
24.815000000000001	3615.6616210937500	7.1640001067519190
25.815000000000001	3647.3444824218750	7.2260001076757909
26.855000000000000	3679.7756347656250	7.2920001086592672
27.937999999999999	3712.4421386718750	7.3620001097023486
29.064000000000000	3744.7065429687500	7.4200001105666162
30.234999999999999	3776.0129394531250	7.4900001116096977
31.454000000000001	3805.8959960937500	7.5500001125037670
32.722000000000001	3833.9428710937500	7.6040001133084303
34.040999999999997	3859.8920898437500	7.6560001140832901
35.412999999999997	3883.6057128906250	7.7120001149177551
36.840000000000003	3905.0561523437500	7.7600001156330114
38.325000000000003	3924.3151855468750	7.8060001163184642
39.869999999999997	3941.4990234375000	7.8480001169443137
41.476999999999997	3956.7670898437500	7.8880001175403596
43.149000000000001	3970.3073730468750	7.9220001180469994
44.887999999999998	3982.3071289062500	7.9560001185536384
46.697000000000003	3992.9594726562500	7.9780001188814644
…		

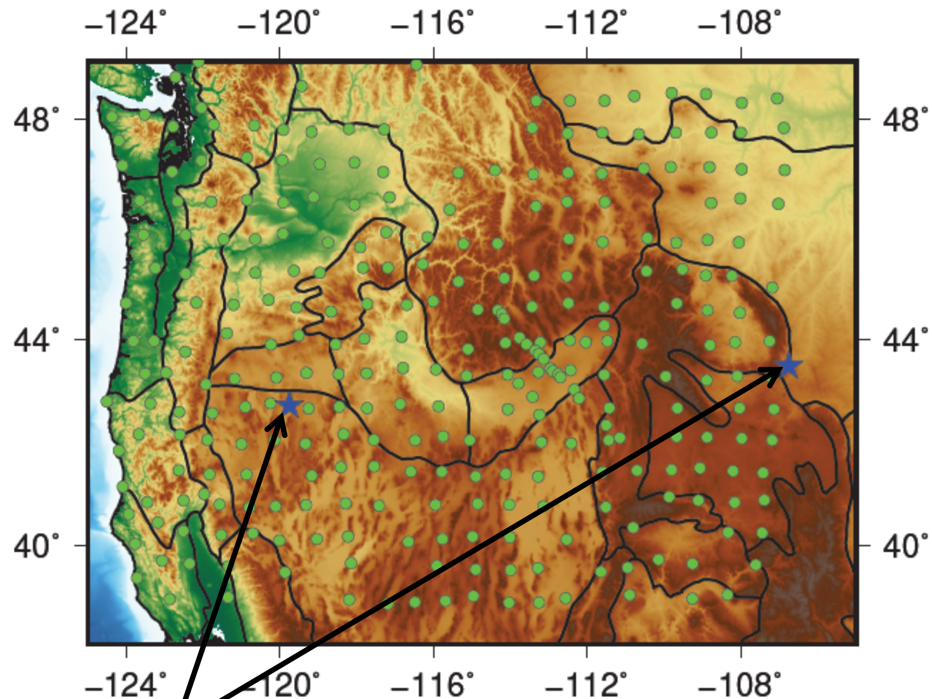
Output files:

- ***out_E-SHF_fwd.dat*** → output surface elevation and heat flow

E_calc (m)= 2487.2612032894394
SHF (mW/m2)= 57.403315101578315

Plotting results

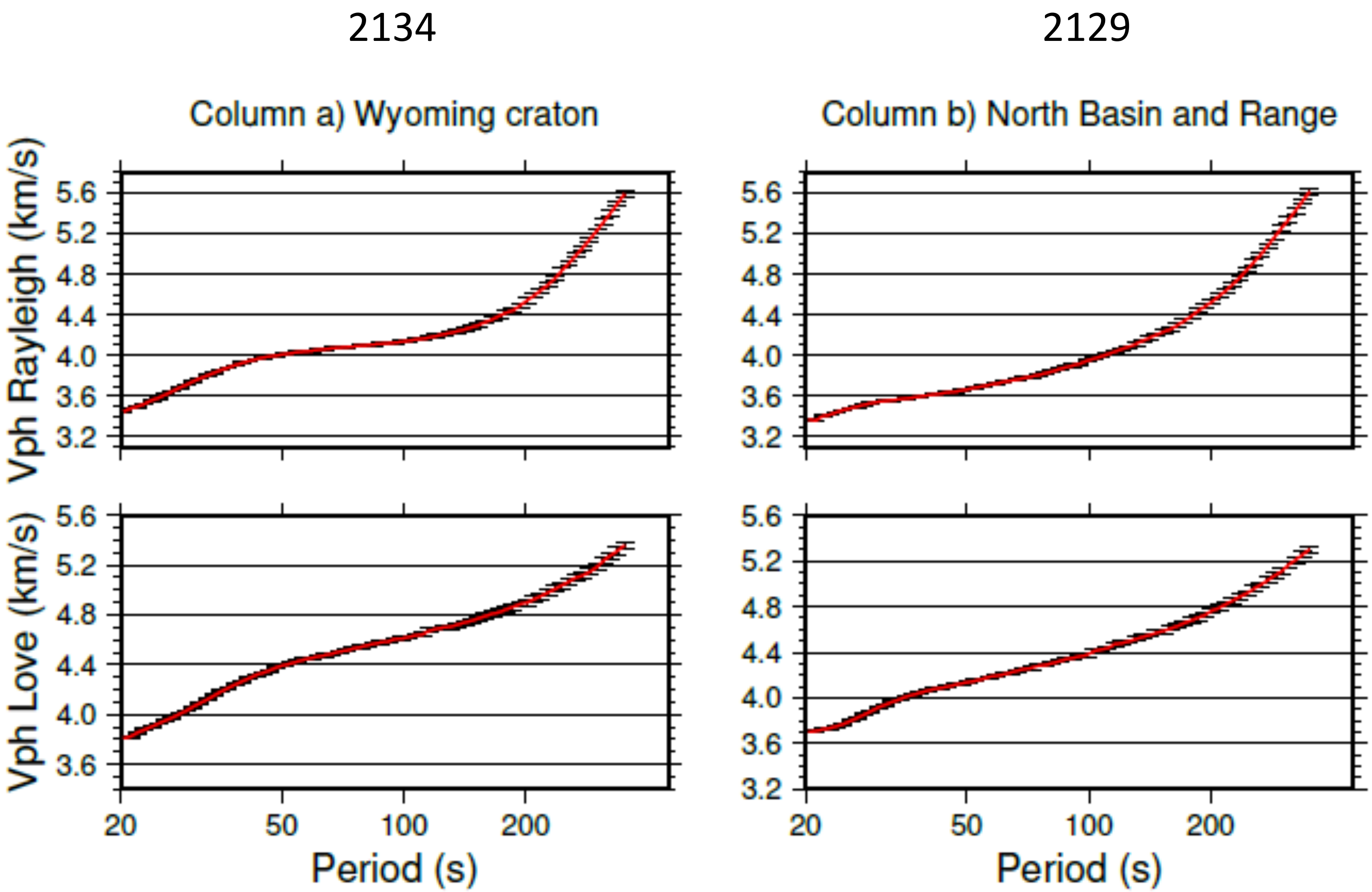
- ***plot_WINTERC_parallel_fwd.job*** **→** plots WINTERC T, rho, Vs model and output surface waves, topography and SHF
- Type on the terminal ./plot_WINTERC_parallel_fwd.job. It will ask for a column number, this is only to plot some real data for reference (put 2134)



Column	Elevation	Surface heat flow	Moho depth
Wyoming craton (WC)	1.9±0.2 km	60±15 mW/m^2	43.4±4.4 km
North Basin and Range (NBR)	1.4±0.1 km	70±10 mW/m^2	31.2±4.6 km

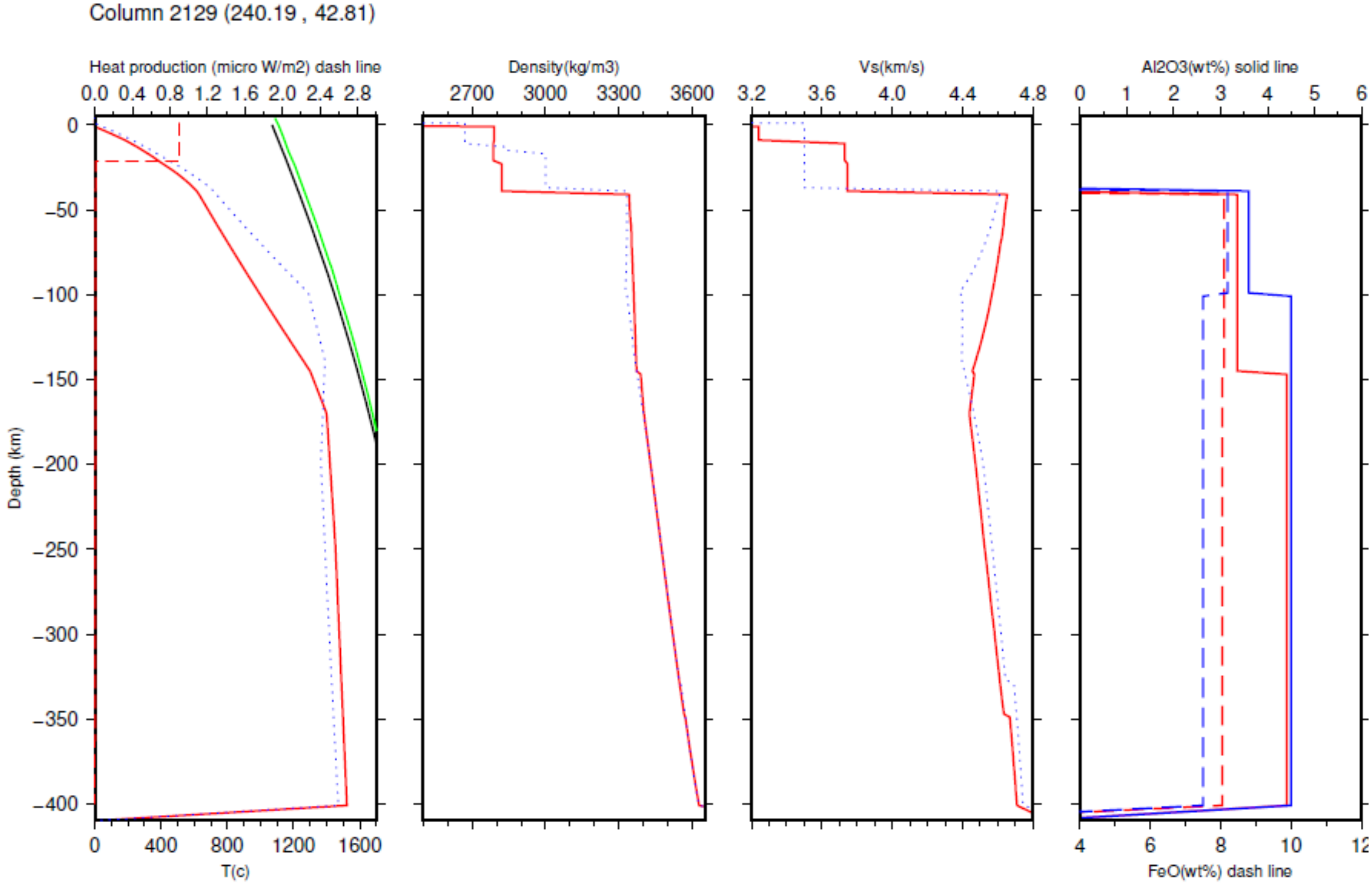
Col number
2134
2129

surface wave dispersion curves input data



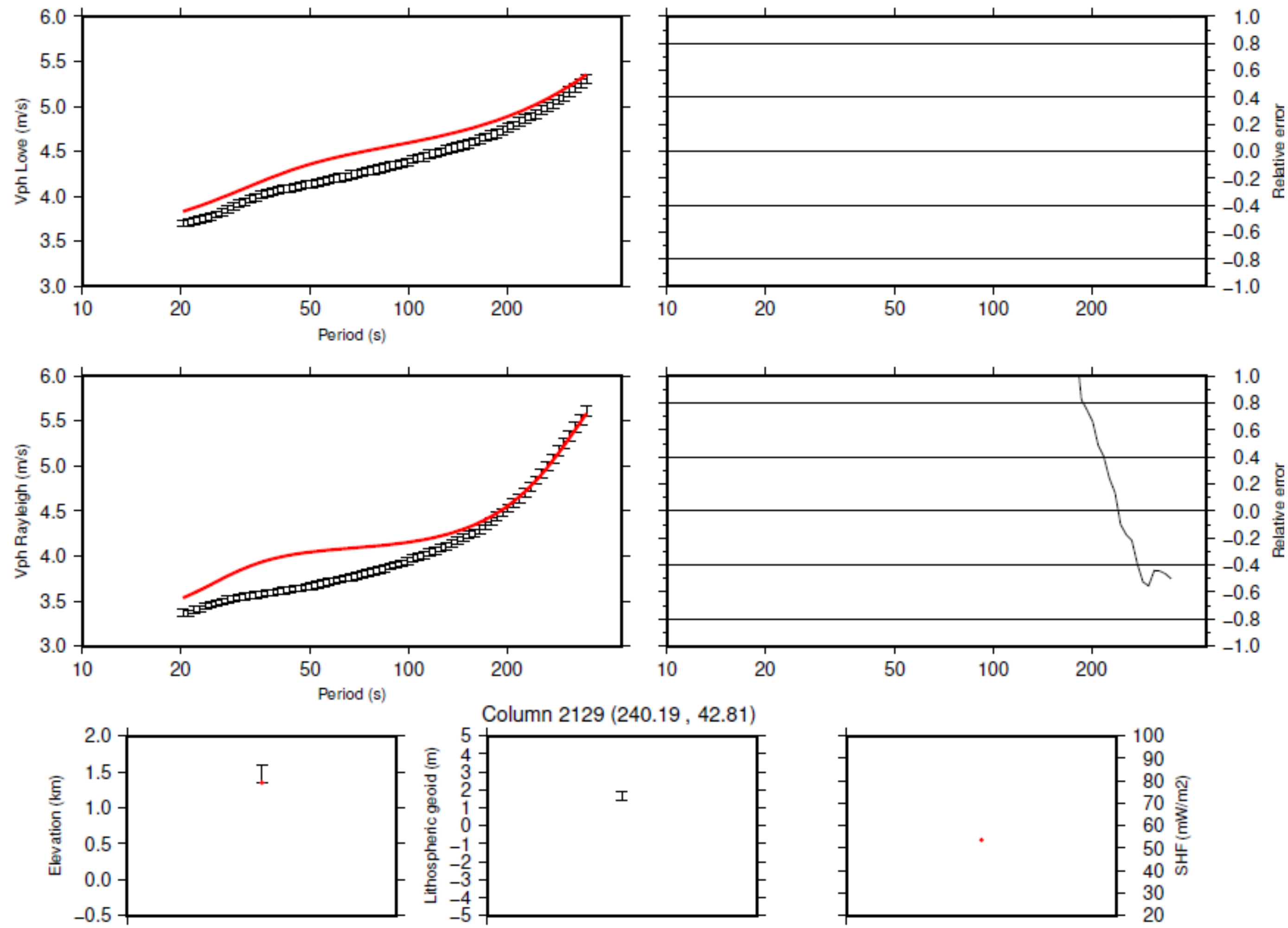
- ***plot_WINTERC_parallel_fwd.job*** → plots WINTERC T, rho, Vs model and output surface waves, topography and SHF. Three pdf output files will be created: WINTERC_var_fwd_*.pdf, phase_vel_fwd_*.pdf , and WINTERC_fwd_anis_*.pdf

WINTERC_var_fwd_*.pdf (***TrhovelsComp_fwd.z***)



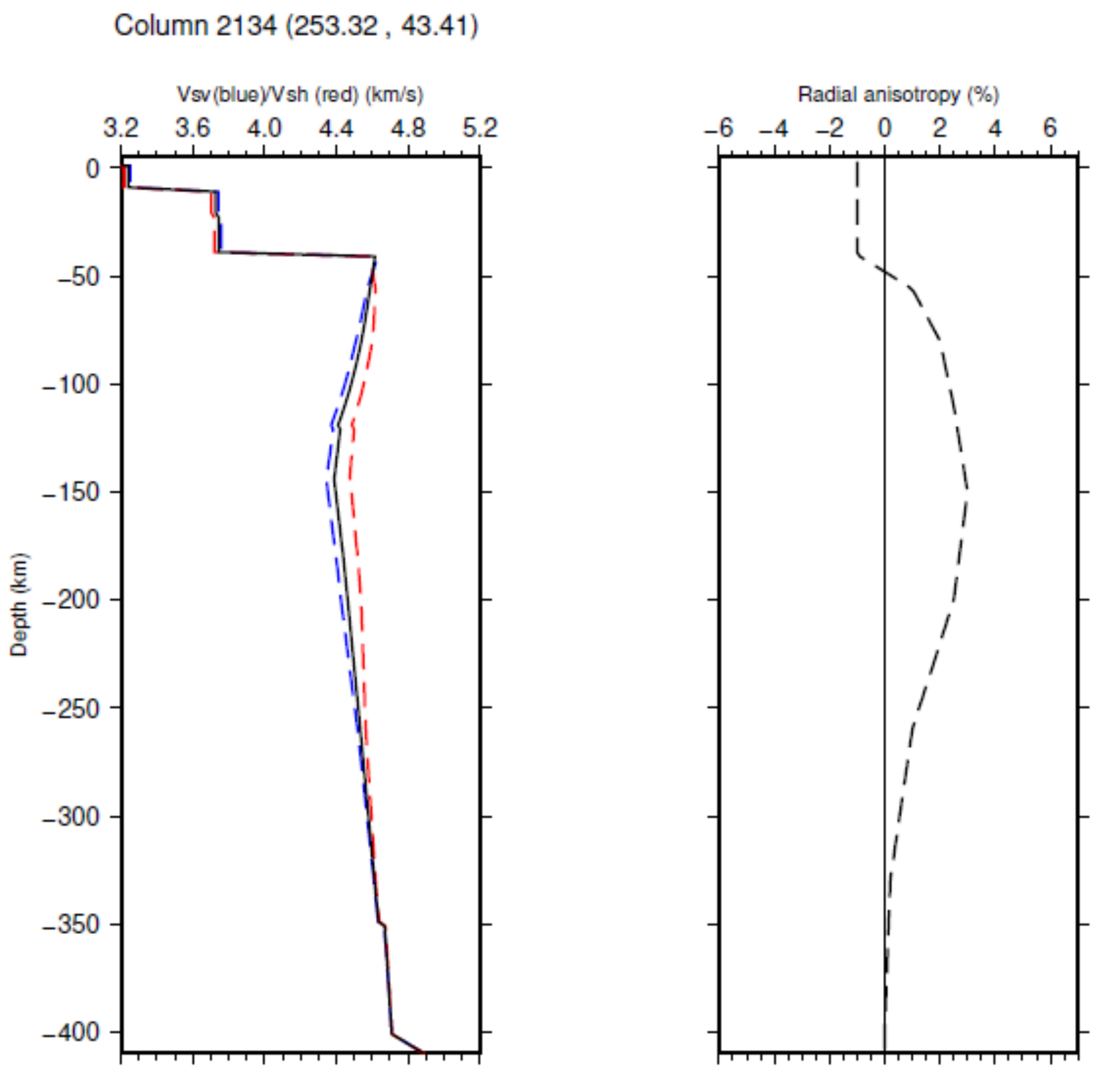
- ***plot_WINTERC_parallel_fwd.job*** → plots WINTERC T, rho, Vs model and output surface waves, topography and SHF

phase_vel_fwd_*.pdf (***out_phase_ray_fwd.dat, out_phase_love_fwd.dat , and out_E-SHF_fwd.dat***)



- ***plot_WINTERC_parallel_fwd.job*** → plots WINTERC T, rho, Vs model and output surface waves, topography and SHF.

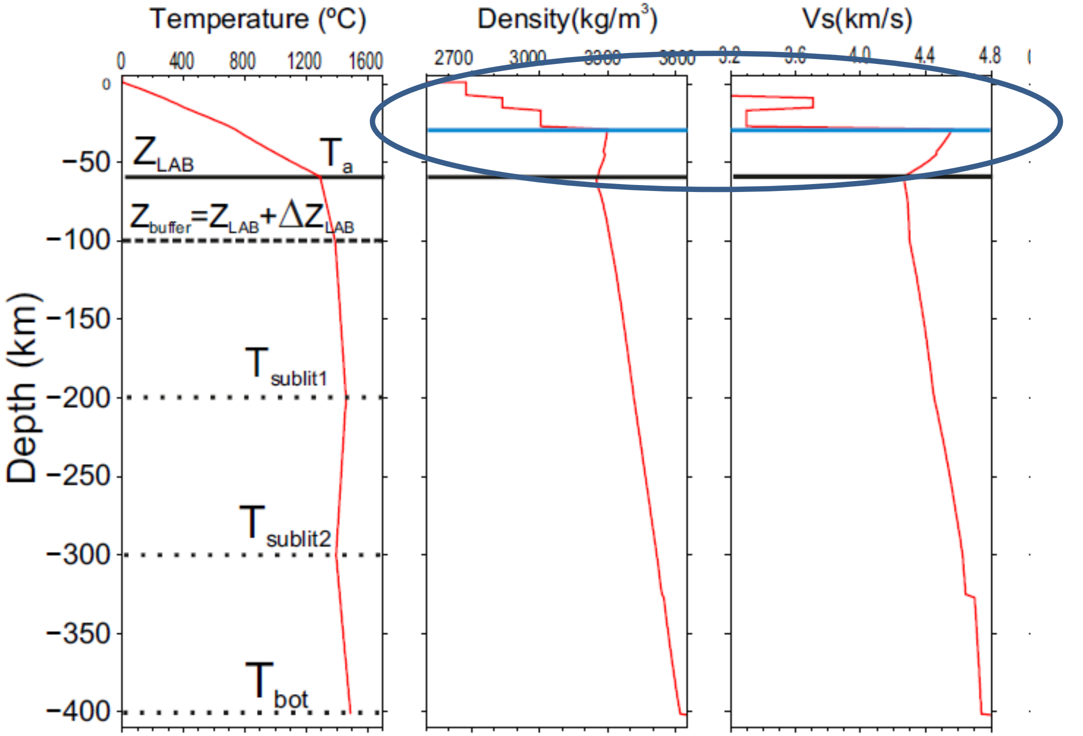
WINTERC_fwd_anis_*.pdf (***TrhovelsComp_fwd.z***)



INPUT files: WINTERC_var_fwd.info

Crustal model: density, Vs, thickness, radiogenic heat production

*SECTION: CRUSTAL LAYERS ! If density <0 then value is ABS(Vs/rho)
DENSITY | Vs | DEPTH | on(1)/off(0) | Reg. factor
2750 3.6 10D0 1 1 1 1D2 1D2 1D2 ! Upper_crust
2750 3.6 20D0 1 1 1 1D2 1D2 1D2 ! Mid_crust
2750 3.6 40D0 1 1 1 1D2 1D2 1D-1 ! Lower_crust
0.9D-6 0 1D-8 ! Radiogenic heat production crust (average) | on(1)/off(0) | Reg. factor
10 30 ! Vs and density crustal roughness coefficients



Crustal parameters are NOT computed thermodynamically!!

Crustal-structure- Things to check:

- What is the effect of the crustal thermal parameters on the calculated topography and surface heat flow?

Lets take heat production, Hc. Its value is read from **WINTERC_var_fwd.info:**

*SECTION: CRUSTAL LAYERS ! If density <0 then value is ABS(Vs/rho)
DENSITY | Vs | DEPTH | on(1)/off(0) | Reg. factor
2750 3.6 10D0 1 1 1 1D2 1D2 1D2 ! Upper_crust
2750 3.6 20D0 1 1 1 1D2 1D2 1D2 ! Mid_crust
2750 3.6 40D0 1 1 1 1D2 1D2 1D-1 ! Lower_crust
0.9D-6 0 1D-8 ! Radiogenic heat production crust (average)

In this example Hc=0.9 microW/m3, lets change the value to Hc=0.4 microW/m3 editing **WINTERC_var_fwd.info:**

0.4D-6 0 1D-8 ! Radiogenic heat production crust (average)

Save the changes in file **WINTERC_var_fwd.info.** Before you run the code, you may want to change the names of the existing output files to avoid overprinting:

type: ./create_backup.job-→creates backup files (*_bak)

Run WINTERC_fwd (Use an input elevation of 1900 m)

type: ./WINTERC_fwd

type: ./WINTERC_fwd

Read the predicted surface topography (E_calc) and heat flow (SHF) from the screen:

….

```
*************************************
MATERIAL ASSIGNATION COMPLETED
THERMAL CALCULATION COMPLETED
E_calc (m) =    2299.8694292090950
SHF (mW/m2) =    41.205730148184131
```

- Or open the file ***out_E-SHF_fwd.dat:***

2299.8694292090950 (E_calc in m)
41.205730148184131 (SHF in mW/m2)
-37.568142895306664

Compare with the previous result (*_bak files)

Crustal-structure- Things to check:

- How much is the predicted isostatic topography affected by changes in the average crustal density?

Input crustal densities are read from **WINTERC_var_fwd.info:**

*SECTION: CRUSTAL LAYERS ! If density <0 then value is ABS(Vs/rho)
DENSITY | Vs | DEPTH | on(1)/off(0) | Reg. factor
2750 3.6 10D0 1 1 1 1D2 1D2 1D2 ! Upper_crust
2750 3.6 20D0 1 1 1 1D2 1D2 1D2 ! Mid_crust
2750 3.6 40D0 1 1 1 1D2 1D2 1D-1 ! Lower_crust

In this example all three layers have rho_c=2750 kg/m3; lets change the value to rho_c=2850 kg/m3 editing **WINTERC_var_fwd.info**

2850 3.6 10D0 1 1 1 1D2 1D2 1D2 ! Upper_crust
2850 3.6 20D0 1 1 1 1D2 1D2 1D2 ! Mid_crust
2850 3.6 40D0 1 1 1 1D2 1D2 1D-1 ! Lower_crust

Save the changes in file **WINTERC_var_fwd.info,** create backup copy (./create_backup.job) and run WINTERC_fwd:

type: ./WINTERC_fwd

type: ./WINTERC_fwd

Read the predicted surface topography (E_calc) and heat flow (SHF) from the screen:

```
….

***********************************
MATERIAL ASSIGNATION COMPLETED
THERMAL CALCULATION COMPLETED
E_calc (m) =    1299.6515991290216
SHF (mW/m2) =    57.403315101578315
MODEL ROUGHNESS Vs (%)    0.0
MODEL ROUGHNESS rho (%)    0.0
```

- Or open the file ***out_E-SHF_fwd.dat:***

1299.6515991290216 (E_calc in m)

57.403315101578315 (SHF in mW/m2)

Compare with the previous result (*_bak files)

Crustal-structure- Things to check:

- What periods in the output phase velocity dispersion curves (Rayleigh and Love) are mostly affected by changes in crustal Vs values?

Input crustal velocities are read from **WINTERC_var_fwd.info:**

*SECTION: CRUSTAL LAYERS ! If density <0 then value is ABS(Vs/rho)
DENSITY | Vs | DEPTH | on(1)/off(0) | Reg. factor
2850 **3.6** 10D0 1 1 1 1D2 1D2 1D2 ! Upper_crust
2850 **3.6** 20D0 1 1 1 1D2 1D2 1D2 ! Mid_crust
2850 **3.6** 40D0 1 1 1 1D2 1D2 1D-1 ! Lower_crust

In this example all three layers have Vs=3.5 km/s; lets change the value editing **WINTERC_var_fwd.info**

2850 3.1 10D0 1 1 1 1D2 1D2 1D2 ! Upper_crust
2850 3.7 20D0 1 1 1 1D2 1D2 1D2 ! Mid_crust
2850 4.3 40D0 1 1 1 1D2 1D2 1D-1 ! Lower_crust

Save the changes in file **WINTERC_var_fwd.info.** and create backup copy and run WINTERC_fwd:

type: ./create_backup.job-→creates backup files (*_bak)

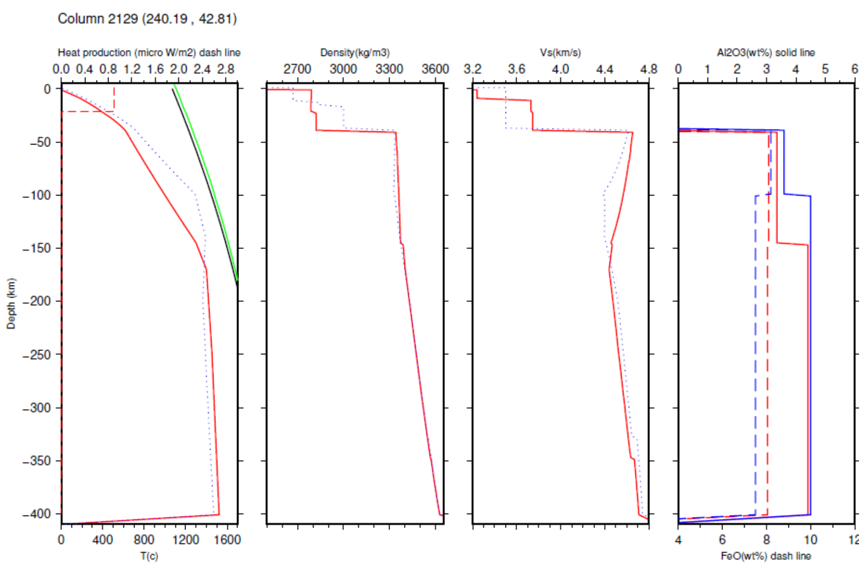
Run WINTERC_fwd: *type: ./WINTERC_fwd*

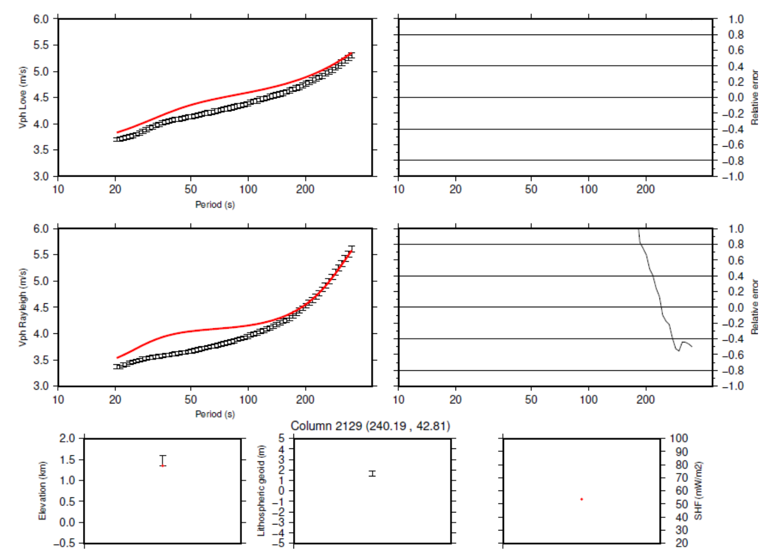
Plot the surface wave dispersion curve results:

type: ./plot_WINTERC_parallel_fwd.job

It will ask for a column number, this is only to plot some real data for reference (put 2134)

Check out the output pdf files: WINTERC_var_fwd_*.pdf, phase_vel_fwd_*.pdf

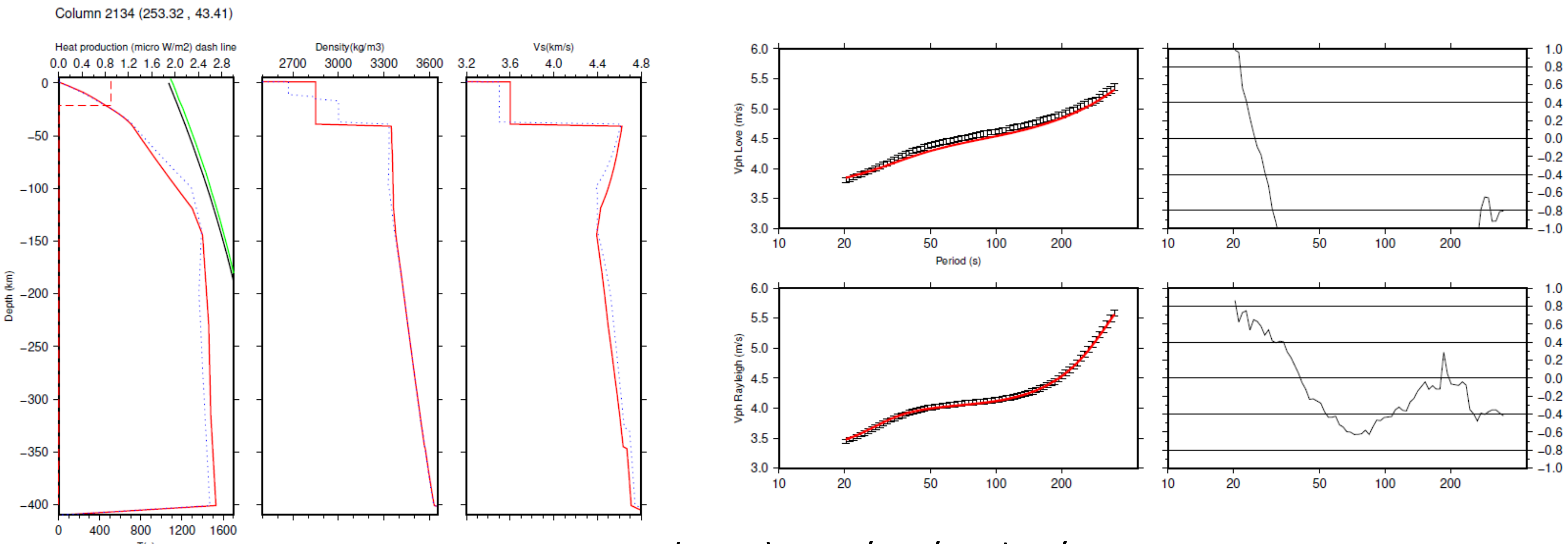




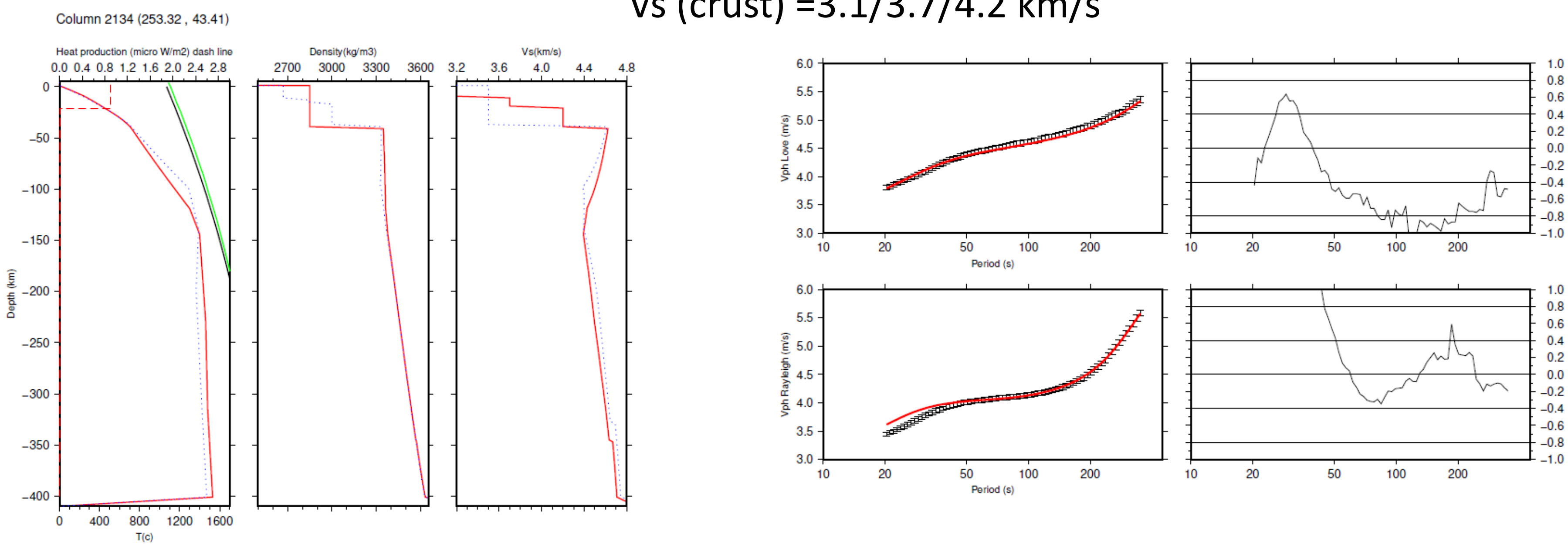
Or open the file: ***out_phase_ray_fwd.dat***→

Period (s)	Vph (m/s)	uncertainty (m/s)
20.366000000000000	3533.1010742187500	6.8940001027286053
21.187000000000001	3560.5078125000000	6.9540001036226755
22.041000000000000	3589.4665527343750	6.9940001042187214

Vs (crust)= 3.6/3.6/3.6 km/s



Vs (crust) =3.1/3.7/4.2 km/s



Crustal-structure- Things to check:

- What is the effect of modifying the Moho depth, Z_c, on the predicted data (elevation, SHF, dispersion curves) ?

WINTERC_var_fwd.info:

*SECTION: CRUSTAL LAYERS ! If density <0 then value is ABS(Vs/rho)
DENSITY | Vs | DEPTH | on(1)/off(0) | Reg. factor
2750 3.6 10D0 1 1 1 1D2 1D2 1D2 ! Upper_crust
2750 3.6 20D0 1 1 1 1D2 1D2 1D2 ! Mid_crust
2750 3.6 **40D0** 1 1 1 1D2 1D2 1D-1 ! Lower_crust

Zc=40 km in this example. Usual range: 50km > Zc >15 km.

INPUT files: WINTERC_var_fwd.info

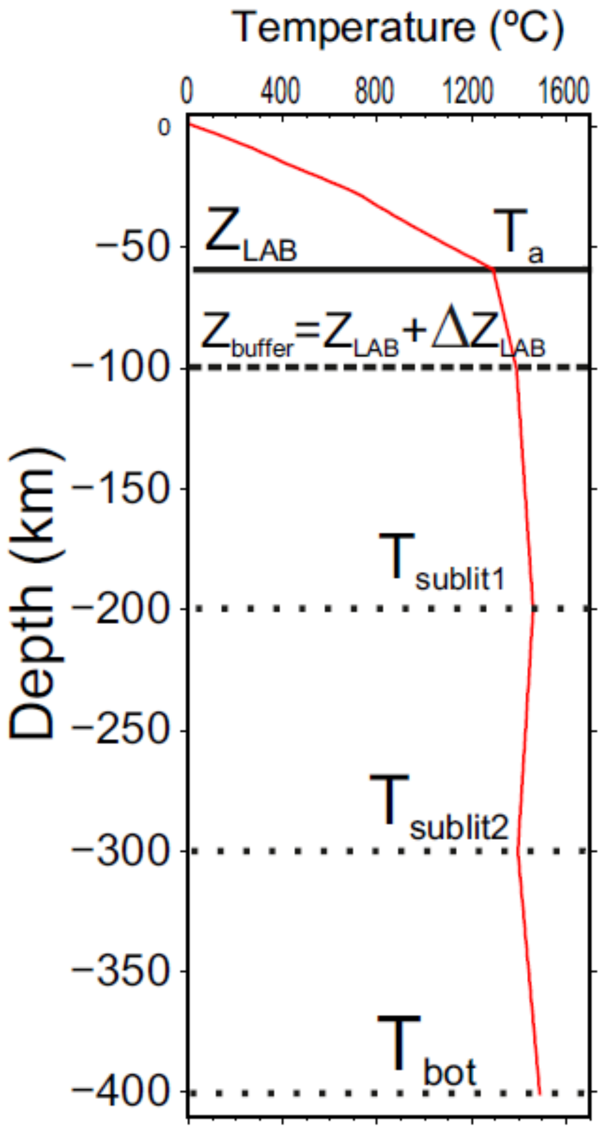
Mantle model: thickness, temperature and composition

*SECTION: MANTLE
120D0 1 1D-2 ! LAB depth (km) | on(1)/off(0) | Reg. factor
1300D0 1 3D2 ! Temperature at the base of the lithosphere in C (T_a) | on(1)/off(0) | Rfactor
1450D0 1 3D2 ! Temperature at 200 km depth in C (T_200) | on(1)/off(0) | Reg.factor
1490D0 1 3D2 ! Temperature at 300 km depth in C (T_300) | on(1)/off(0) | Reg. factor
1520D0 1 3D2 ! Temperature at the base, 400 km, in C (T_bot) | on(1)/off(0) | Reg. factor
3.35 1 6D0 ! Al2O3 in the lithospheric mantle in wt% | on(1)/off(0) | Reg. factor
8.1 1 4D1 ! FeO in the lithospheric mantle in wt% | on(1)/off(0) | Reg. factor
4.41 1 4D1 ! Al2O3 in the sub-lithospheric mantle in wt% | on(1)/off(0) | Reg. factor
8.05 1 4D1 ! FeO in the sub-lithospheric mantle in wt% | on(1)/off(0) | Reg. factor

Geotherm in WINTERC

Parameters characterizing the geotherm:

- ✓ *Lithosphere-Asthenosphere Boundary (LAB) depth ZLAB
- ✓ *Temperature at the LAB, Ta
- ✓ *Thickness of the thermal buffer, dZLAB
- ✓ *Temperature at sublithospheric nodes, from top bottom: reference adiabatic gradient ± delta (usually 100



Mantle model: thickness, temperature and composition- Things to check:

- What is the effect of changing the LAB depth, Z_LAB?

Reset to the reference model before you start:

Type: cp WINTERC_var_fwd.info_start WINTERC_var_fwd.info

Run WINTERC_fwd and Plot the surface wave dispersion curve results:

type: ./WINTERC_fwd

type: ./plot_WINTERC_parallel_fwd.job

Z_lab value is read from **WINTERC_var_fwd.info:**

SECTION: MANTLE
120D0 1 1D-2 ! LAB depth (km) | on(1)/off(0) | Reg. factor
1300D0 1 3D2 ! Temperature at the base of the lithosphere in C (T_a) | on(1)/off(0) |
…

In this example Z_LAB=120 km, lets change the value Z_LAB= 80 km editing **WINTERC_var_fwd.info**

80D0 1 1D-2 ! LAB depth (km) | on(1)/off(0) | Reg. factor
1300D0 1 3D2 ! Temperature at the base of the lithosphere in C (T_a) | on(1)/off(0) |

Save the changes in file **WINTERC_var_fwd.info,** create backup copy and run WINTERC_fwd:

type: ./create_backup.job-→creates backup files (*_bak)

type: ./WINTERC_fwd

Plot the surface wave dispersion curve results:

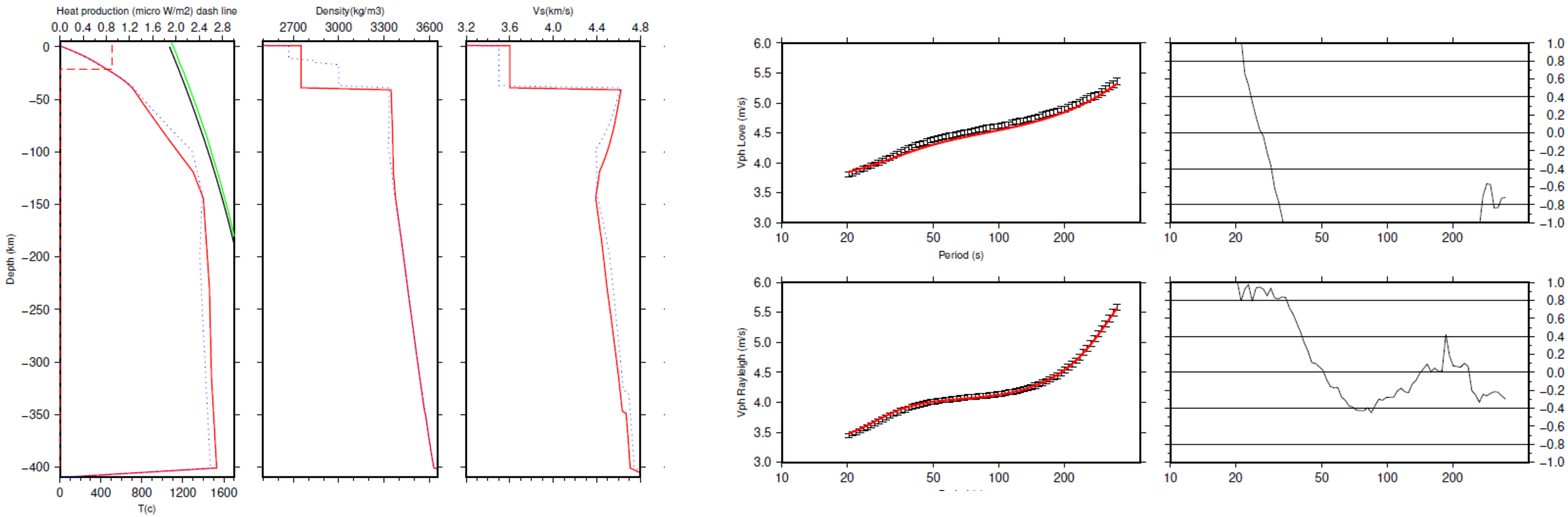
type: ./plot_WINTERC_parallel_fwd.job

Now compare the cases Z_LAB=120 km (*_bak files) and Z_LAB=80 km

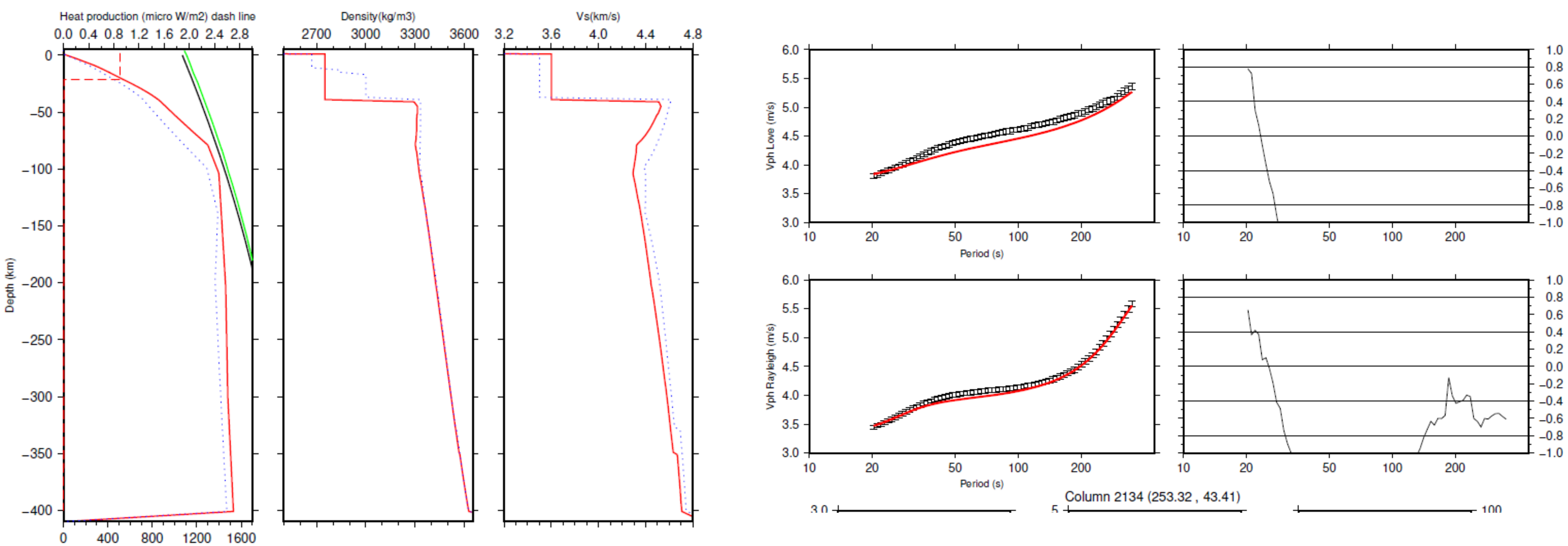
Z_LAB=120 km	**Z_LAB=80 km**
E_calc (m)= 2487.2612032894394	E_calc (m)= 3347.8955296902568
SHF (mW/m2)= 57.403315101578315	SHF (mW/m2)= 65.663088664979000

You can also check the differences in the output files e.g., ***TrhovelsComp_fwd.z, out_phase_ray_fwd.dat*** etc.

Z_LAB=120 km



Z_LAB=80 km



Mantle model: thickness, temperature and composition- Things to check:

- How much is the predicted isostatic topography and surface wave phase velocities affected by changes in mantle composition? (usual upper mantle range: 1 wt% <Al2O3 < 5 wt%)

Reset to the isotropic model before you start:

Type: cp WINTERC_var_fwd.info_start WINTERC_var_fwd.info

Edit **WINTERC_var_fwd.info**

…
3.35 1 6D0 ! Al2O3 in the lithospheric mantle in wt%
8.1 1 4D1 ! FeO in the lithospheric mantle in wt%
4.41 1 4D1 ! Al2O3 in the sub-lithospheric mantle in wt%
8.05 1 4D1 ! FeO in the sub-lithospheric mantle in wt%

- What periods are mostly affected by changes in the sublithospheric temperature? (± 100 K)

…
1460D0 1 3D2 ! Temperature at 200 km depth in C (T_200)
1480D0 1 3D2 ! Temperature at 300 km depth in C (T_300)
1530D0 1 3D2 ! Temperature at the base, 400 km, in C (T_bot)

- What is the effect of melt (or pre-melt)? Where is melt concentrated? (Heat up your lithosphere…)

INPUT files: WINTERC_var_fwd.info

Radial anisotropy

$$R_{anis} = \frac{V_{SH} - V_{SV}}{V_s}$$

Rayleigh s. waves = f(Vsv)
Love s. waves = f(VSH)

$$V_s = \frac{2V_{SV} + V_{SH}}{3}$$

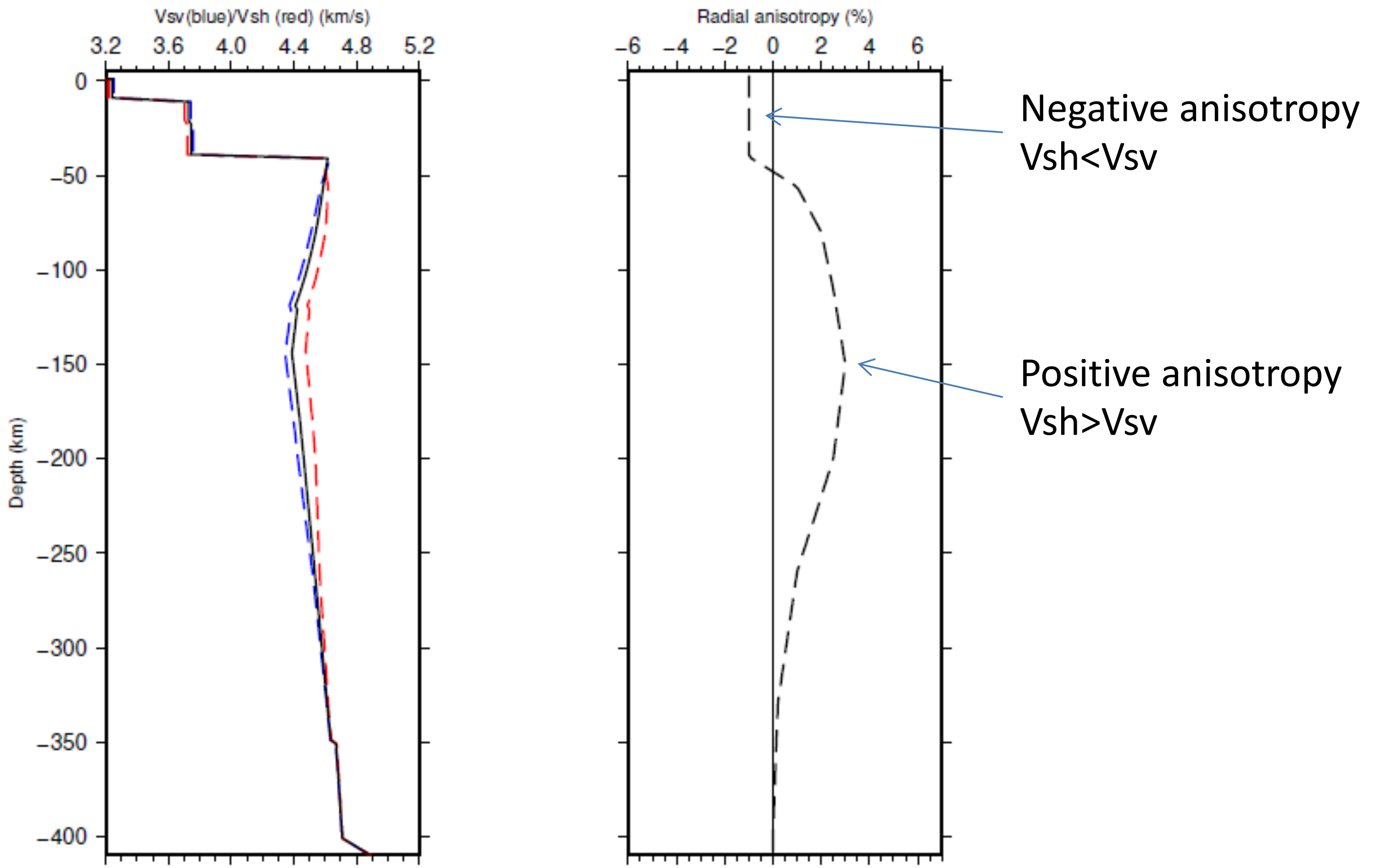
*SECTION: RADIAL ANISOTROPY
1 ! 0-->No Radial anisotropy; 1-->Radial anisotropy as defined in next 11 lines ;
7D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
14D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
25D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
56D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
80D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
110D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
150D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
200D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
260D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
330D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
400D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor

Radial anisotropy

$$R_{anis} = \frac{V_{SH} - V_{SV}}{V_s}$$

$$V_s = \frac{2V_{SV} + V_{SH}}{3}$$

Rayleigh s. waves = f(Vsv)
Love s. waves = f(VSH)



Radial anisotropy in WINTERC

Z_Moho=45 km

Z_Moho=50 km

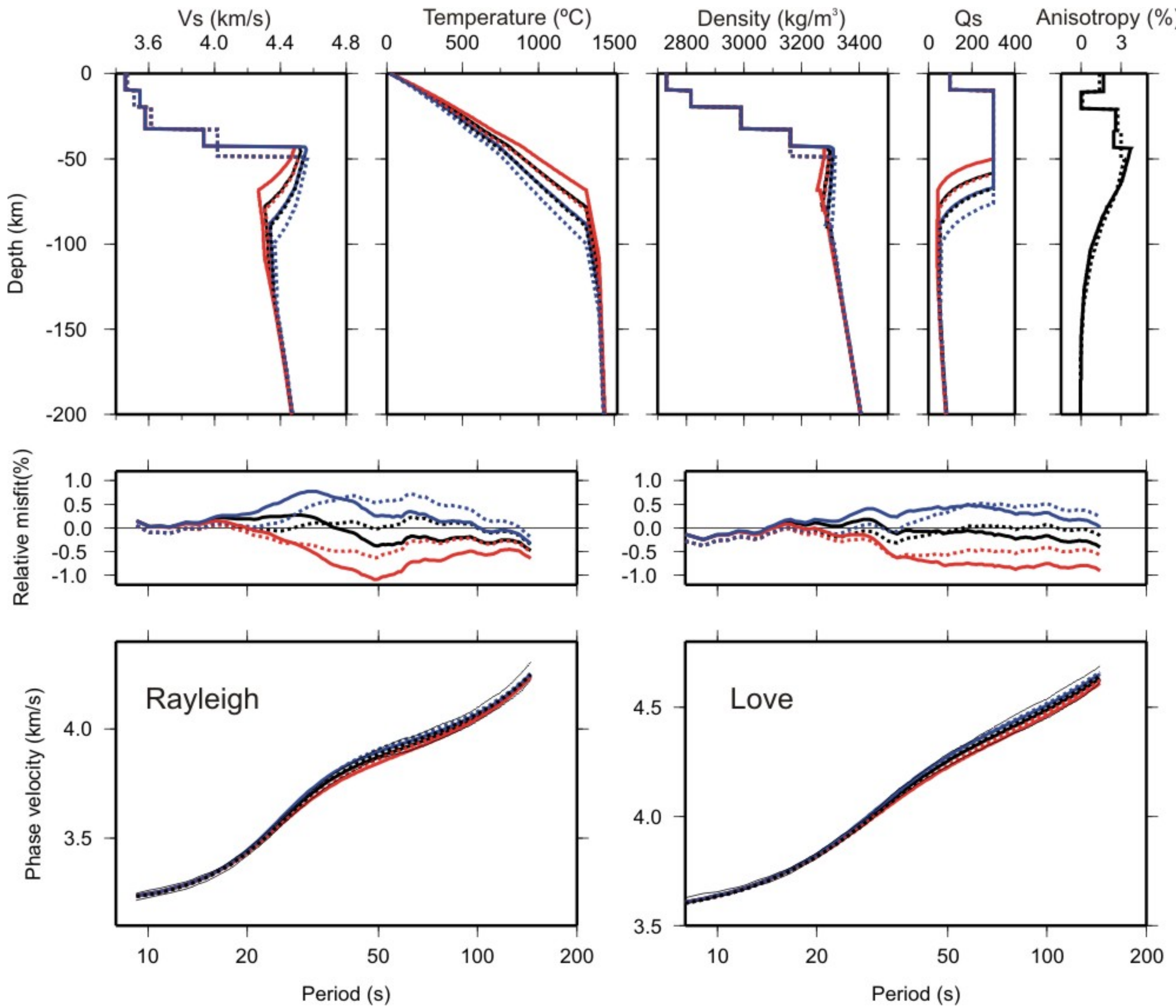
"Warm" models
Z_LAB+10 km

Preferred models

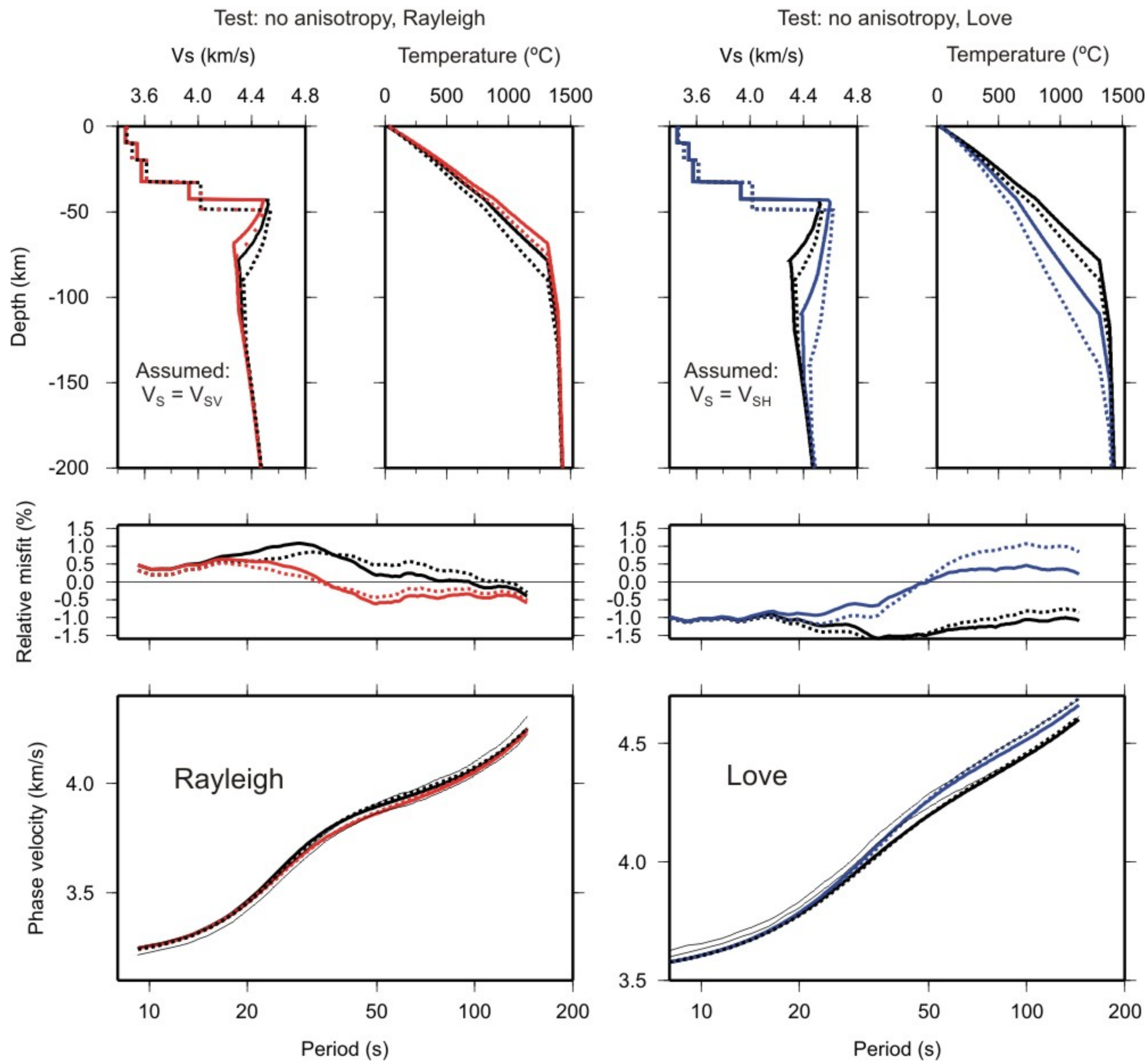
Z_LAB=80 km

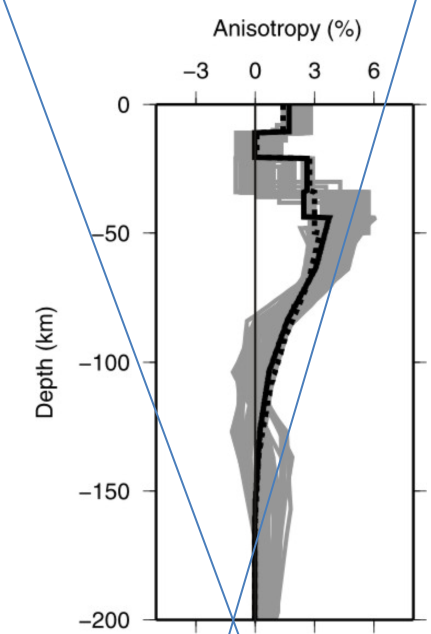
Z_LAB=90 km

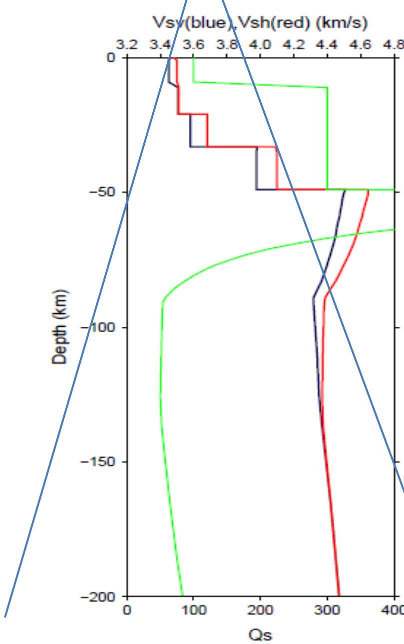
"Cold" models
Z_LAB-10 km



(Ignoring) Radial anisotropy







Radial anisotropy - *Things to check:*

- What is the effect of a ±5% zigzag pattern in mantle anisotropy on the predicted Rayleigh and Love phase velocities with respect to an isotropic model?

Lets first update **WINTERC_var_fwd.info** file:

Type: cp WINTERC_var_fwd.info_anis WINTERC_var_fwd.info

This is an isotropic model:
*SECTION: RADIAL ANISOTROPY
1 ! 0-->No Radial anisotropy; 1-->Radial anisotropy as defined in next 11 lines ;
7D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
14D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
25D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
56D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
80D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
110D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
150D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
200D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
260D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
330D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
400D0 **0** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor

Run WINTERC_fwd for the isotropic model

type: ./WINTERC_fwd

Plot the surface wave dispersion curve results:

type: ./plot_WINTERC_parallel_fwd.job

And create backup copy:

type: ./create_backup.job-→creates backup files (*_bak)

Now lets introduce the zigzag pattern in **WINTERC_var_fwd.info** :

*SECTION: RADIAL ANISOTROPY
1 ! 0-->No Radial anisotropy; 1-->Radial anisotropy as defined in next 11 lines ;
10D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
20D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
40D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
56D0 **5** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
80D0 **-5** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
110D0 **5** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
150D0 **-5** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
200D0 **5** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
260D0 **-5** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
330D0 **5** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
400D0 **-5** 1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor

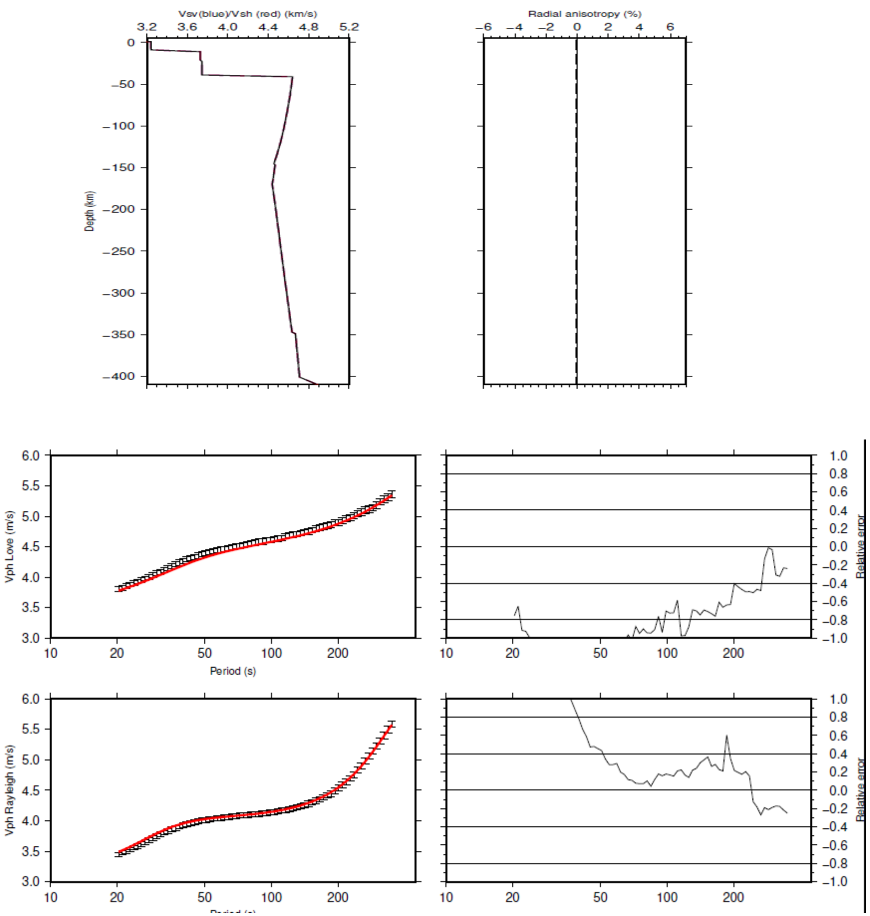
Run WINTERC_fwd for the anisotropic model

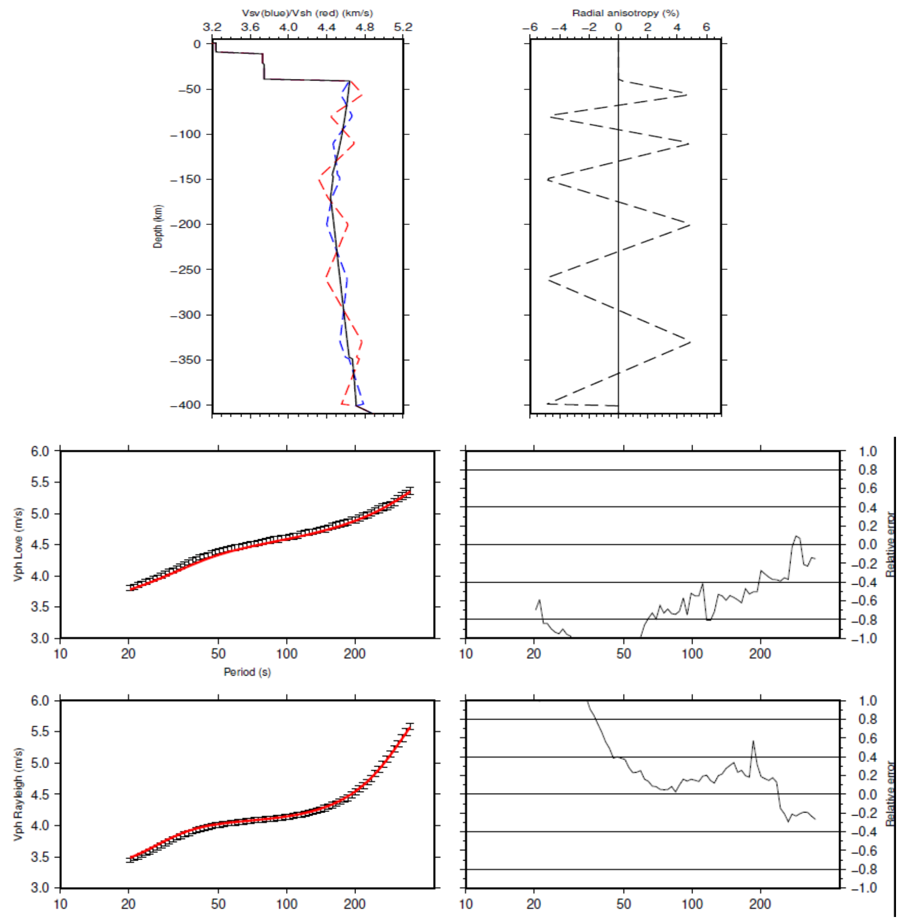
type: ./WINTERC_fwd

Plot the surface wave dispersion curve results and input anisotropy:

type: ./plot_WINTERC_parallel_fwd.job

Now compare the isotropic (*_bak files) and anisotropic zigzag cases:





Radial anisotropy - *Things to check:*

- Can you improve the data fit for Rayleigh and Love modifying the anisotropy in the crust (first three values in **WINTERC_var_fwd.info**)?

*SECTION: RADIAL ANISOTROPY
1 ! 0-->No Radial anisotropy; 1-->Radial anisotropy as defined in next 11 lines ;
10D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
20D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
40D0 **0** 1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor

Reset to the isotropic model before you start:

Type: cp WINTERC_var_fwd.info_anis WINTERC_var_fwd.info

Rayleigh s. waves = f(Vsv)
Love s. waves = f(VSH)

Positive anisotropy
Vsh>Vsv

Negative anisotropy
Vsh<Vsv

WINTERC inversion

Input files:

- **[ ].lis file:** list of inversion column including input data
- ***WINTERC_var.info***: input model variables
- ***WINTERC_param.info***: input parameters
- ***WINTERC_ref.info***: reference column (regularization)

WINTERC inversion

Example of **[ ].lis** file for 6 columns:

```
-6
dc00_000782_61.40_60.18    782    61.40    60.18    96.82    27.89    8.78    0.74    58.67    18    45.68    3.61    96.82  -40000.00
dc00_006342_101.79_-2.50   6342   101.79   -2.50   469.31   461.57   15.70    1.37    80.36   31.10    32.48    6.48   469.31  -40000.00
dc00_004867_298.76_11.73   4867   298.76   11.73  -1390.02  616.69   -3.59    2.57    46.40   26.90    22.08    8.16  -1390.02  -40000.00
dc00_000523_341.01_68.14    523   341.01   68.14  -895.74   309.68    6.33    0.19   144.00   70.49    14.81    3.90  -895.74    3.45
dc00_004512_285.81_14.90   4512   285.81   14.90  -3905.65  404.85   -1.50    0.32    53.91   17.78    18.54    2.37  -3905.65   141.90
dc00_011131_153.39_-57.30  11131  153.39  -57.30  -3414.26  150.01    8.39    0.19    50.00  100000.00  10.49    4.16  -3414.26   20.77
```

The first negative number indicates the number of 1D columns that will be inverted.
Then, for each line we have:
1/the name of the file containing the surface wave dispersion curves
2/a column number that identifies it uniquely
3/ long
4/ lat
5/ surface elevation (m)
6/ uncertainty surface elevation (m)
7/ lithospheric geoid anomaly (m) (not in use currently)
8/ uncertainty lithospheric geoid anomaly (m) (not in use currently)
9/ surface het flow (mW/m2)
10/ uncertainty surface het flow (mW/m2)
11/ moho depth (km)
12/ uncertainty moho depth (km)
13/ ice elevation (if no ice Elev=Elev_ice)
14/ age oceanic lithosphere (-40000.00 if continental)

WINTERC inversion

Example of **[ ].lis** file for 6 columns:

-6

dc00_000782_61.40_60.18	782	61.40	60.18	96.82	27.89	8.78	0.74	58.67	18	45.68	3.61	96.82	-40000.00
dc00_006342_101.79_-2.50	6342	101.79	-2.50	469.31	461.57	15.70	1.37	80.36	31.10	32.48	6.48	469.31	-40000.00
dc00_004867_298.76_11.73	4867	298.76	11.73	-1390.02	616.69	-3.59	2.57	46.40	26.90	22.08	8.16	-1390.02	-40000.00
dc00_000523_341.01_68.14	523	341.01	68.14	-895.74	309.68	6.33	0.19	144.00	70.49	14.81	3.90	-895.74	3.45
dc00_004512_285.81_14.90	4512	285.81	14.90	-3905.65	404.85	-1.50	0.32	53.91	17.78	18.54	2.37	-3905.65	141.90
dc00_011131_153.39_-57.30	11131	153.39	-57.30	-3414.26	150.01	8.39	0.19	50.00	100000.00	10.49	4.16	-3414.26	20.77

The expected path for the surface wave dispersion data is:

CWD/GEO_DATA/Rayleigh/dc_MOD_nod/[Rayleigh file name, e.g.,**dc00_000782_61.40_60.18**]
CWD/GEO_DATA/Love/dc_MOD_nod/[Rayleigh file name, e.g.,**dc00_000782_61.40_60.18**]
Note that both Rayleigh and Love dispersion files have the same name for a given column, only the path is changing.

WINTERC_var.info

```
*SECTION: CRUSTAL LAYERS !   If density <0 then value is ABS(Vs/rho)
DENSITY |  Vs   | DEPTH | on(1)/off(0) | Reg. factor
2790  3.241   9.2D0  1 1 1     1D2  1D2 1D2     ! Upper_crust
2787  3.73 21.3D0 1 1 1     1D2  1D2 1D2     ! Mid_crust
2820.5 3.746   40.1D0 1 1 1     1D2  1D2 1D-1     ! Lower_crust
.9D-6 0 1D-8   ! Radiogenic heat production crust (average) | on(1)/off(0) | Reg. factor
10  30     ! Vs and density crustal roughness coefficients
*SECTION: MANTLE
146.2D0 1 1D-2   ! LAB depth (km) | on(1)/off(0) | Reg. factor
1300D0  1 3D2  ! Temperature at the base of the lithosphere in C (T_a)   | on(1)/off(0) | Reg. factor
1452.3D0  1 3D2  ! Temperature at 200 km depth in C (T_200)              | on(1)/off(0) | Reg. factor
1487.3D0  1 3D2  ! Temperature at 300 km depth in C (T_300)              | on(1)/off(0) | Reg. factor
1522.4D0  1 3D2  ! Temperature at the base of the model, 400 km, in C (T_bot)  | on(1)/off(0) | Reg. factor
3.35 1 6D0  ! Al2O3 in the lithospheric mantle in wt%               | on(1)/off(0) | Reg. factor
8.1 1 4D1  ! FeO in the lithospheric mantle in wt%                 | on(1)/off(0) | Reg. factor
4.41 1 4D1  ! Al2O3 in the sub-lithospheric mantle in wt%            | on(1)/off(0) | Reg. factor
8.05 1 4D1  ! FeO in the sub-lithospheric mantle in wt%             | on(1)/off(0) | Reg. factor
1    ! reg_var_all
*SECTION: RADIAL ANISOTROPY
1 ! 0-->No Radial anisotropy; 1-->Radial anisotropy as defined in next 11 lines ;
7D0   0  1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
14D0  0  1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
25D0  0  1 1D2 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
56D0  0  1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
80D0  0  1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
110D0 0  1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
150D0 0  1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
200D0 0  1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
260D0 0  1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
330D0 0  1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
400D0 0  1 5D1 ! depth (km) | anistropy (%) | on(1)/off(0) | Reg. factor
*SECTION: TRANSITION ZONE
4.890 1 4D1  !Vs at 410 discontinuity | on(1)/off(0) | Reg. factor
5.532  1 8D1  !Vs at 660 discontinuity | on(1)/off(0) | Reg. factor
3.83 1 1D1  !anistropy (%) at 410 discontinuity | on(1)/off(0) | Reg. factor
-8.2 1 1D1  !anistropy (%) at 660 discontinuity | on(1)/off(0) | Reg. factor
*SECTION: TRANSIENT TEMPERATURES
500D0 1 3D2 ! d_temperature at t=0   | on(1)/off(0) | Reg. factor
*SECTION: THERMAL BUFFER
25D0 1 3D2 ! Thickness thermal lithospheric base buffer (km)   | on(1)/off(0) | Reg. factor
!Regularization factors (reg_var) are related to the norm SUM(reg_var(i)*|x(i)-x_var_ref(i)|/x_var_ref(i)) added to the objective function
!reg_var_all controls the overall weight of regularization with respect to the reference model x_ref
!Crustal roughness coefficients are related to the vertical variation of Vs and rho (e.g. SUM( rough_coeff*|rho_i+1-rho_i|) added to the objective function
```

WINTERC inversion

WINTERC_param.info

*Paramters for WINTERC
204 !Num of vertical nodes (N_z)
2 !Vertical grid step in km (d_z)
0D0 !Temperature at the surface in C (T_s)
5 !Max topography in km (E_max)
5.3 !Thermal conductivity at room conditions for mantle
1E-08 !Rad heat production mantle
7.69E-12 !Pressure coeff for thermal conductivity mantle
1.25 !GRÜNEISEN PARAMETER for thermal conductivity mantle
4.3 !PRESS DERIVATIVE OF ISOTHERM BULK MOD for thermal conductivity mantle
130 !ISOTHERM BULK MOD for thermal conductivity mantle
0.5 ! Sublithospheric thermal gradient between z_buffer and 400 km (K/km)
100 ! Temperature anomaly (K) @200 km wrt reference temperature from ref Sublithospheric thermal gradient
100 ! Temperature anomaly (K) @300 km wrt reference temperature from ref Sublithospheric thermal gradient
100 ! Temperature anomaly (K) @bottom model wrt reference temperature from ref Sublithospheric thermal gradient
300D0 ! Crustal Qs attenuation
0D0 ! Crustal thermal exp coeff (for density)
0.00E+00 ! Crustal press coefficient (for density)
2.2 ! Thermal conductivity upper crust
2.5 ! Thermal conductivity mid crust
2.1 ! Thermal conductivity lower crust
1.75 ! Vp/Vs ratio upper crust (if <0 if will be assumed as the fixed value of ABS(Vp))
1.75 ! Vp/Vs ratio mid crust (if <0 if will be assumed as the fixed value of ABS(Vp))
1.81 ! Vp/Vs ratio lower crust (if <0 if will be assumed as the fixed value of ABS(Vp))
3   ! Melt - Vs experimental model (1-->Hammond & Humphreys 2000, org cuspate relaxed; 2-->Hammond & Humphreys 2000, tubules at F<1 % and film inclusions at F>1 %, 3-->Chantel et al., 2016)
1   ! Peridotite solidus (1-->Katz et al. (2003); 2-->Hirschmann (2000) G3; 3-->Serafian et al (2017) Sci dry; 4-->Serafian et al (2017) Sci 450 ppm wt% H2O)

WINTERC inversion

WINTERC_ref.info-->Reference column

2670 !Rho upper crust
2850 !Rho mid crust
3010 !Rho lower crust
3500 !Vs upper crust
3500 !Vs mid crust
3500 !Vs lower crust
10D3 ! Depth upper crust
22D3 ! Depth mid crust
35D3 ! Depth Moho
100D3 ! Depth LAB
1290D0 ! Temperature LAB
1420 ! Temperature 200 km
1470 ! Temperature 300 km
1500 ! Temperature Bottom
3.6 !Al2O3 Lithosphere
8.2 ! FeO Lithosphere
4.5 !Al2O3 subithosphere
8.1 ! FeO sublithosphere
.7D-6 ! Av heat production crust
5041.52 !Vs at 410 discontinuity
5569.85   !Vs at 660 discontinuity

Running WINTERC from a terminal:

*Open a terminal and go to ~/ materials/ WINTERC_3DEARTH-school

*Edit input model file WINTERC_var.info as needed

*Edit input .lis file containing the inversion columns as needed (e.g. US.lis)

*type: mpirun -np {num processors } WINTERC_bwd_damp_mpi_cov [*.lis]. In our example for US.lis file with 2 columns:

mpirun -np 2 WINTERC_bwd_damp_mpi_cov US.lis

You can pipe the output on screen log to a user defined file:

mpirun -np 2 WINTERC_bwd_damp_mpi_cov US.lis>logfile

mpirun – np 2 WINTERC_bwd_damp_mpi_cov US.lis

```
Reading input variables file WINTERC_var.info
 N_col_mp en read         2
 Total number of columns:          2
 List of column numbers:       2134       2129
 RADIAL ANISTROPY ON
 Reading input reference variable vector:WINTERC_ref.info
 Reading input parameters file WINTERC_param.info
 namefile         2 dc00_002129_240.19_42.81
 RAYLEIGH SURFACE WAVES INVERSION SWITCHED ON
 LOVE SURFACE WAVES INVERSION SWITCHED ON
 Reading input variables file WINTERC_var.info
 N_col_mp en read         1
 RADIAL ANISTROPY ON
 Reading input reference variable vector:WINTERC_ref.info
 Reading input parameters file WINTERC_param.info
 namefile         1 dc00_002134_253.32_43.41
 RAYLEIGH SURFACE WAVES INVERSION SWITCHED ON
 LOVE SURFACE WAVES INVERSION SWITCHED ON
 NUMBER OF DATA POINTS:       149
 TOTAL NUMBER OF VARIABLES:          32
NUMBER OF DATA POINTS:       149
 TOTAL NUMBER OF VARIABLES:          32
 Inverting for variables:...
 ///////////////////////////////
 Temp buffer thickness
 ! Rho Upper_crust
 ! Rho Midd_crust
 ! Rho Lower_crust
 ! Vs Upper_crust
 ! Vs Midd_crust
 ! Vs Lower_crust
 ! Depth Upper_crust
 ! Depth Mid_crust
 ! Moho depth
 ....
```

mpirun – np 2 WINTERC_bwd_damp_mpi_cov US.lis (continuation)

```
CALL to LITMOD_jac: LITMOD_1D function
 ////////////////////////////////////
 ############### PROGRAM WINTERC ##############
 #        Parallel Version                 #
  ************************************
 COLUMN NUMBER:        2129
    Crustal densities(kg/m3):   2670.0  2852.0  2952.0
       Crustal iso Vs (m/s):   3190.0  3860.0  3700.0
Depth of crustal layers (km):  10.0 20.0 31.2
  Av crust heat (micro W/m3): 0.90E-06
  d_T transient initial (km): 500.0
Age oceanic lithosphere (Ma):    -40000.26
            LAB depth (km):  90.0
Thermal buffer thickness (km): 40.0
        LAB temperature (C):   1300.0
   Temperature at 200 km (C):   1420.0
   Temperature at 300 km (C):   1470.0
Bottom model temperature (C):   1520.0
     Vs at 410 km disc (m/s):   5042.0
     Vs at 660 km disc (m/s):   5570.0
          Al2O3 (wt%) Litho:  3.60
            FeO (wt%) Litho:  8.10
       Al2O3 (wt%) sub-Litho:  4.40
         FeO (wt%) sub-Litho:  8.05
   Radial anistropy crust(%):      0.0     0.0     0.0
     Radial anistropy mantle, z= 56 km:      0.0
     Radial anistropy mantle, z= 80 km:      0.0
    Radial anistropy mantle, z= 110 km:      0.0
    Radial anistropy mantle, z= 150 km:      0.0
    Radial anistropy mantle, z= 200 km:      0.0
    Radial anistropy mantle, z= 260 km:      0.0
    Radial anistropy mantle, z= 330 km:      0.0
    Radial anistropy mantle, z= 400 km:      0.0
   Radial anistropy mantle,410 km disc:      0.0
   Radial anistropy mantle,660 km disc:      0.0
 ************************************
 MATERIAL ASSIGNATION COMPLETED
```

Radial anistropy mantle,410 km disc: -2.6
  Radial anistropy mantle,660 km disc: -10.0
****

MATERIAL ASSIGNATION COMPLETED
THERMAL CALCULATION COMPLETED
E_calc (m) =   971.52142353553791
SHF (mW/m2) =   77.094239045129953
MODEL MISFIT DATA: 6.3679687196851447
MODEL MISFIT REFERENCE: 2.8510570320124797
MODEL ROUGHNESS Vs (%)   10.017276510758569
MODEL ROUGHNESS rho (%)   17.128390297285971
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

DAMP REFINEMENT ITERATION: 1
ITERATION NUMBER: 1

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
CALL to LITMOD_jac: JACOBIAN
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
CALL to LITMOD_jac: LITMOD_1D function
//////////////////////////////////////

WINTERC inversion

Output files :

- ***[ ].lis_out_var.xyz→ main output variables***
- ***[ ].lis_out_data.xyz → data residual and misfits***
- ***[ ].lis_out_dens.xyz →density in some nodes***
- ***[ ].lis_out_T.xyz →Temperature in some nodes***
- ***[ ].lis_out_rad-anis.xyz →radial anisotropy***
- ***[ ].lis_out_adiab.xyz→sublithospheric potential temperature and adiabatic gradient***

- Each of the ***[ ].lis_out_*.xyz*** contains one line per inverted model column

WINTERC inversion

Output files, for each column a folder Column_[ ] is created; inside it the code writes the output files for that individual column: Column_[ ] /

- ***TrhovelsComp_[ ].z*** →output 1D column with depth, temperature, density, seismic velocities, mantle composition
- ***out_phase_ray_[ ].dat***→ output Rayleigh phase velocity
- ***out_phase_love_[ ].dat***→ output Love phase velocity
- ***out_E-SHF_[ ].dat*** →output surface elevation and heat flow
- ***variances_prior_[ ].dat*** →output prior uncertainties
- ***Cov_post_[ ].dat*** →output posterior covariance matrix
- ***LITMOD_out_WINTERC_data_[ ].lis*** →output data misfits
- ***LITMOD_out_WINTERC_var_[ ].dat*** →output inversion variables

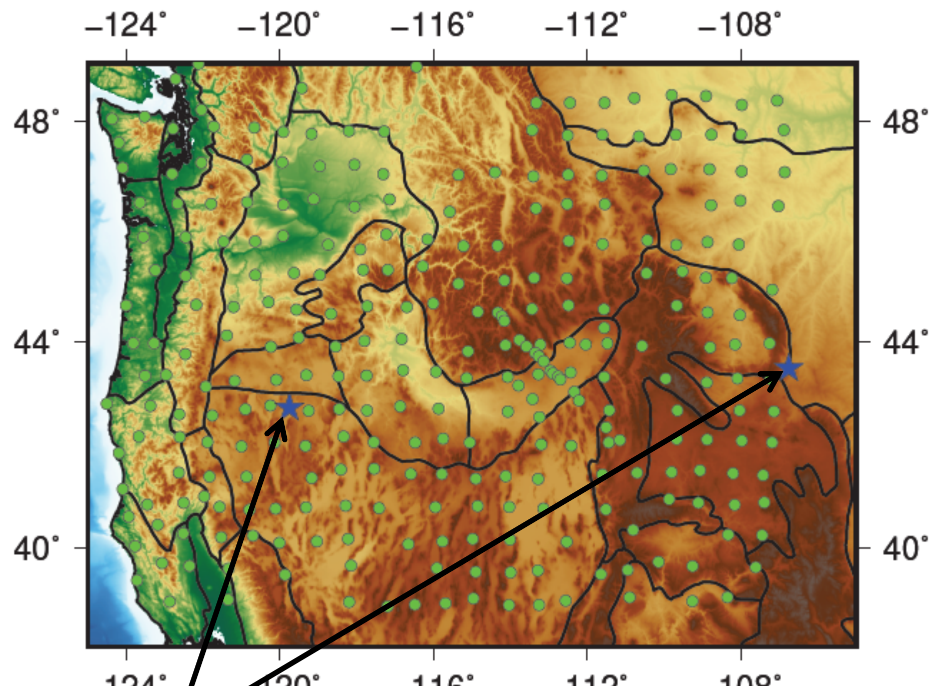
- ***LITMOD_out_WINTERC_var_[ ].dat*** →output inversion variables

```
253.32071199999999       43.414949000000000
  14183.006989259497     var! Temp buffer thickness
  2789.9453657951367     var! Rho Upper_crust
  2787.1945986798460     var! Rho Midd_crust
  2820.4818133877416     var! Rho Lower_crust
  3241.5779546251638     var! Vs Upper_crust
  3731.0164047700991     var! Vs Midd_crust
  3746.4547610606282     var! Vs Lower_crust
  9219.1626552539146     var! Depth Upper_crust
  21306.609863053018     var! Depth Mid_crust
  40105.479077169970     var! Moho depth
  146241.27113231580     var! LAB depth
  1300.0000000000000     fix! Temperature base lithosphere (T_a)
  1452.2729104310924     var! Temperature at 200 km depth
  1487.2852311270462     var!  Temperature at 300 km depth
  1522.4096513006891     var! Temperature base model 400 km (T_bot)
  3.3510792092689390     var! Al2O3 lithospheric mantle
  8.0999999999999996     fix! FeO lithospheric mantle
  4.4162892802187637     var! Al2O3 sub-lithospheric mantle
  8.0500000000000007     fix! FeO sub-lithospheric mantle
 -9.0995758031859122E-003 var! Rad anisotropy Upper_crust
  5.2168858705579158E-003 var! Rad anisotropy Midd_crust
  6.6951626819076196E-002 var! Rad anisotropy Lower_crust
  4.5184679548609184E-002 var! Rad anisotropy mantle z=56 km
  1.5502648421700948E-002 var! Rad anisotropy mantle z=80 km
 -1.2107789851035803E-002 var! Rad anisotropy mantle z=110 km
 -1.6269497240075880E-002 var! Rad anisotropy mantle z=150 km
 -2.6251055339786026E-003 var! Rad anisotropy mantle z=200 km
  1.1058368511872243E-002 var! Rad anisotropy mantle z=260 km
```

…

Plotting results

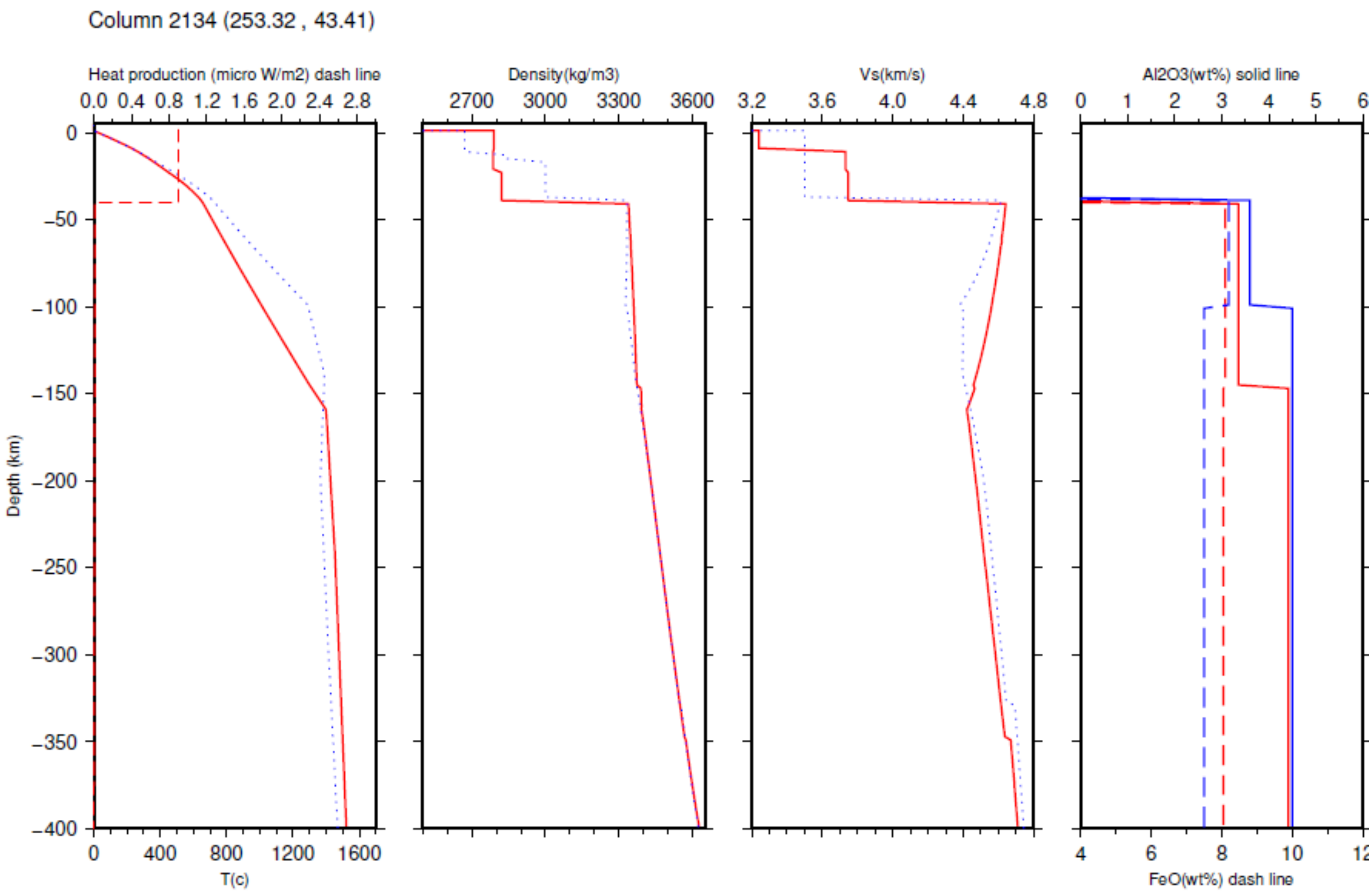
- ***plot_WINTERC_parallel.job*** → plots WINTERC T, rho, Vs model and output surface waves, topography and SHF
- Type on the terminal ./plot_WINTERC_parallel.job. It will ask for a column number, (put either 2134 or 2129)



Column	Elevation	Surface heat flow	Moho depth	Col number
Wyoming craton (WC)	1.9±0.2 km	60±15 mW/m^2	43.4±4.4 km	2134
North Basin and Range (NBR)	1.4±0.1 km	70±10 mW/m^2	31.2±4.6 km	2129

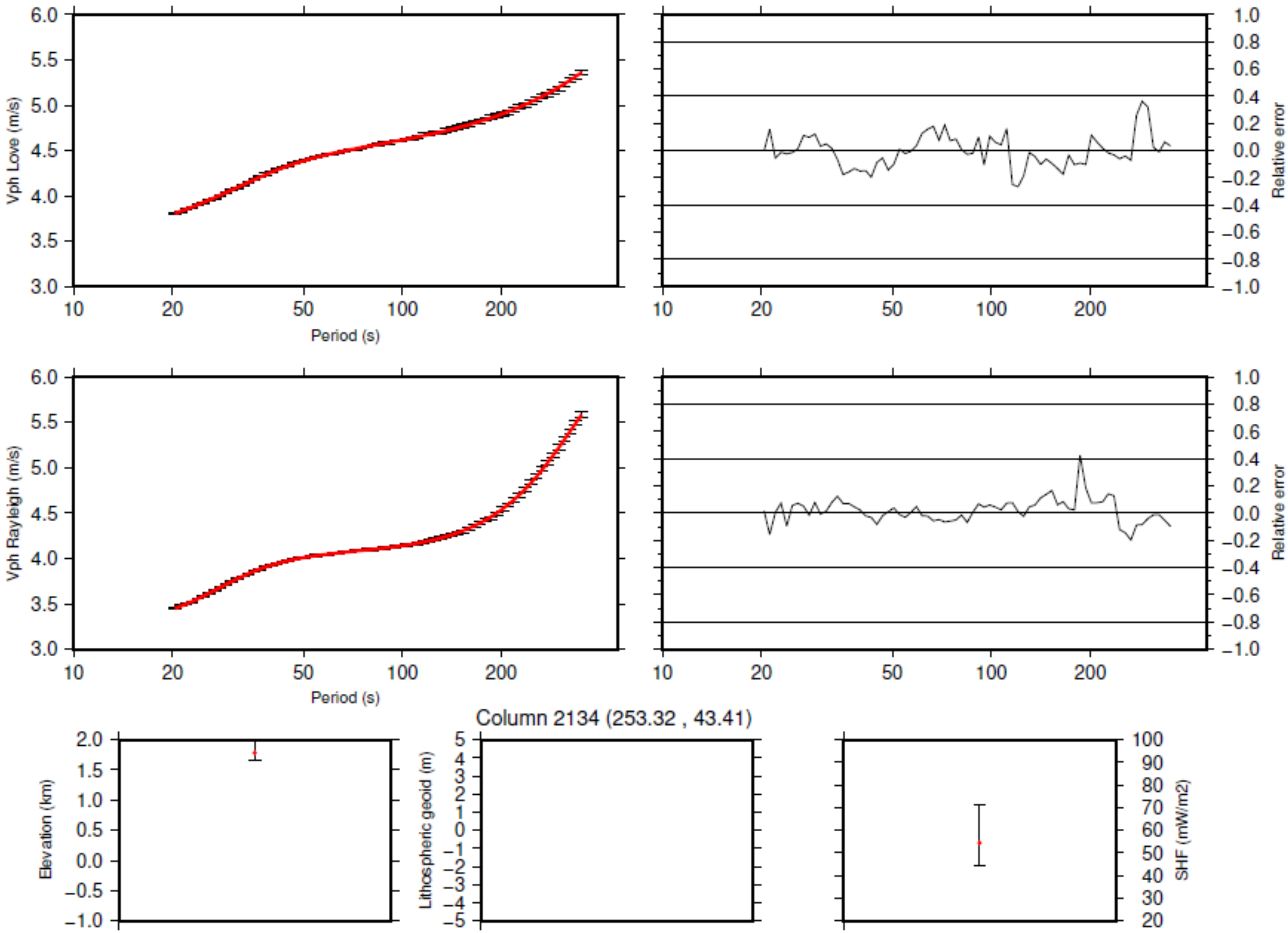
- ***plot_WINTERC_parallel.job*** **→** plots WINTERC T, rho, Vs model and output surface waves, topography and SHF. Three pdf output files will be created: phase_vel_*.pdf
- Lithosphere_*.pdf, and Anis_*.pdf

Lithosphere_*.pdf (**Column_[ ]/ *TrhovelsComp_[ ].z***)



- ***plot_WINTERC_parallel.job*** → plots WINTERC T, rho, Vs model and output surface waves, topography and SHF

  phase_vel_*.pdf (**Column_[ ]/ *out_phase_ray_fwd.dat,* Column_[ ]/ *out_phase_love_[ ].dat , and* Column_[ ]/ *out_E-SHF_[ ].dat***)



- ***plot_WINTERC_parallel.job*** → plots WINTERC T, rho, Vs model and output surface waves, topography and SHF.

Anis_*.pdf (**Column_[ ]/ *TrhovelsComp_[ ].z***)