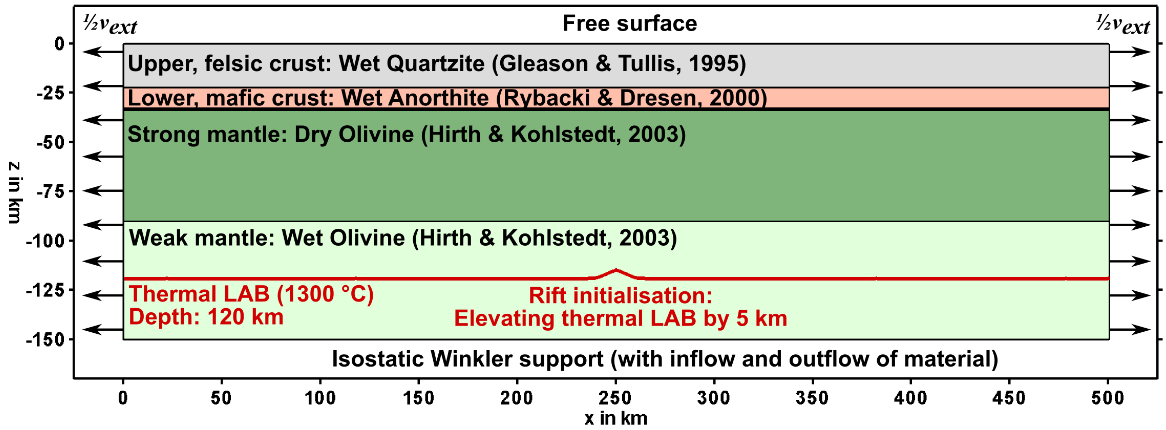
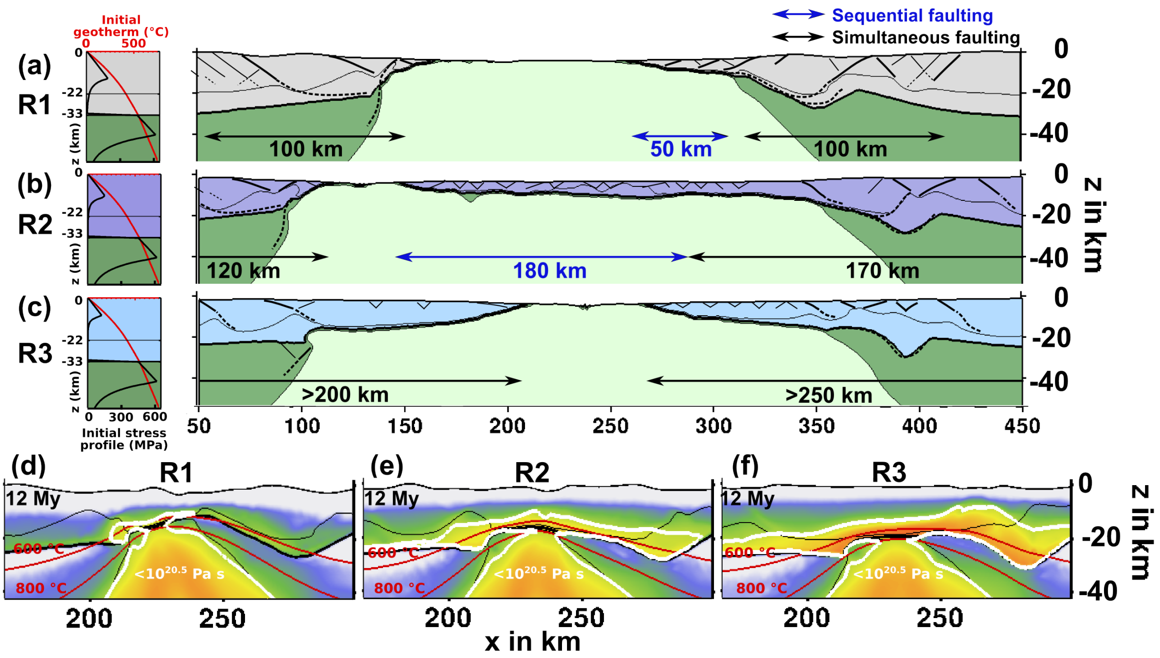


Supplementary Figure 1

Model setup. *The initial vertical strength distribution has been computed for a strain rate of* $10^{-15.27}$ s^{-1} *(corresponding to 8 mm/yr extension of the 500 km wide model domain).*



Supplementary Figure 2

Effect of crustal rheology. (a-f) *Scenarios with 8 mm/yr extension velocity, but with entirely felsic crustal composition featuring three different quartzite flow laws **R1**[15], **R2**[16], **R3**[16] (cf. Supplementary Table 2) that feature a respective decrease in crustal strength. The width of simultaneously faulted areas is indicated by black arrows, while sequentially faulted domains are depicted by blue arrows. Crustal rheology affects final margin architecture by two means. (i) Weak crust enhances initial crust-mantle decoupling (Fig. 5g) and associated distributed faulting (black arrows). (ii) If rift migration occurs, weak crust efficiently maintains the exhumation channel and hence rift migration (Fig. 3h,i). This leads to asymmetric, wide sequentially faulted margins. The detailed evolution of all simulations can be found in Supplementary Figure 4. A concise interpretation of each model evolution is given in the Supplementary Discussion at the end of this file.*

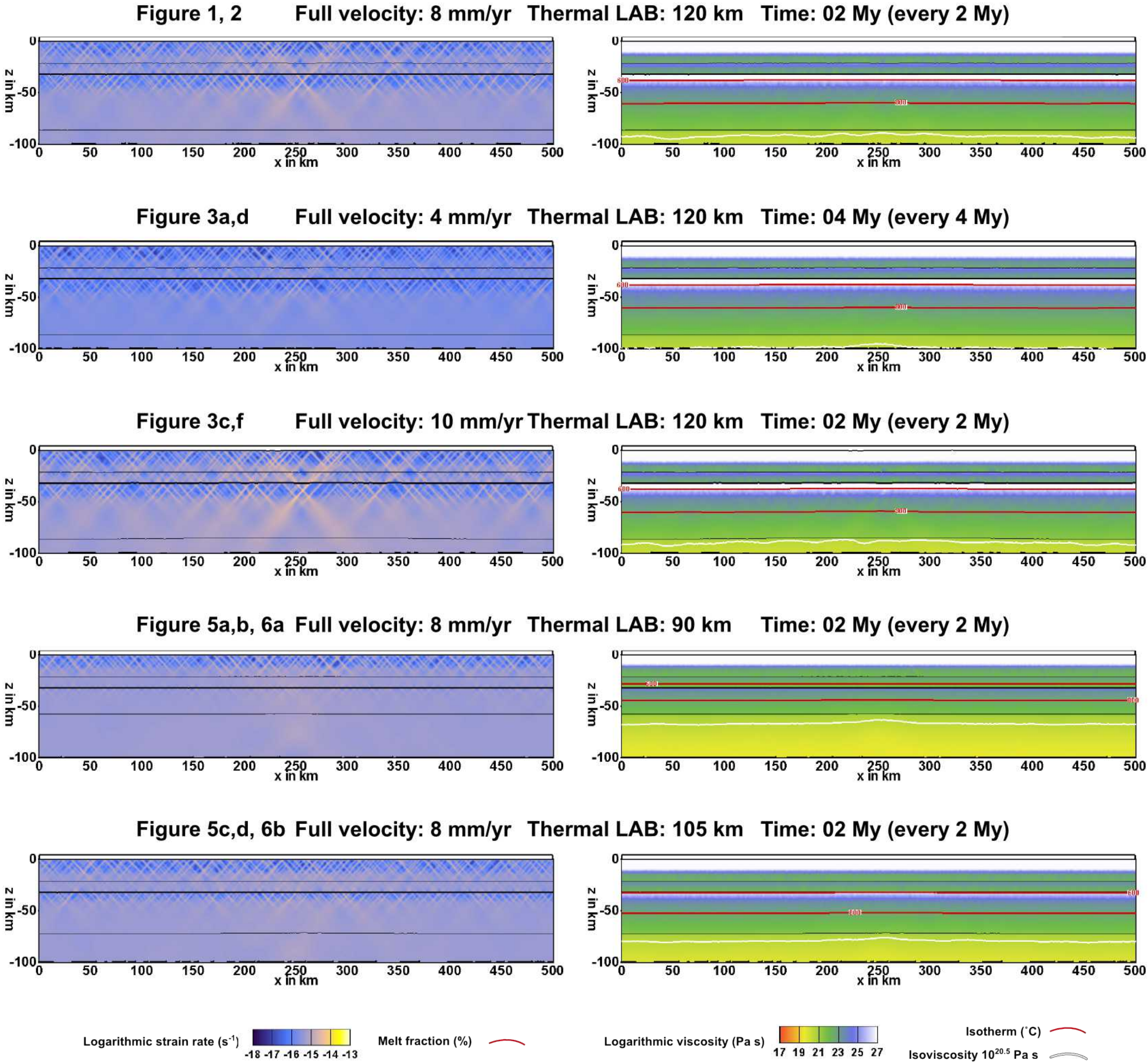


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 02 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 04 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 02 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 02 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 02 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
Logarithmic strain rate (s^-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

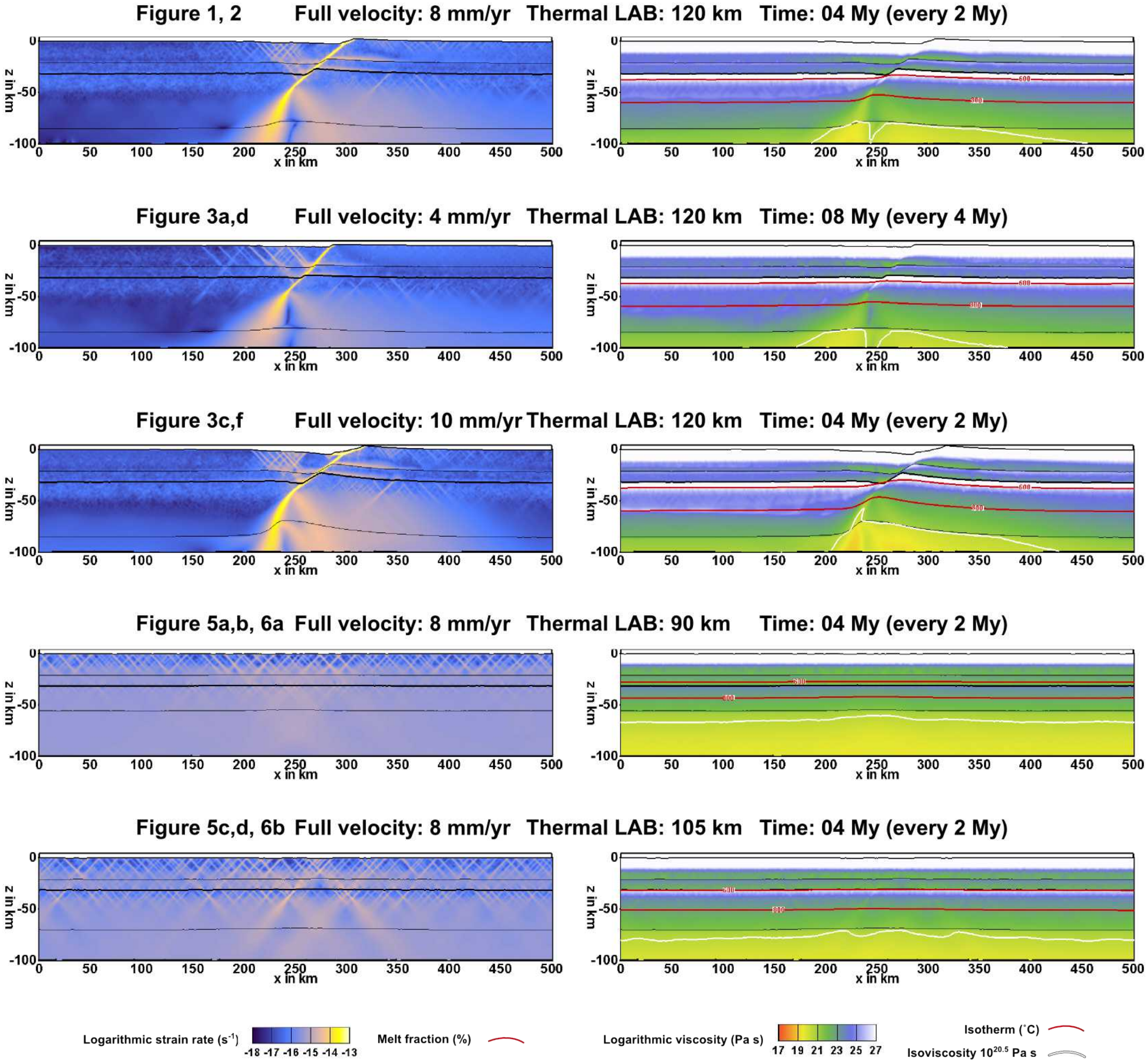


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 04 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 08 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 04 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 04 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 04 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
600
900
Logarithmic strain rate (s⁻¹)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

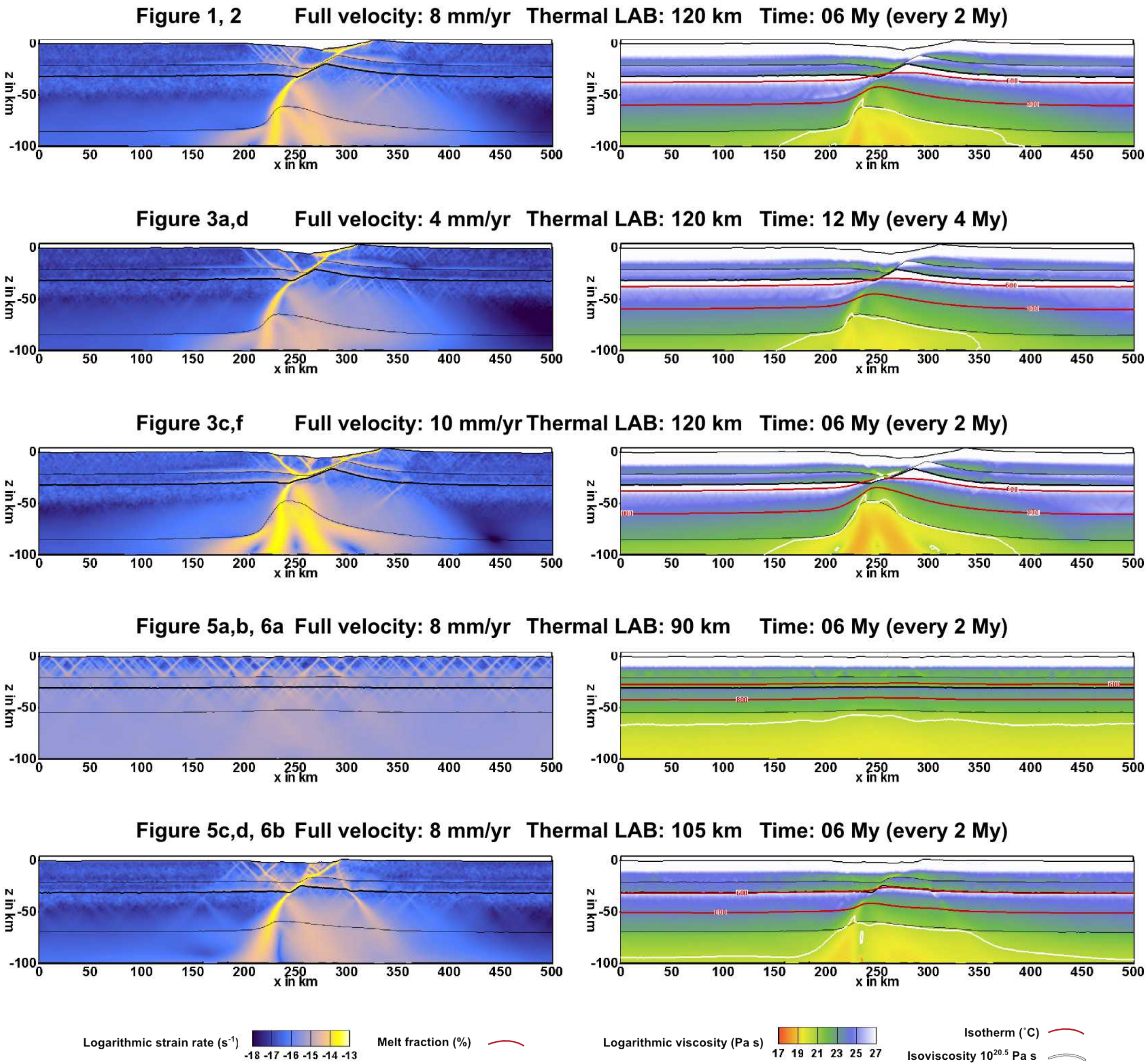


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 06 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 12 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 06 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 06 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 06 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
600
800
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity $10^{20.5}$ Pa s

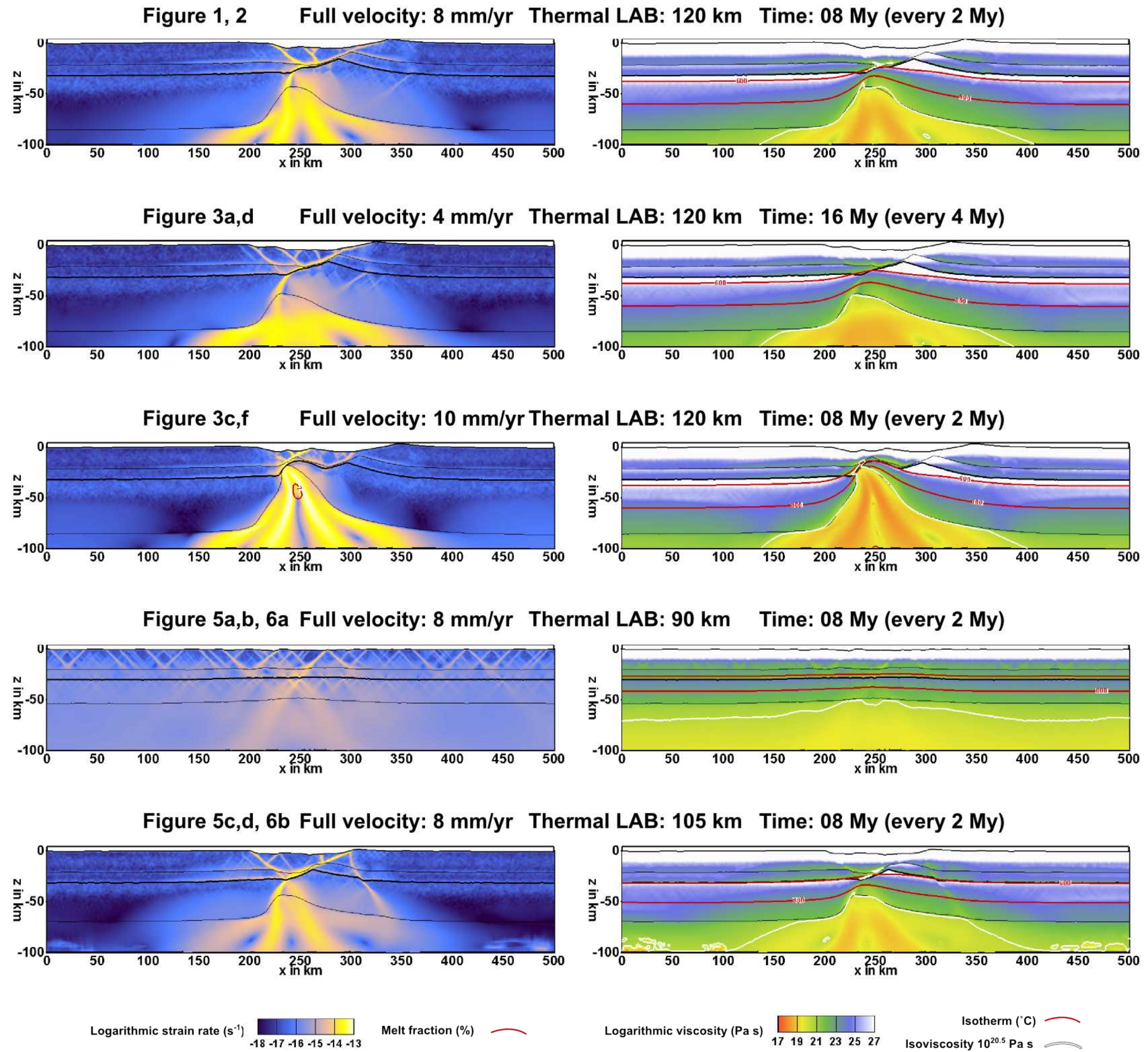


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 08 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 16 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 08 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 08 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 08 My (every 2 My)
z in km
x in km
Logarithmic strain rate (s-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

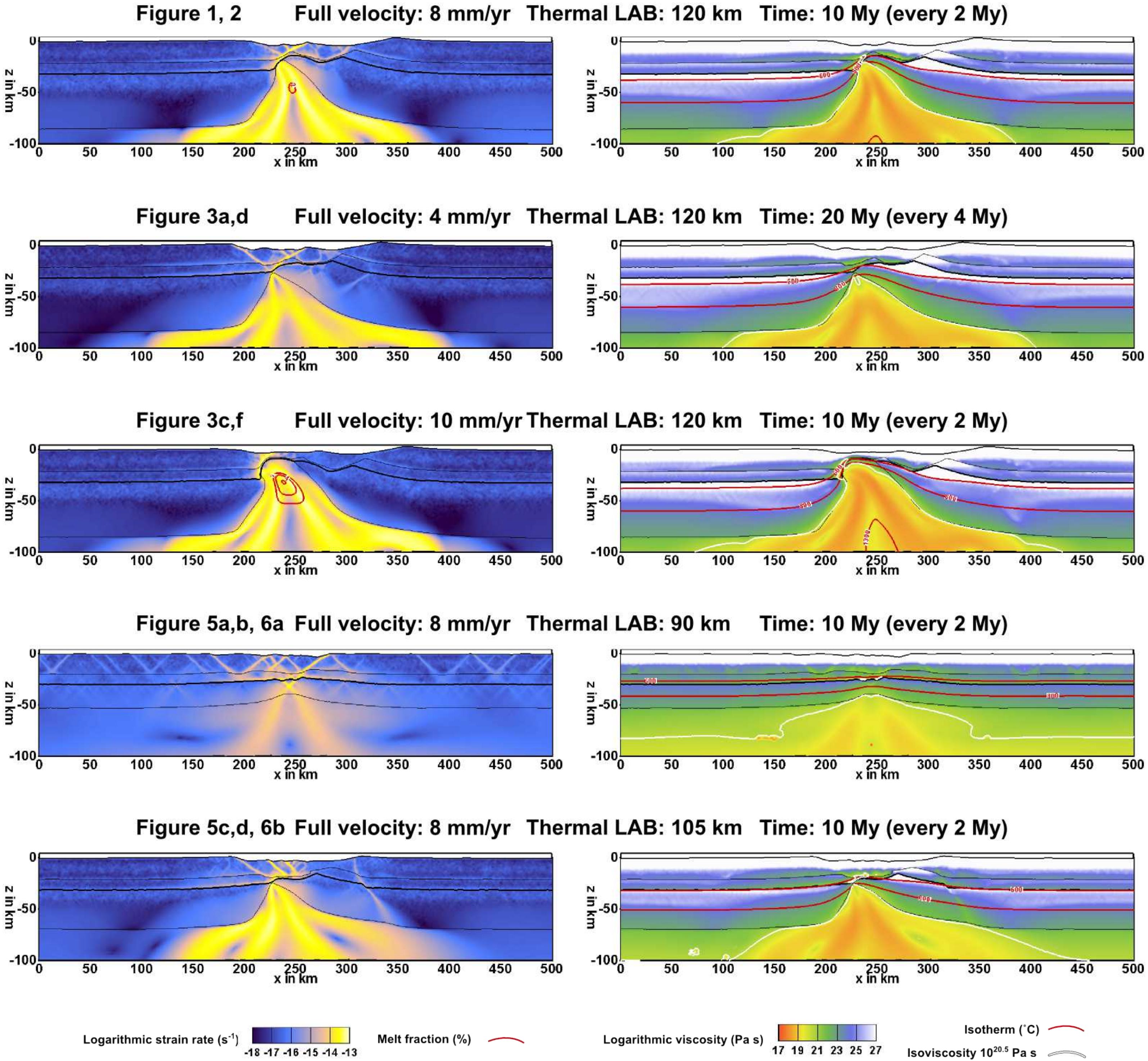


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 10 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 20 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 10 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 10 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 10 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
600
900
1300
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity $10^{20.5}$ Pa s

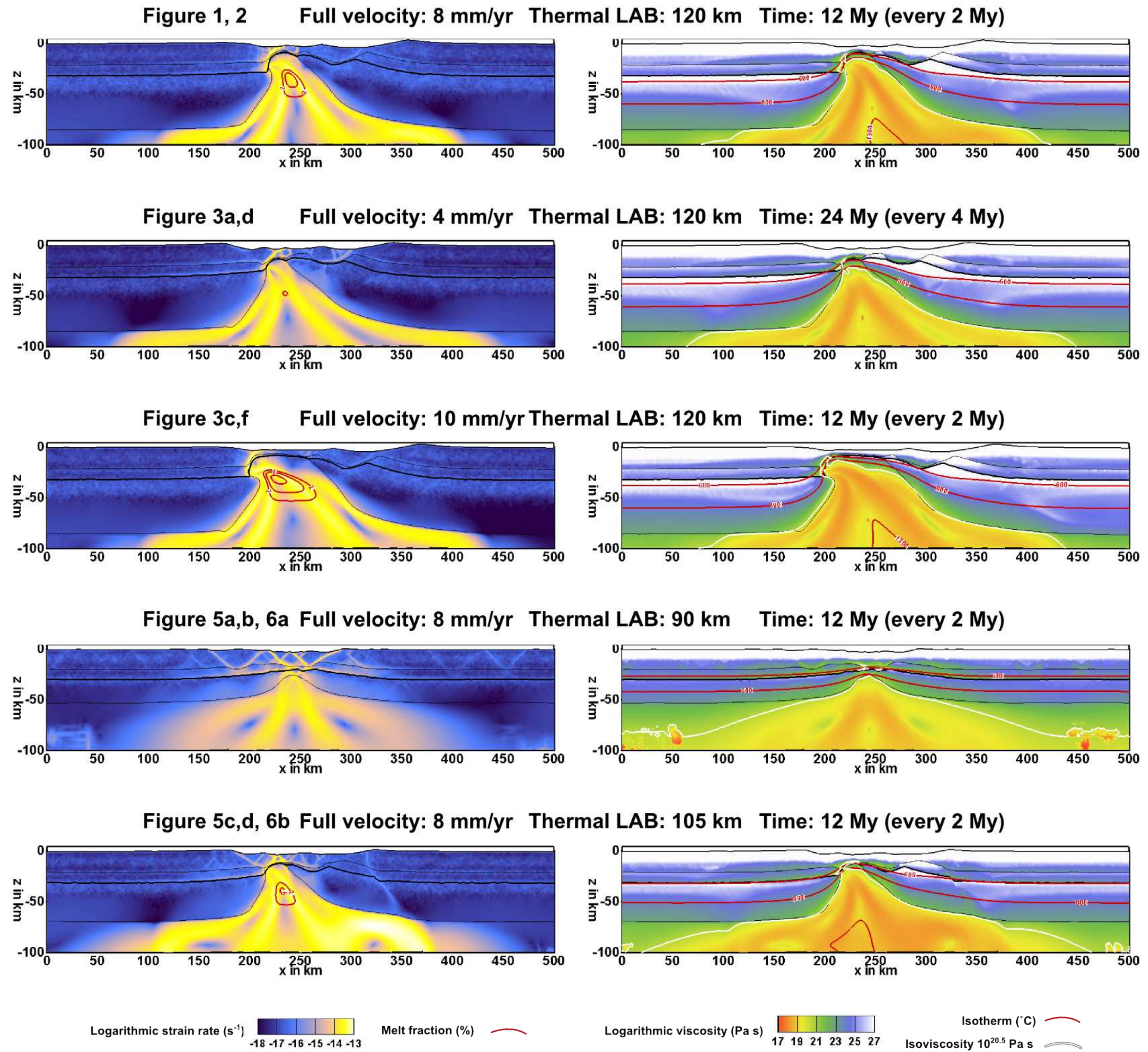


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 12 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 24 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 12 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 12 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 12 My (every 2 My)
z in km
x in km
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (°C)
Isoviscosity $10^{20.5}$ Pa s

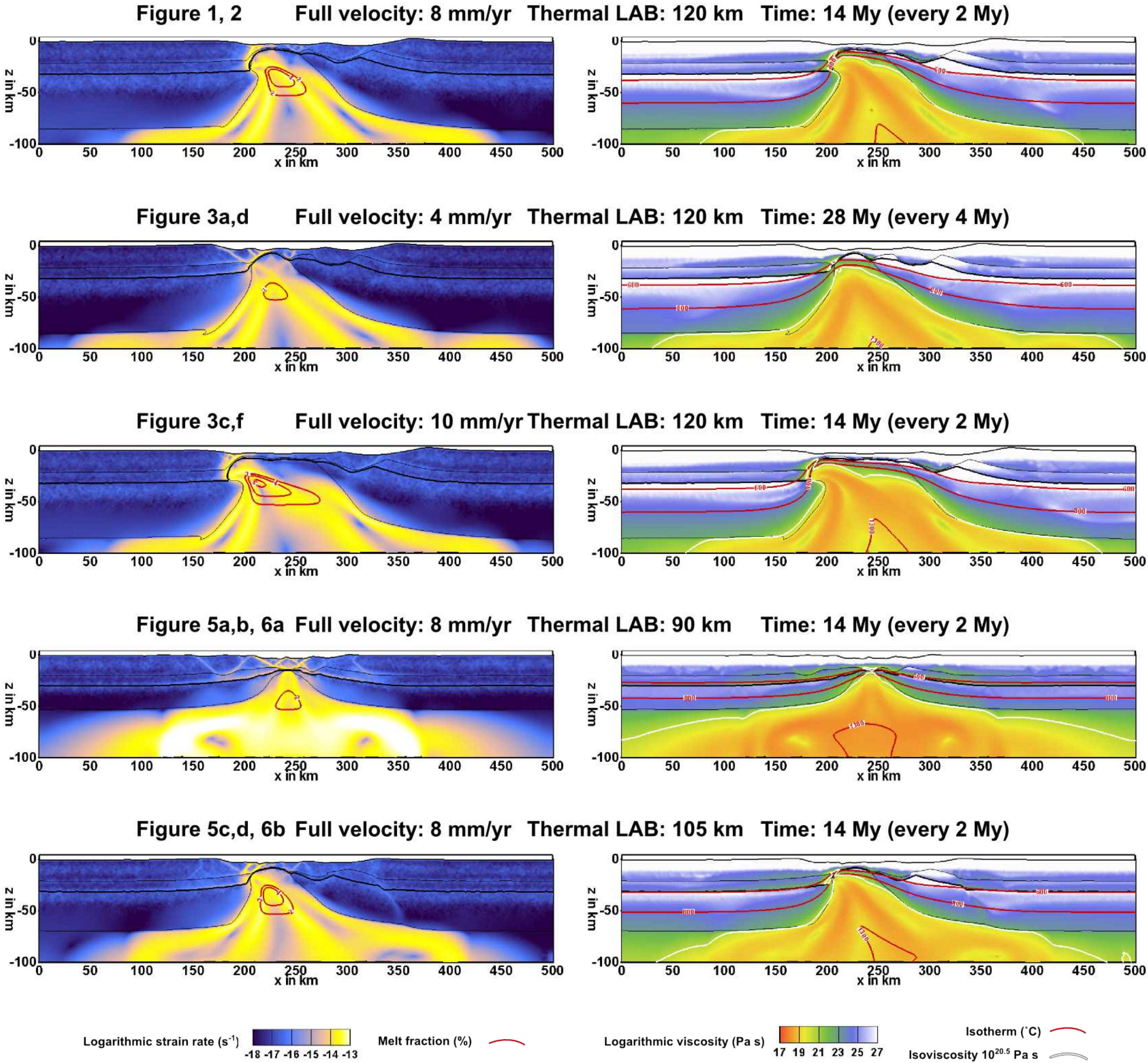


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 14 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 28 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 14 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 14 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 14 My (every 2 My)
z in km
x in km
Logarithmic strain rate (s⁻¹)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (°C)
Isoviscosity 10^20.5 Pa s

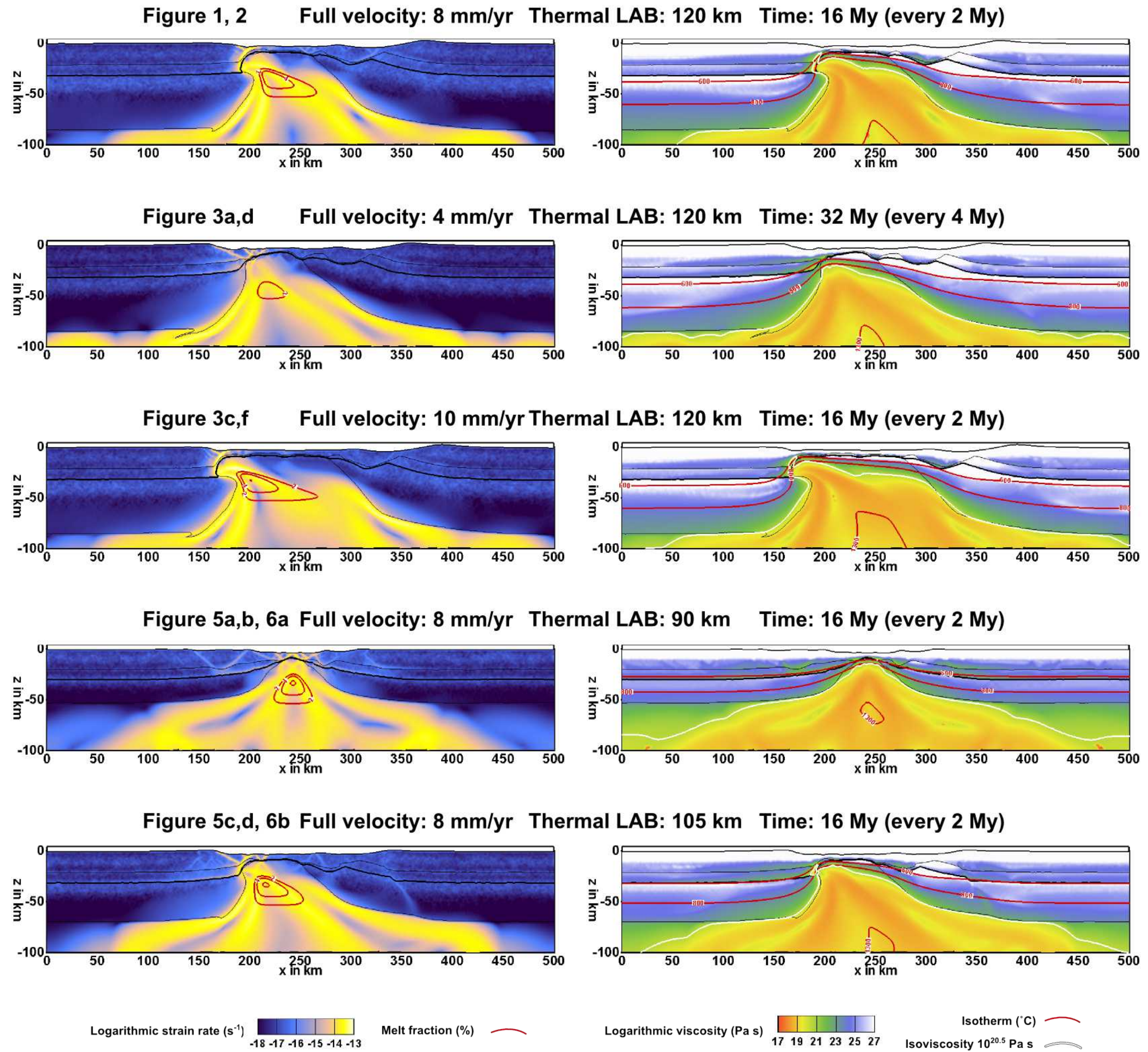


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 16 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 32 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 16 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 16 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 16 My (every 2 My)
z in km
x in km
Logarithmic strain rate (s^-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

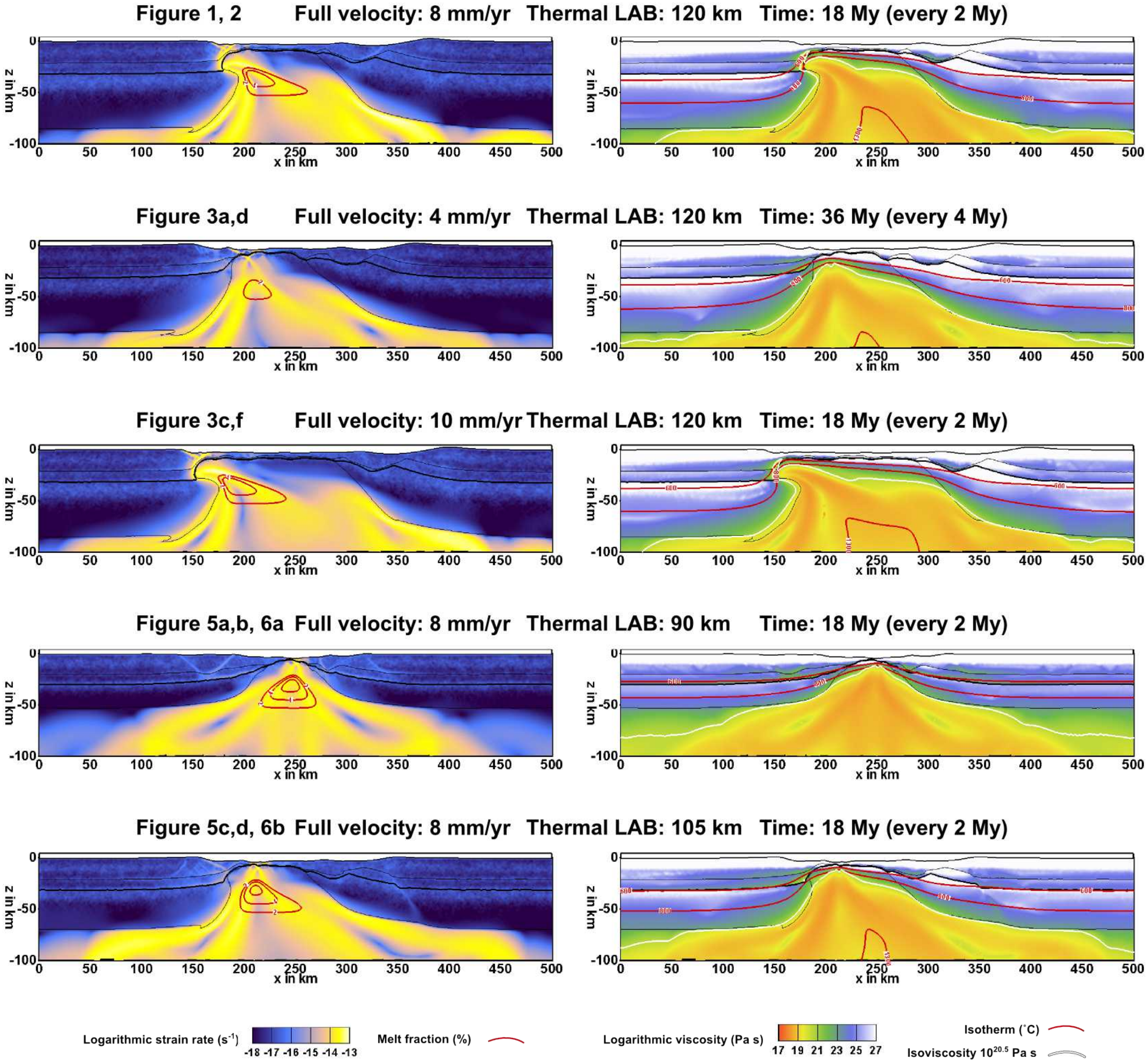


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 18 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 36 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 18 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 18 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 18 My (every 2 My)
z in km
x in km
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (°C)
Isoviscosity $10^{20.5}$ Pa s

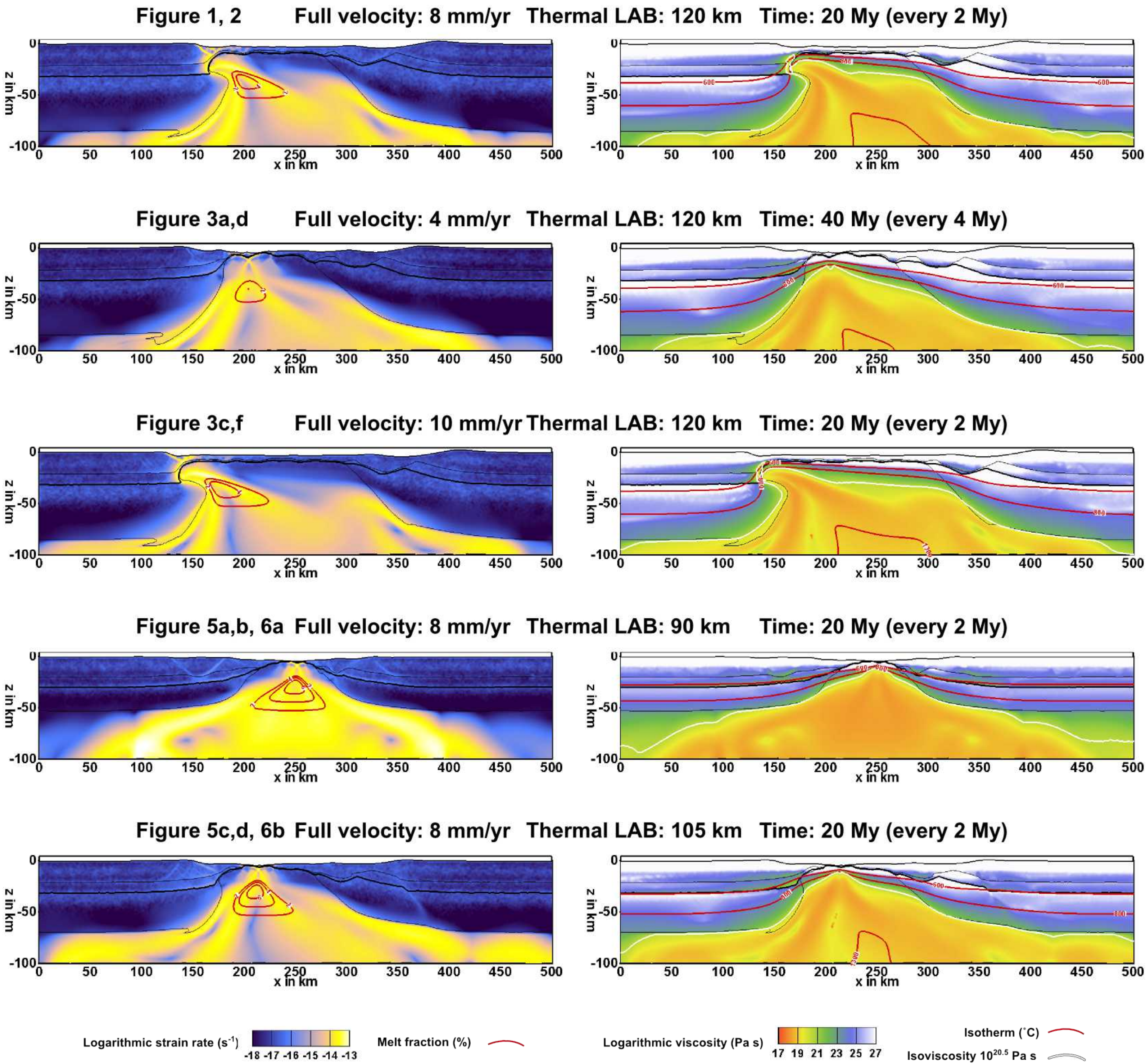


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 20 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 40 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 20 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 20 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 20 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
600
800
1300
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10$^{20.5}$ Pa s

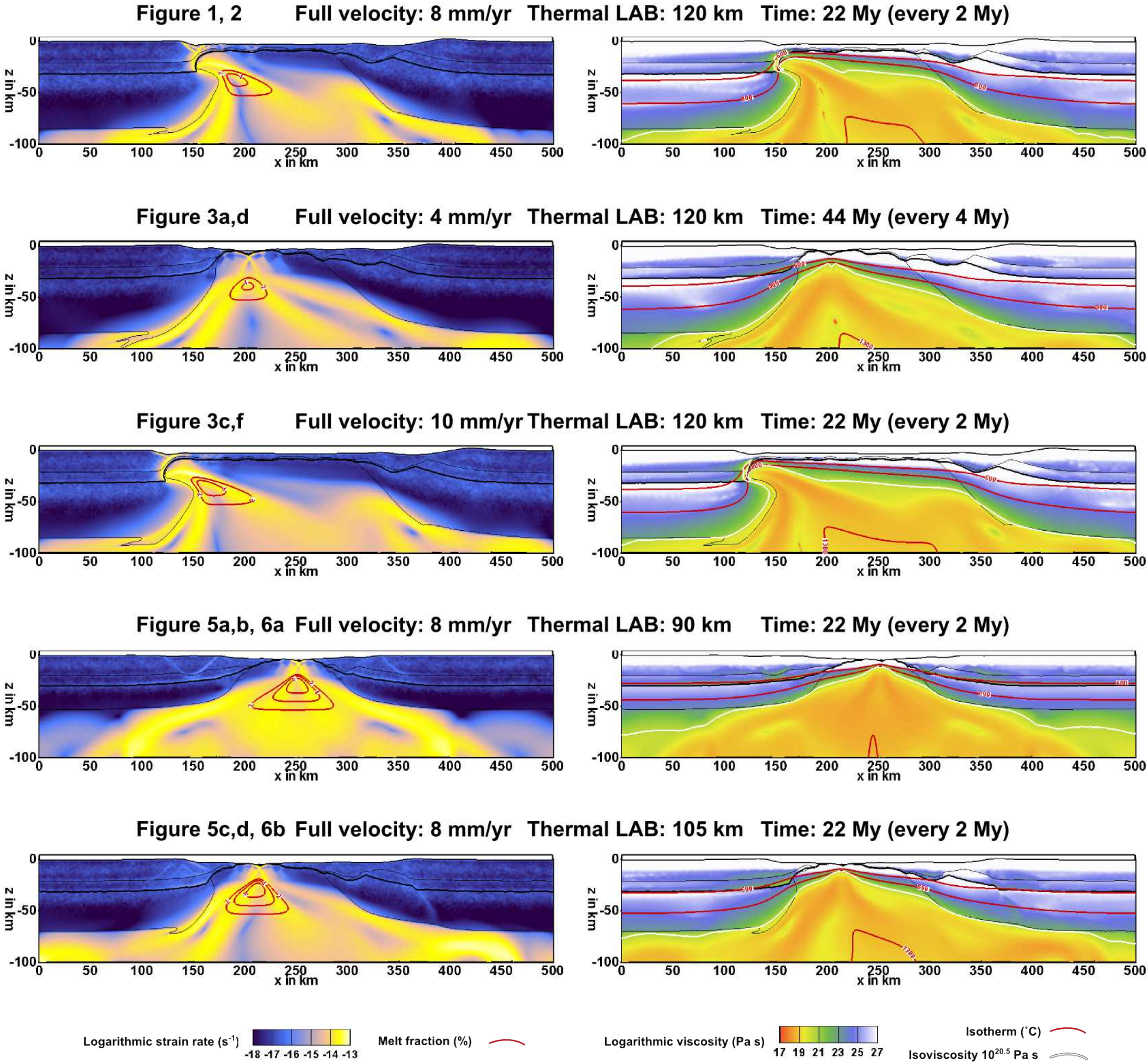


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 22 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 44 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 22 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 22 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 22 My (every 2 My)
z in km
x in km
Logarithmic strain rate (s⁻¹)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

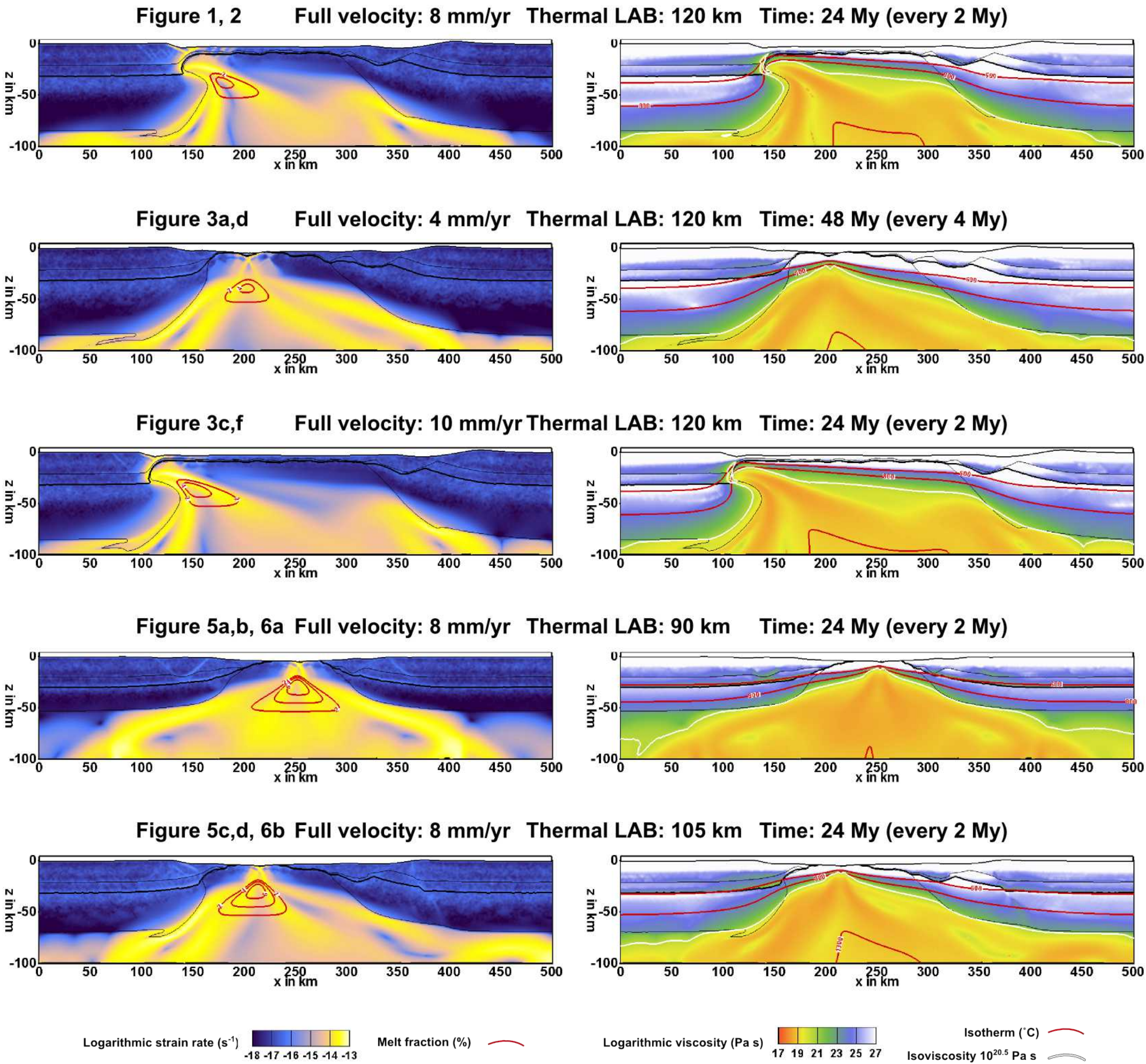


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 24 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 48 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 24 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 24 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 24 My (every 2 My)
z in km
x in km
Logarithmic strain rate (s⁻¹)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

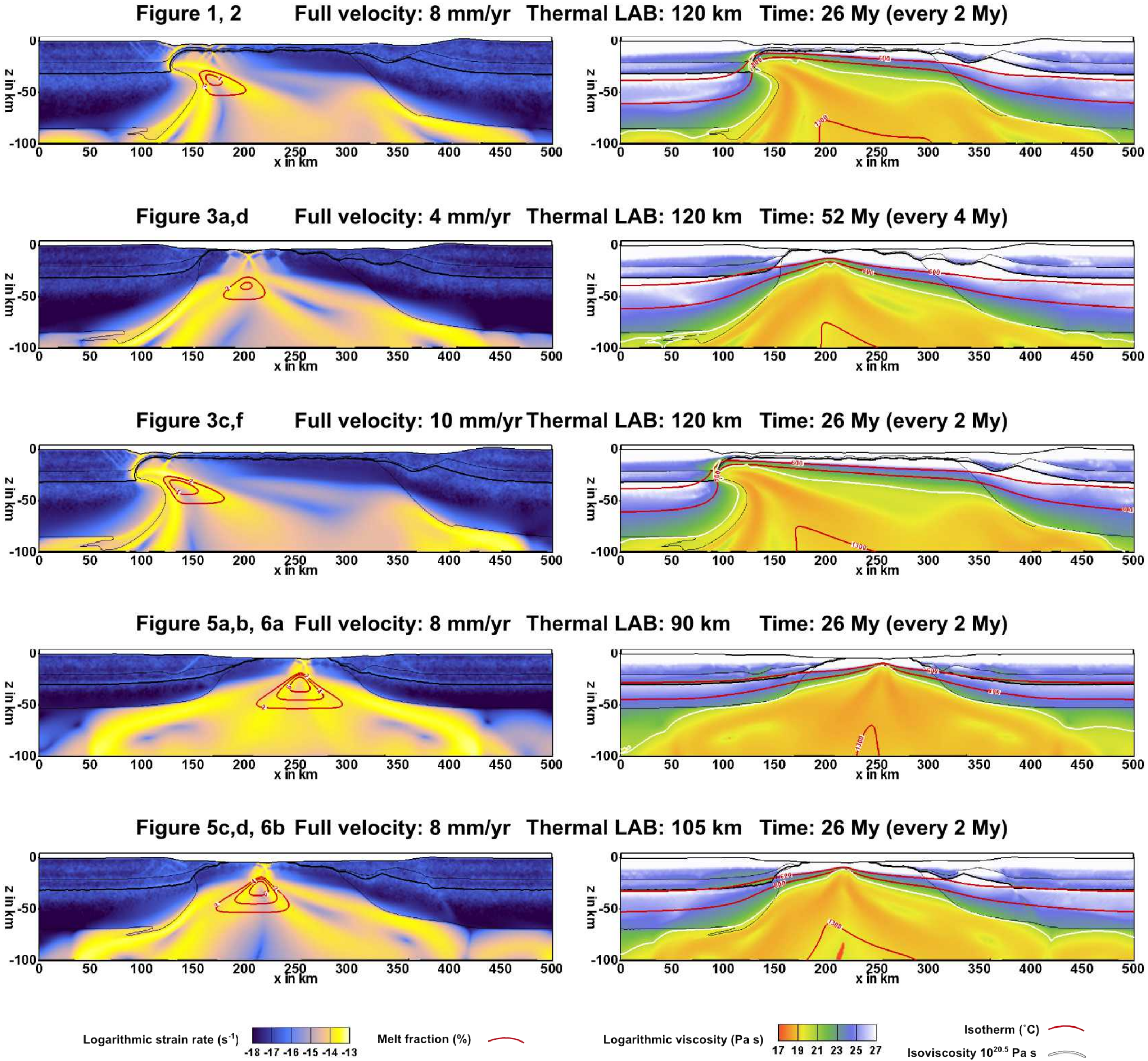


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 26 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 52 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 26 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 26 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 26 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity $10^{20.5}$ Pa s

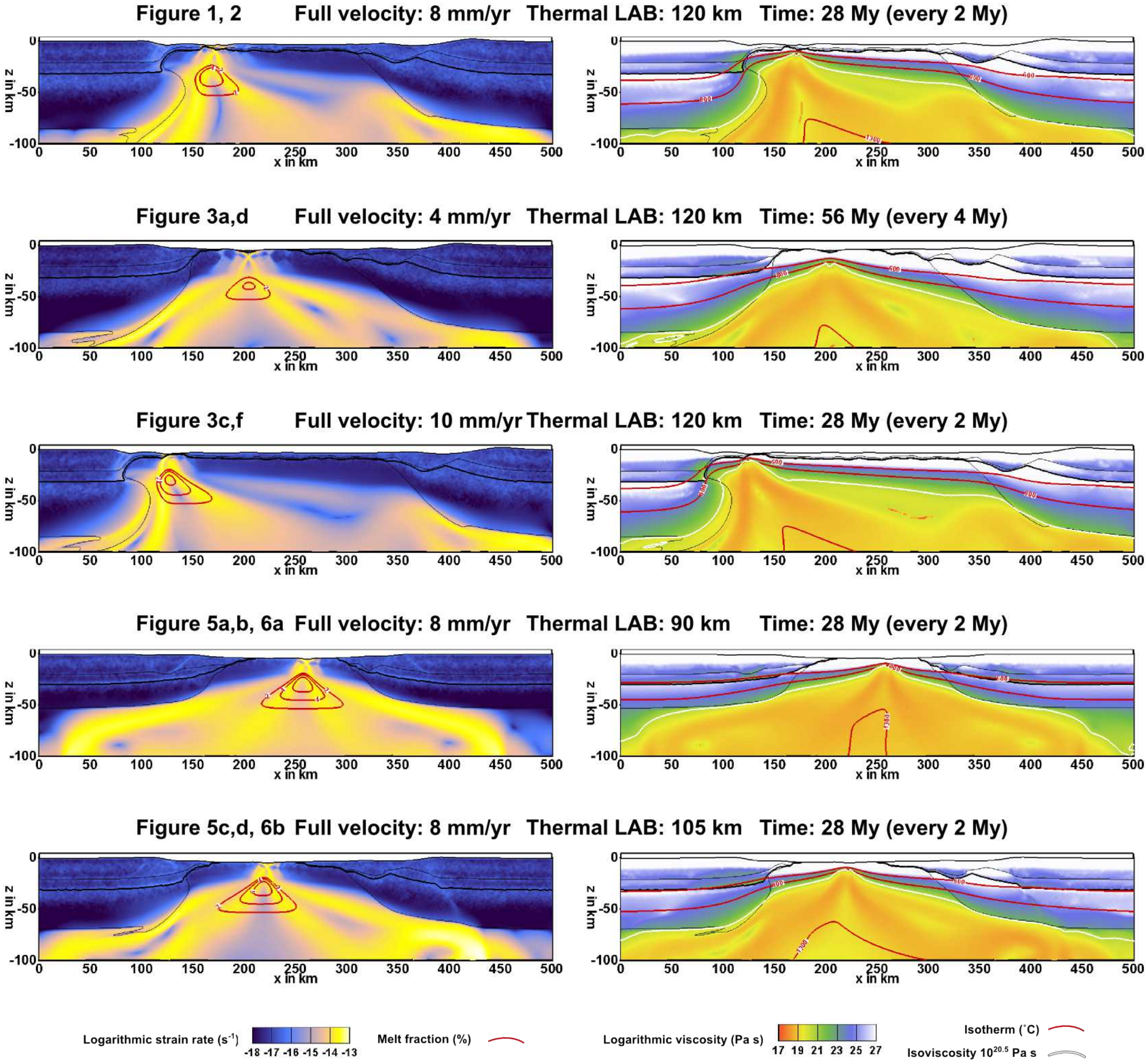


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 28 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 56 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 28 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 28 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 28 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity $10^{20.5}$ Pa s

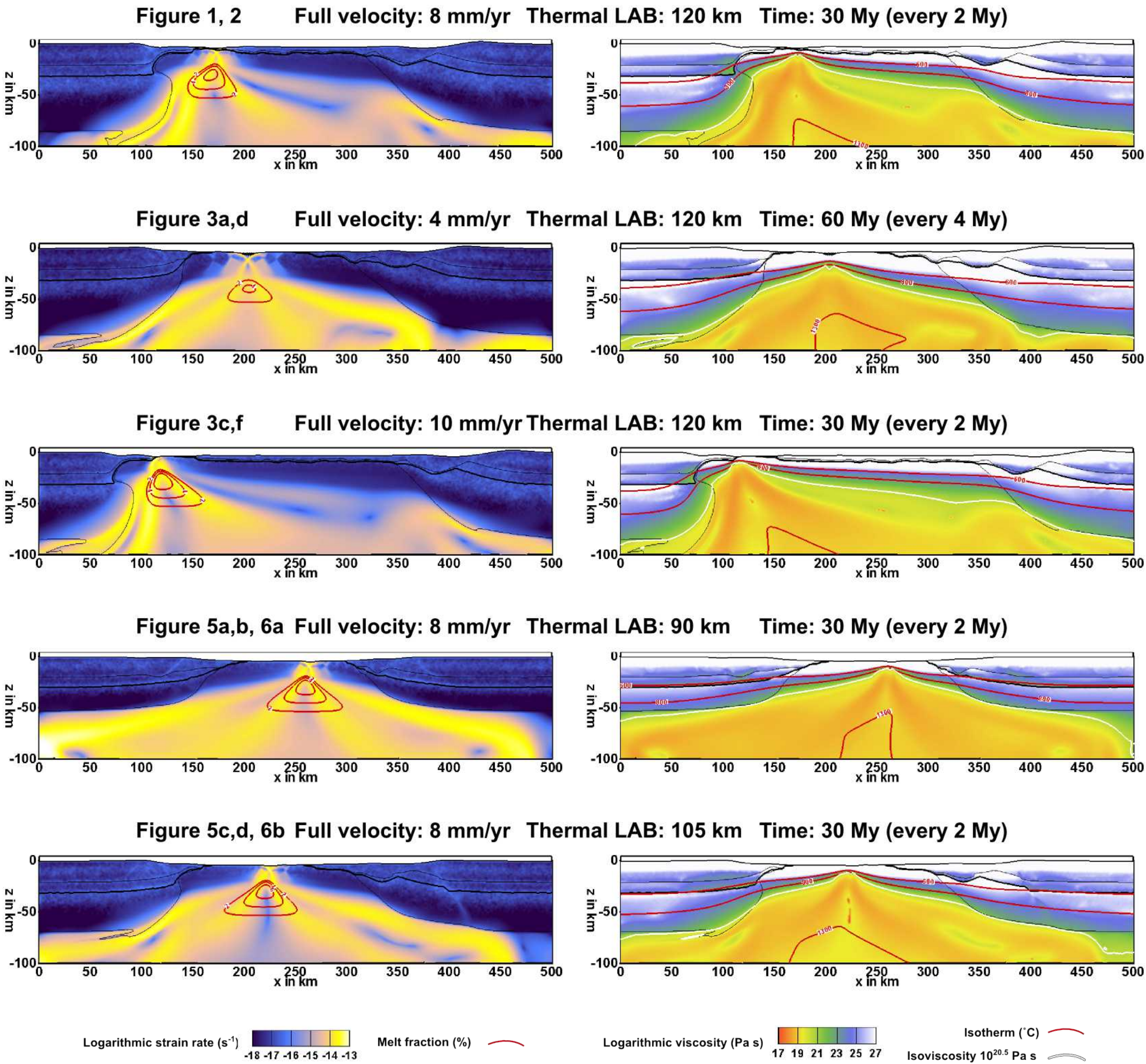


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 30 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 60 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 30 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 30 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 30 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
Logarithmic strain rate (s⁻¹)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

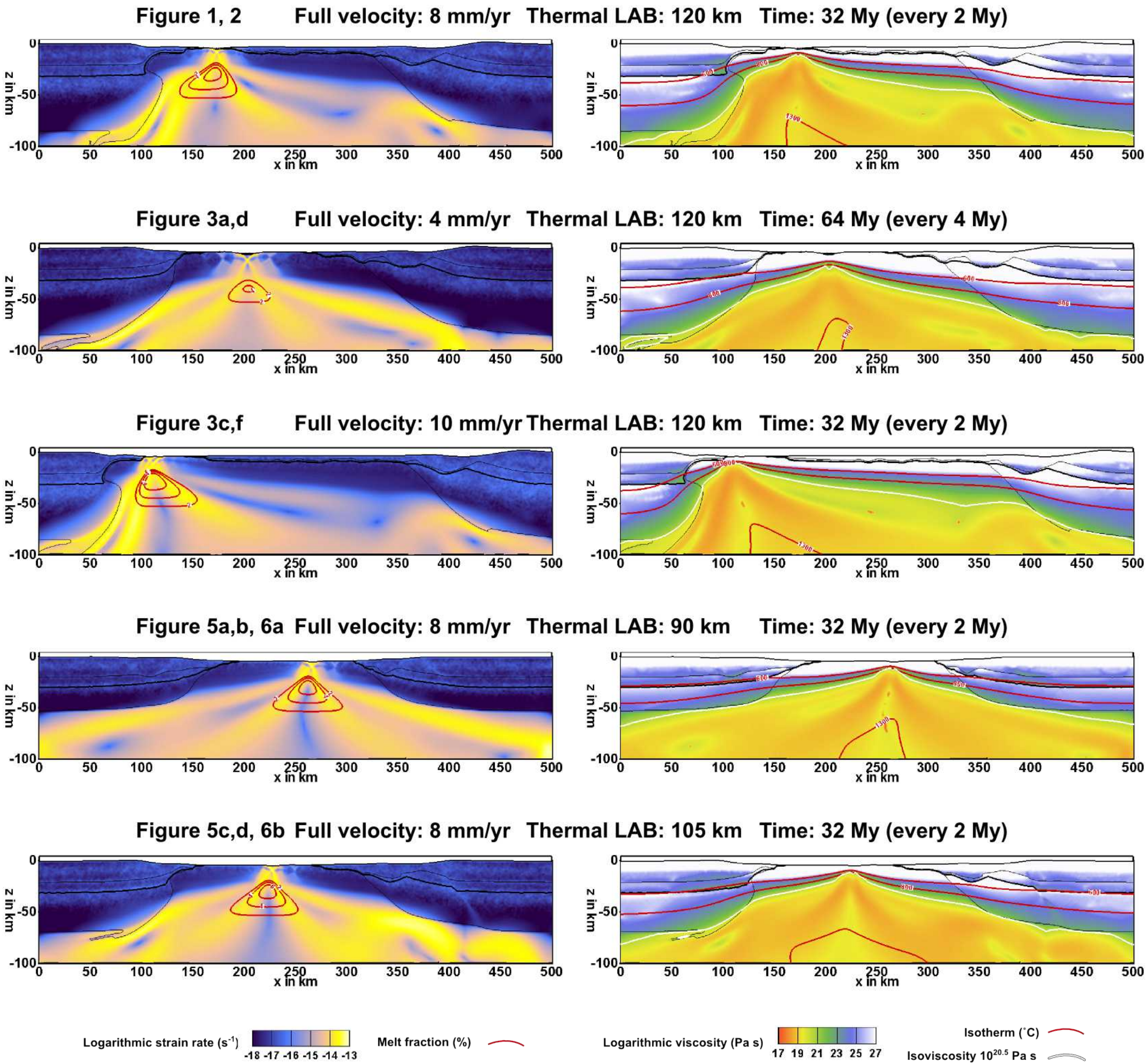


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 32 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 64 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 32 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 32 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 32 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity $10^{20.5}$ Pa s

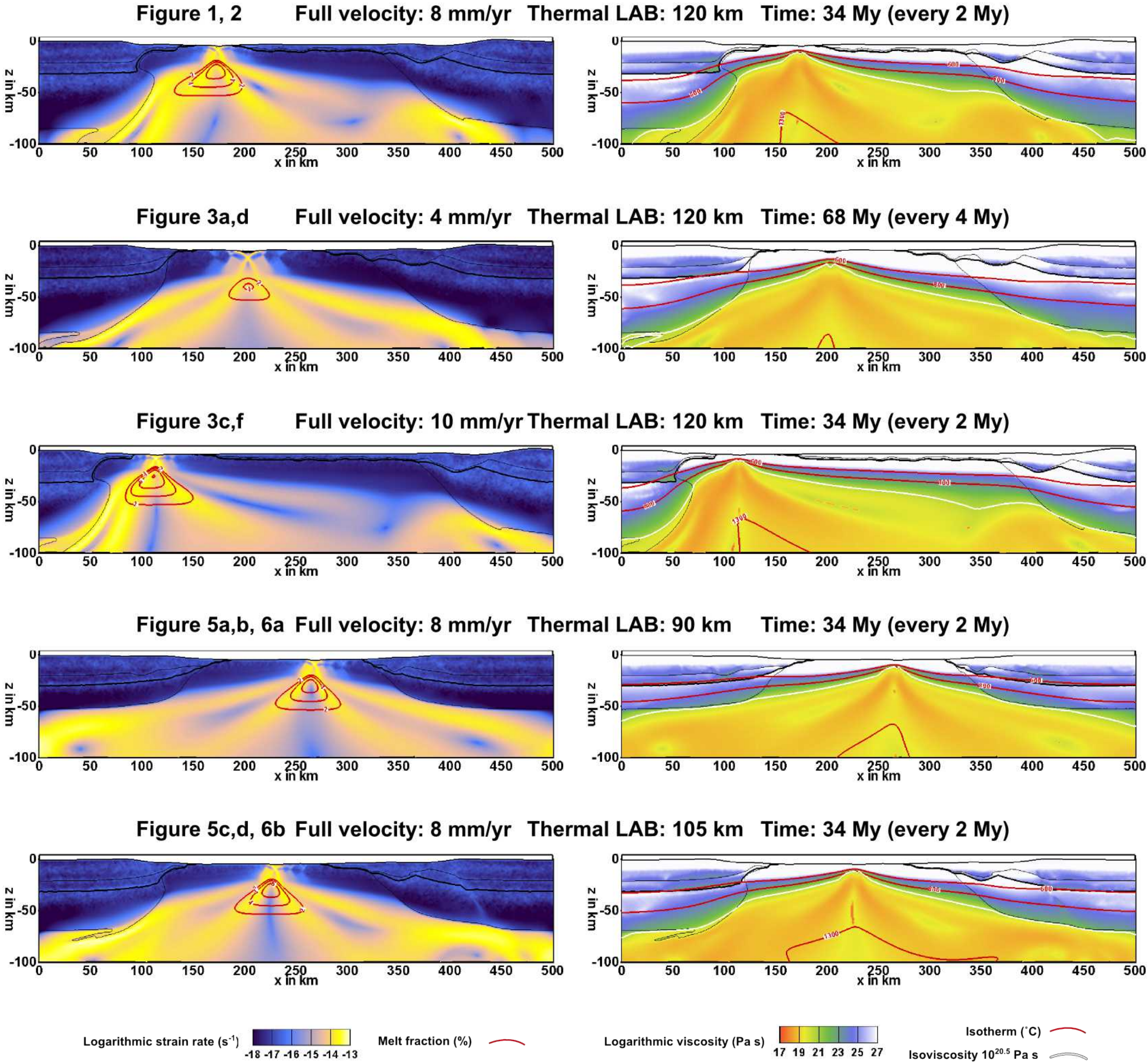


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 34 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 68 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 34 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 34 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 34 My (every 2 My)
z in km
x in km
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity $10^{20.5}$ Pa s

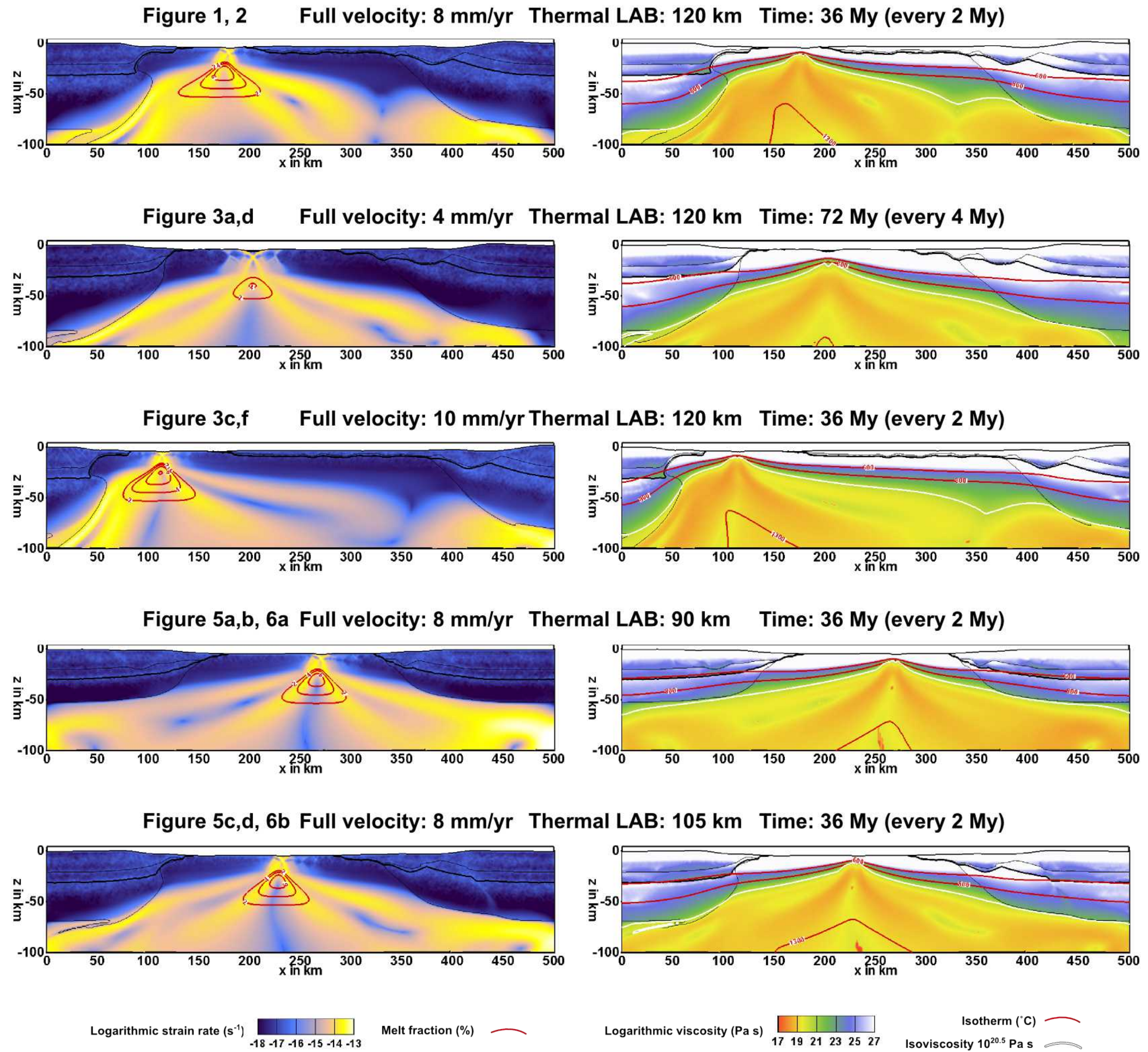


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 36 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 72 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 36 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 36 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 36 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
600
900
1300
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (°C)
Isoviscosity $10^{20.5}$ Pa s

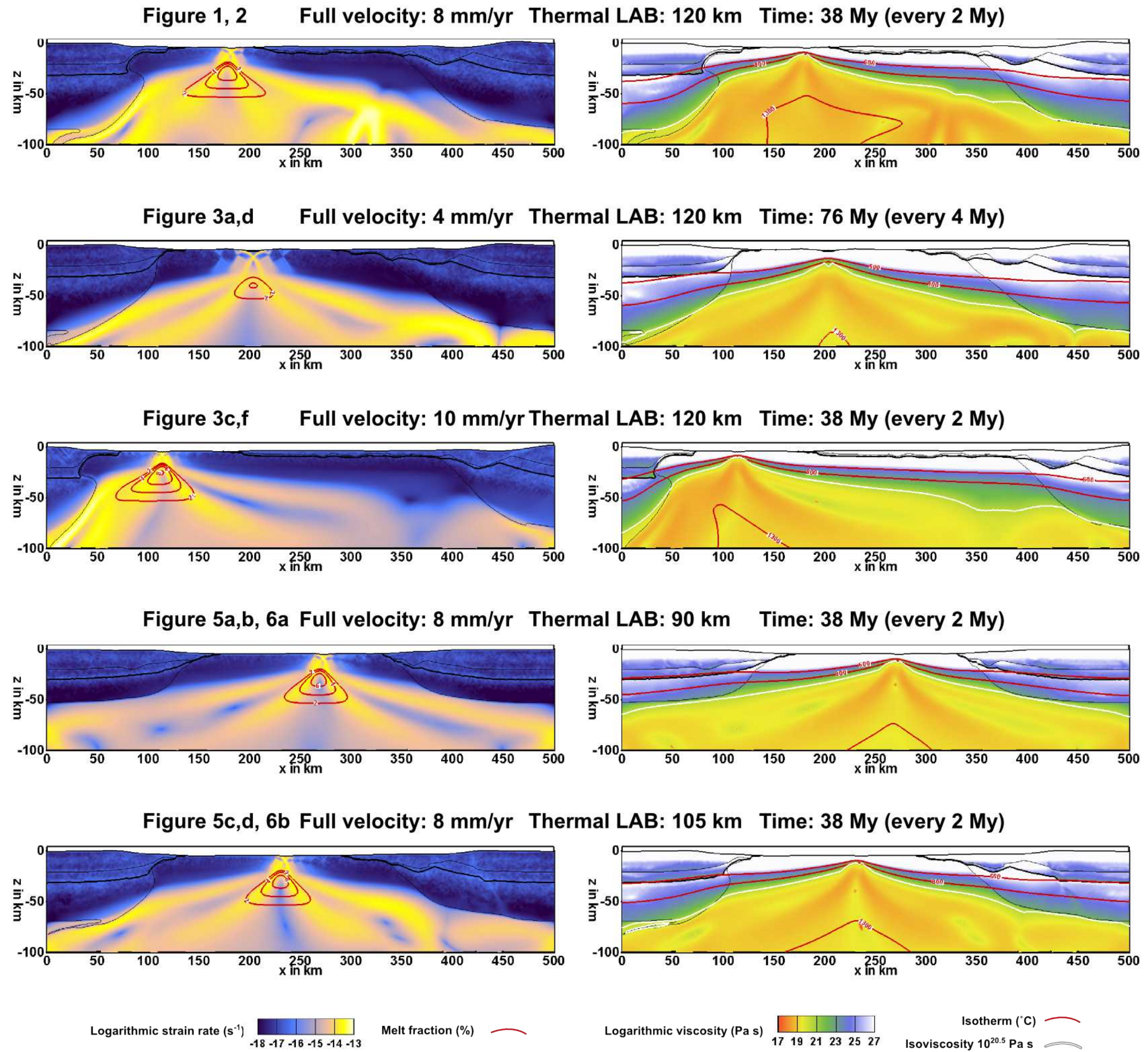


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 38 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 76 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 38 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 38 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 38 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
Logarithmic strain rate (s-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

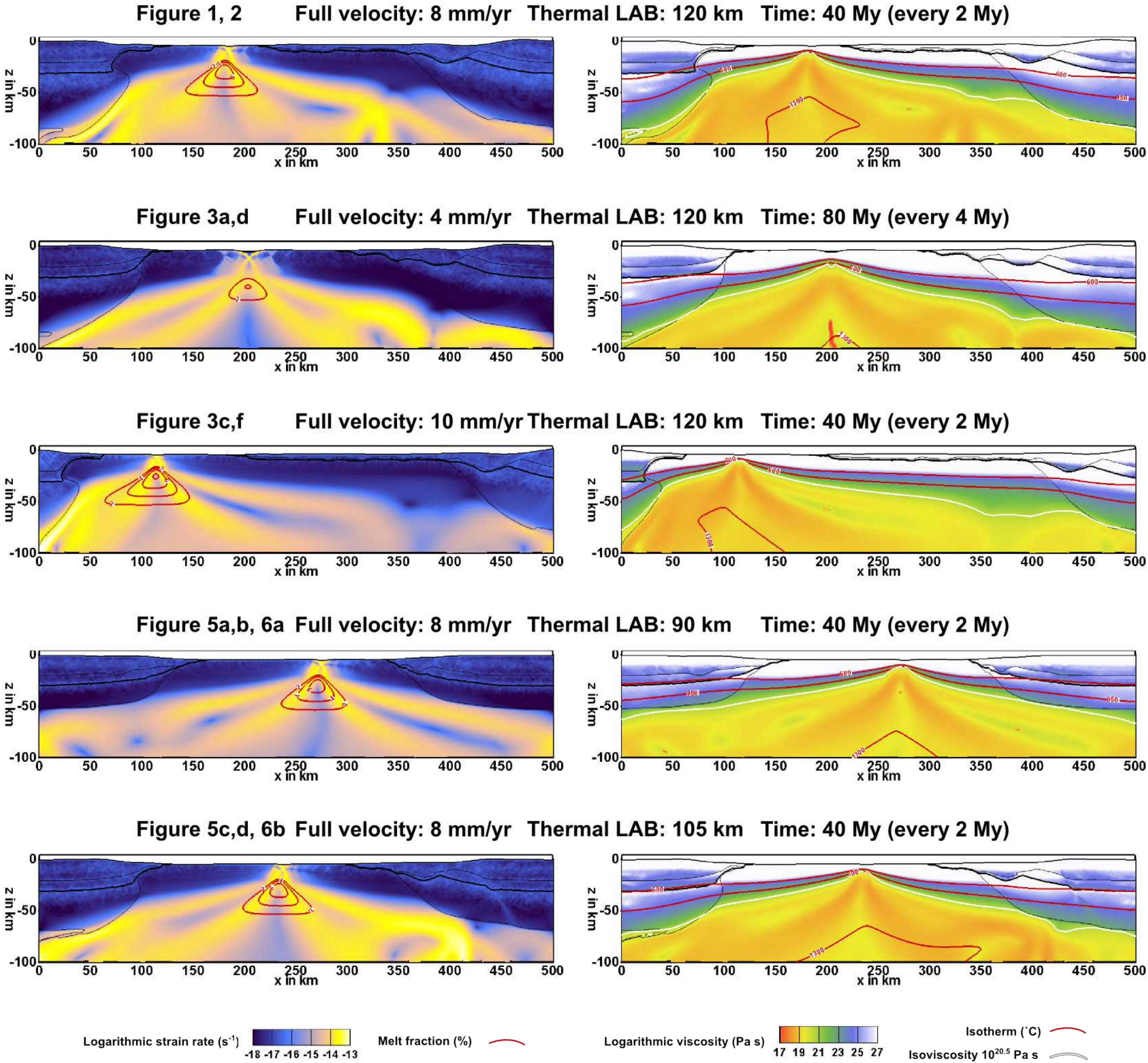
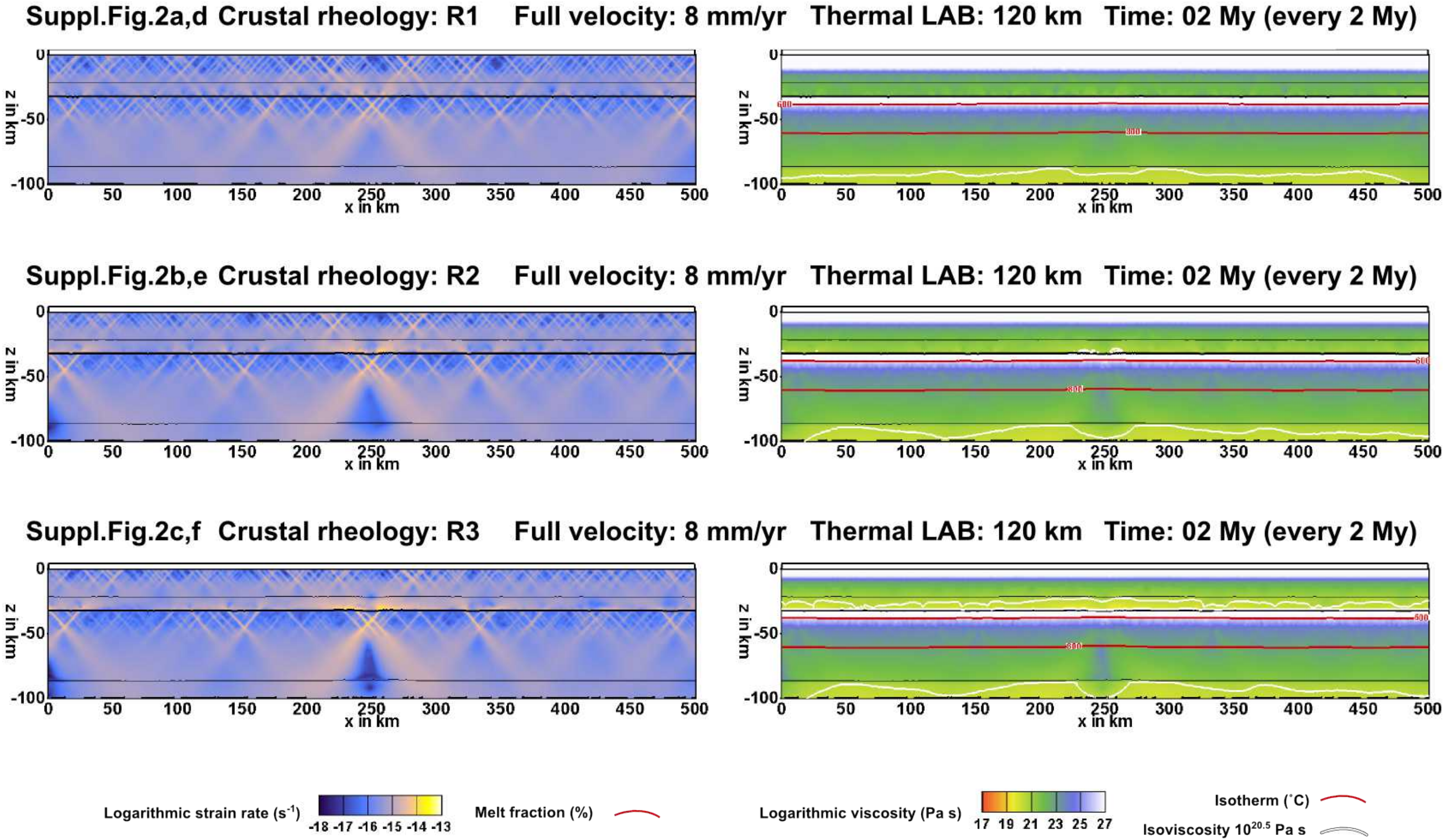
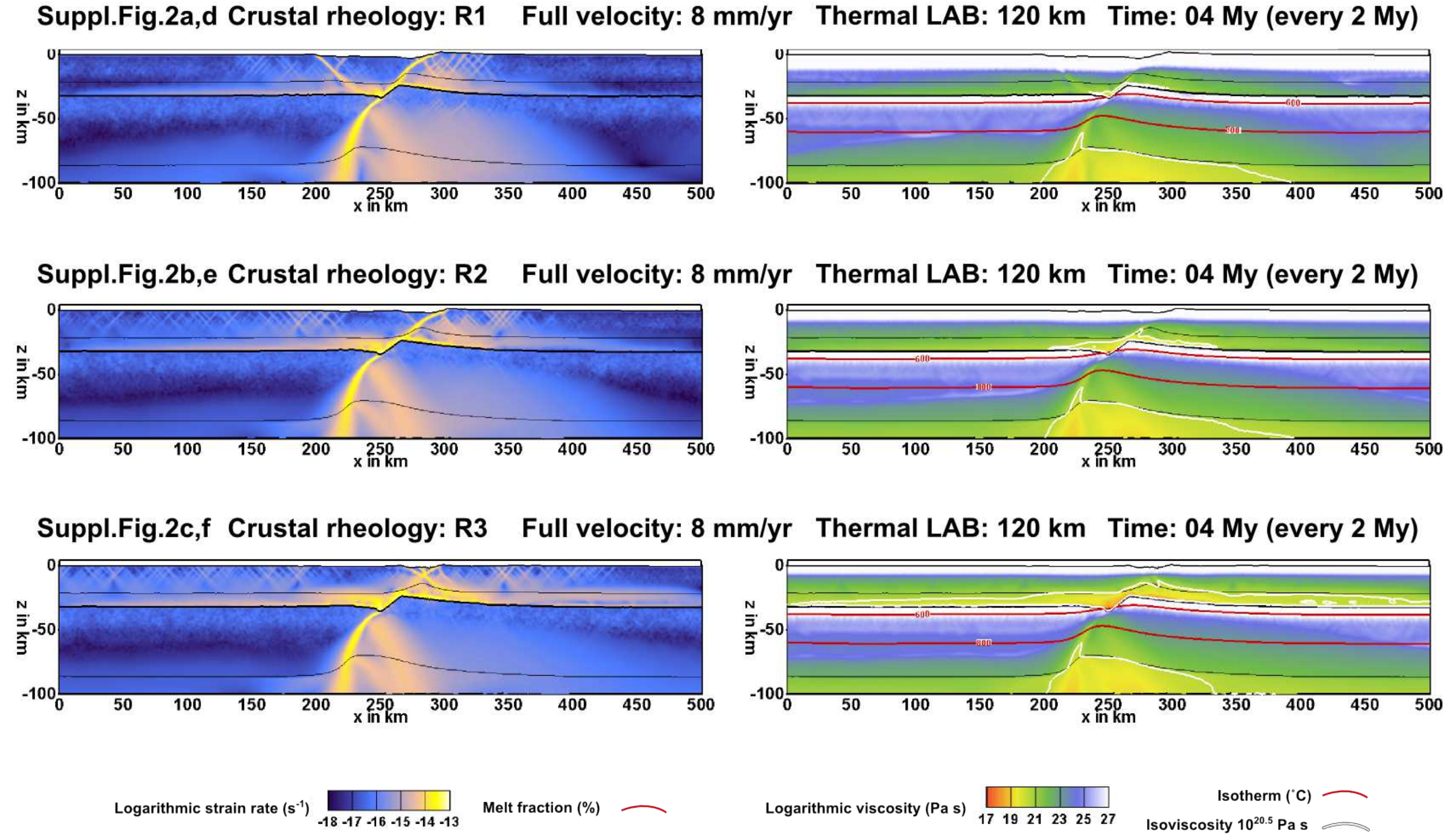


Figure 1, 2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 40 My (every 2 My)
Figure 3a,d Full velocity: 4 mm/yr Thermal LAB: 120 km Time: 80 My (every 4 My)
Figure 3c,f Full velocity: 10 mm/yr Thermal LAB: 120 km Time: 40 My (every 2 My)
Figure 5a,b, 6a Full velocity: 8 mm/yr Thermal LAB: 90 km Time: 40 My (every 2 My)
Figure 5c,d, 6b Full velocity: 8 mm/yr Thermal LAB: 105 km Time: 40 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
600
1300
Logarithmic strain rate (s^-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (°C)
Isoviscosity 10^20.5 Pa s

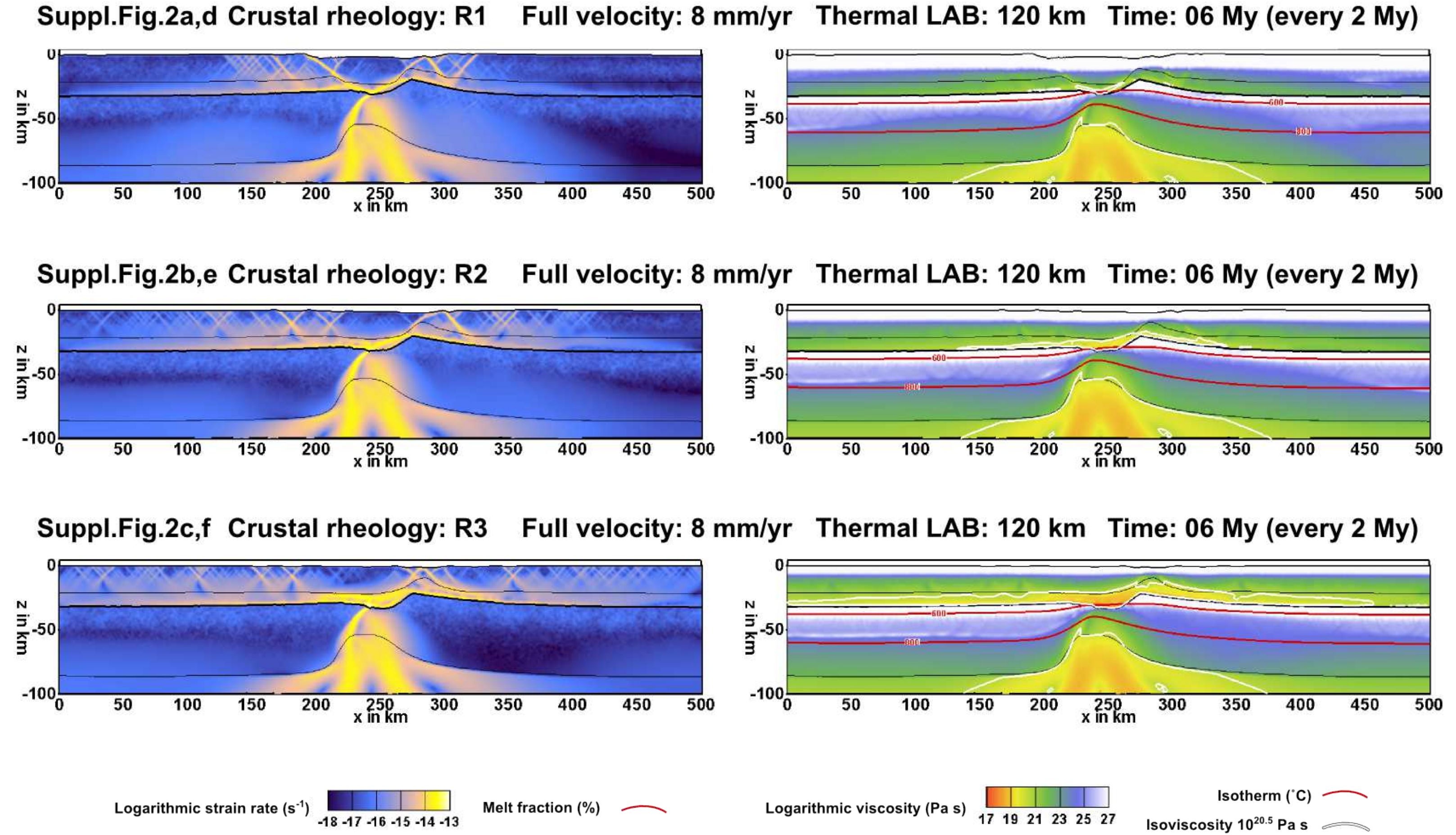
Supplementary Figure 3

Detailed evolution of models shown in Fig. 1-6. *The left panel shows logarithmic strain rate, melt fraction (red contours), and material boundaries (black lines). The right panel depicts logarithmic viscosity, 600 °C and 800 °C isotherms (red lines), the isoviscosity contour of $10^{20.5}$ Pas (white line), and material boundaries (black lines).* Grey regions where viscosity is maximal deform via brittle behaviour. *Note that velocities are varied so that the displayed model time differs.*

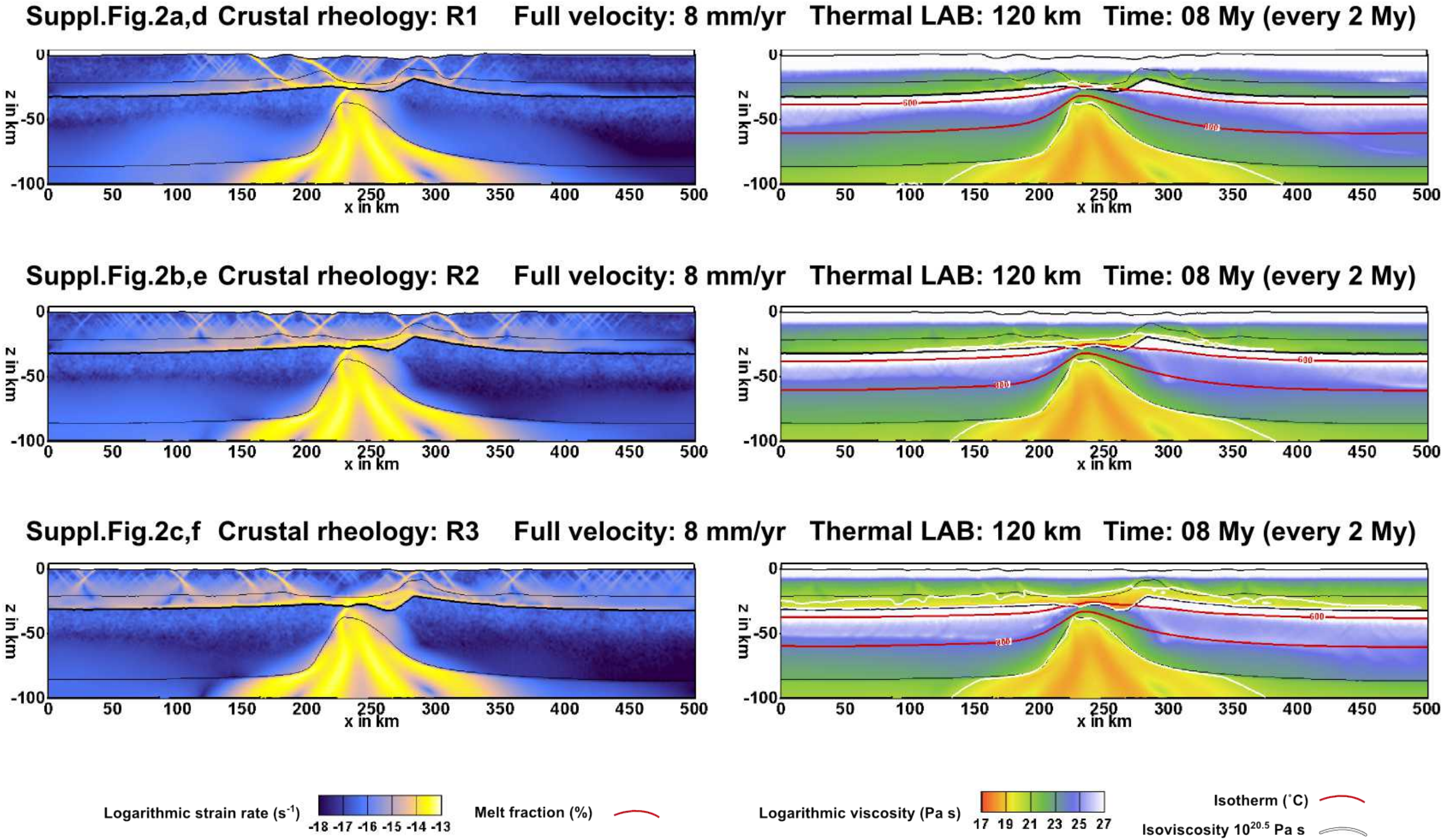

Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 02 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 02 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 02 My (every 2 My)
z in km
x in km
Logarithmic strain rate (s-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

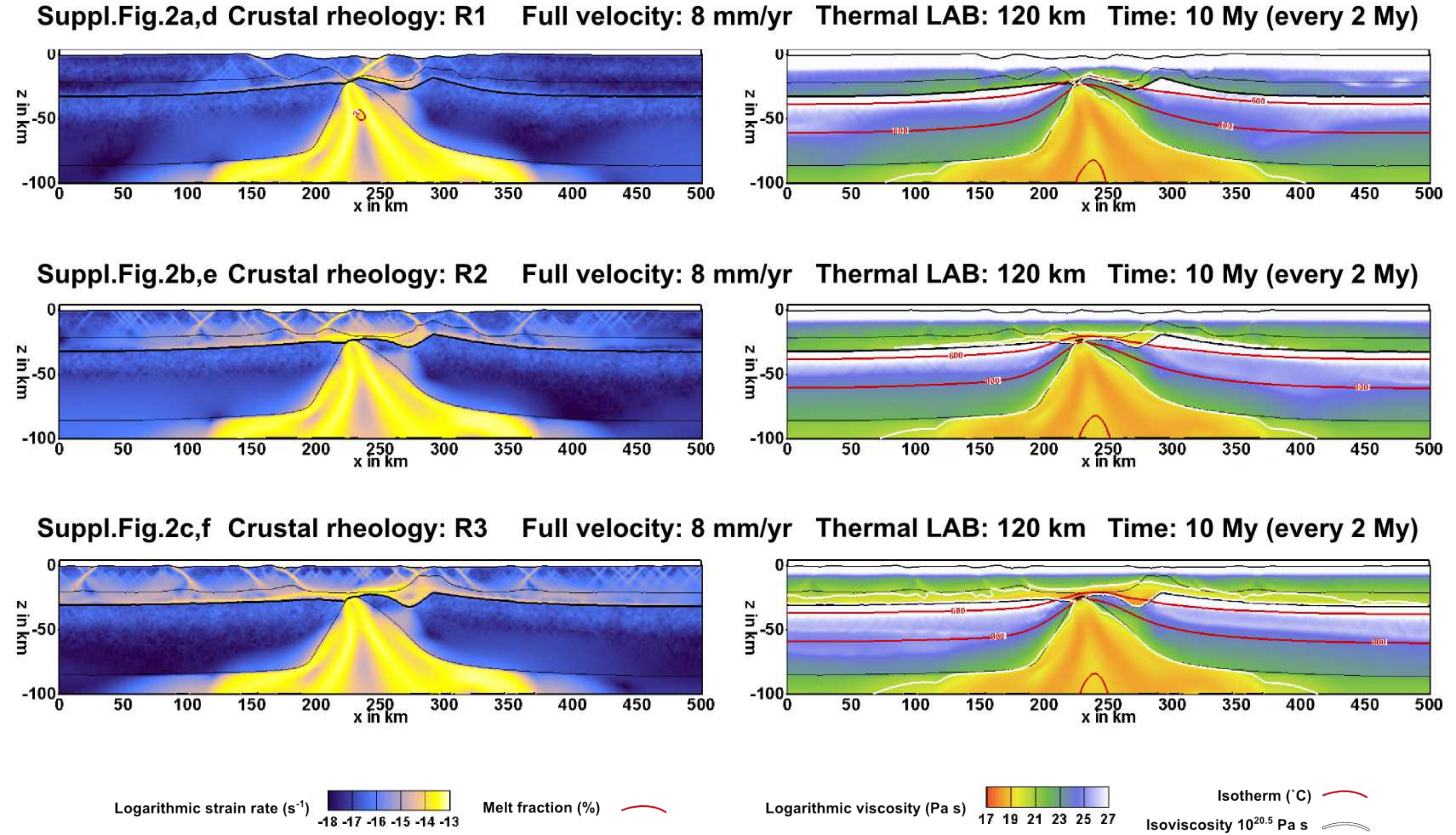


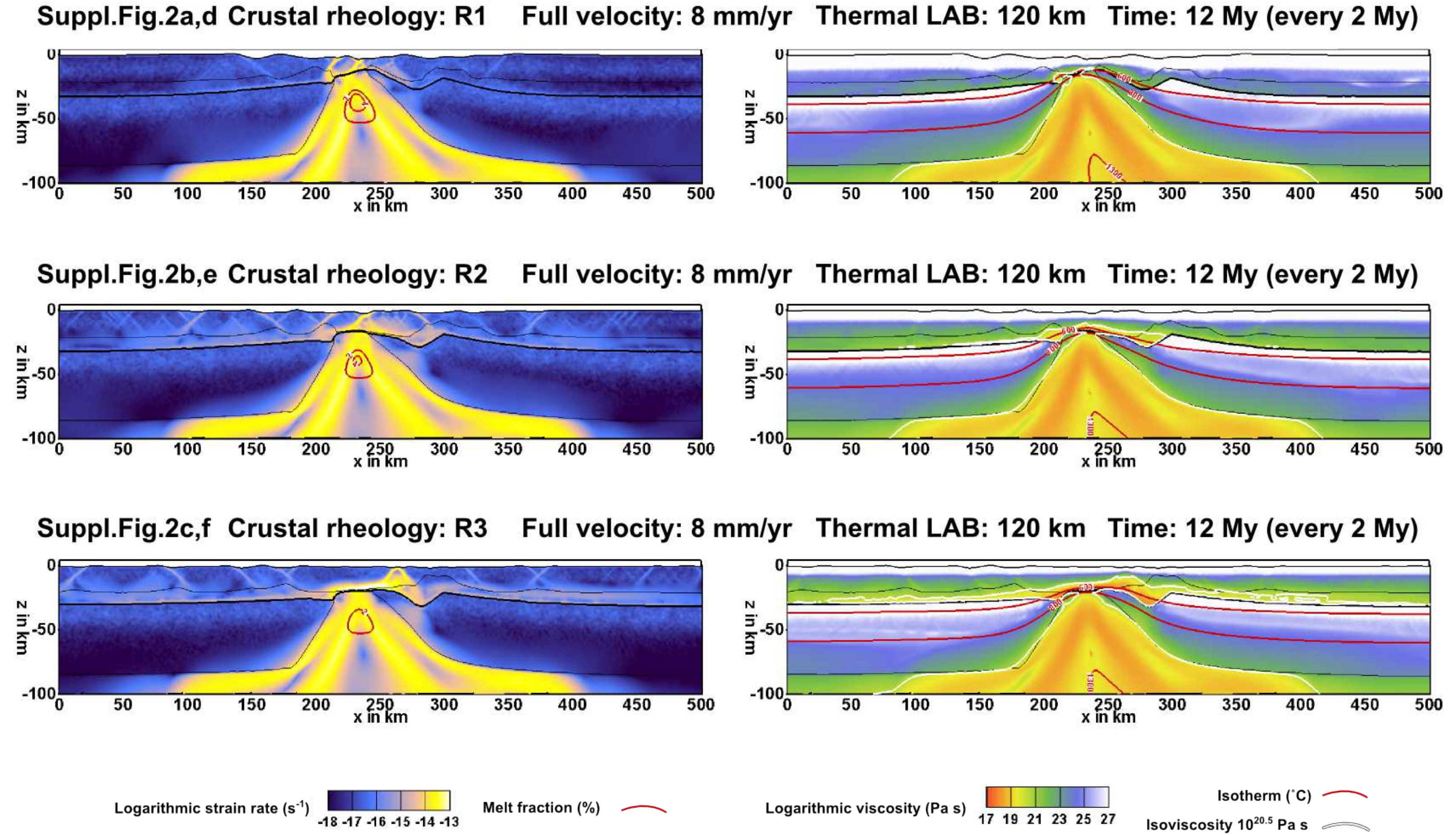
Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 04 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 04 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 04 My (every 2 My)
z in km
0
-50
-100
x in km
0 50 100 150 200 250 300 350 400 450 500
600
800
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10$^{20.5}$ Pa s

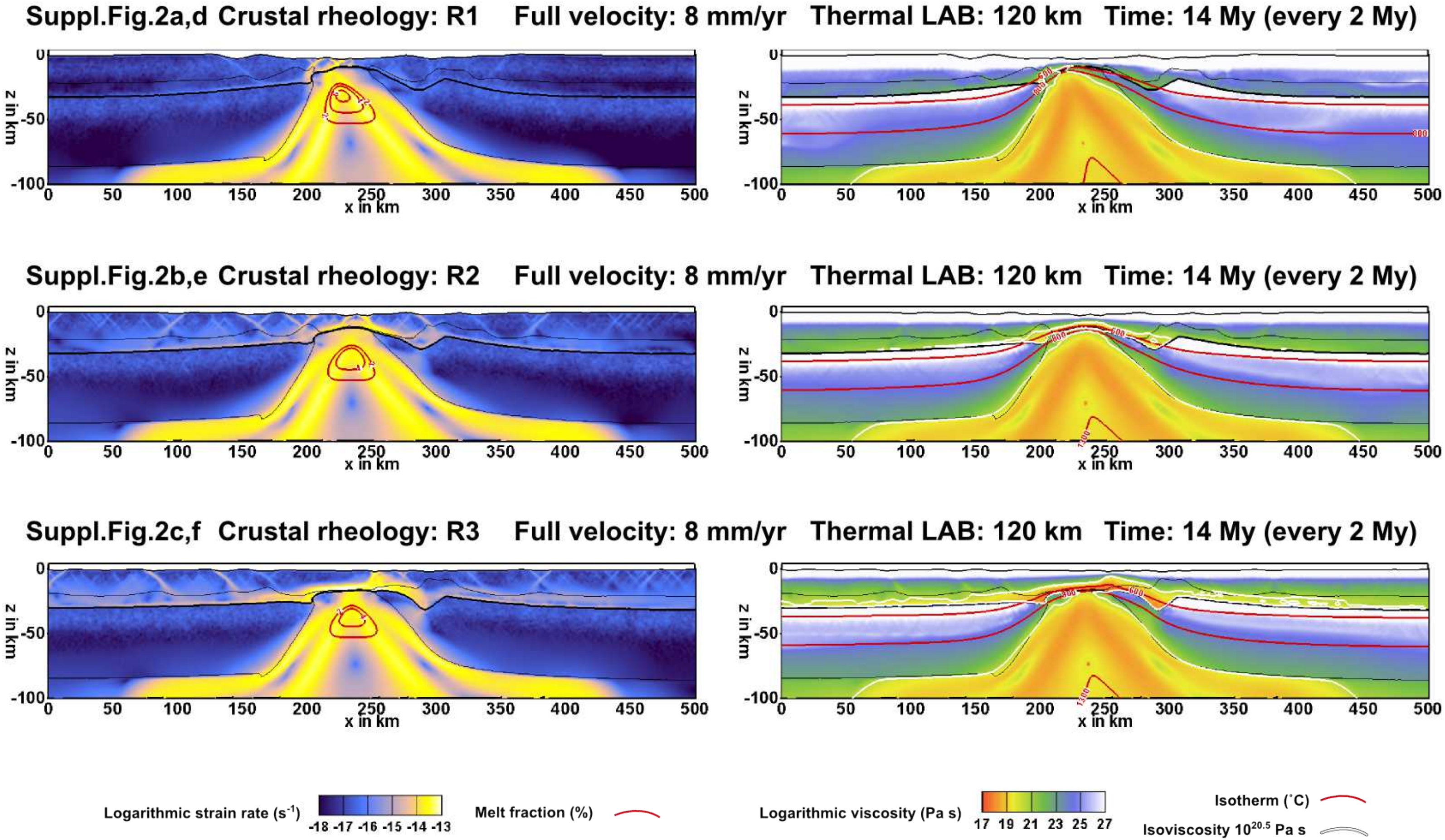


Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 06 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 06 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 06 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
600
800
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity $10^{20.5}$ Pa s

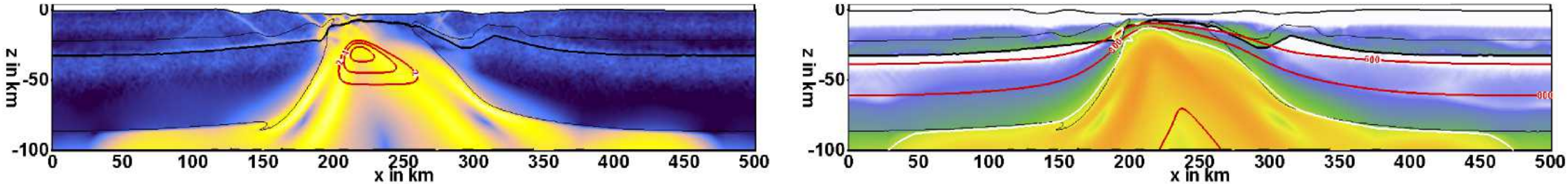

Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 08 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 08 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 08 My (every 2 My)
z in km
x in km
0
-50
-100
0
50
100
150
200
250
300
350
400
450
500
600
Logarithmic strain rate (s^-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s


Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 10 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 10 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 10 My (every 2 My)
z in km
0
-50
-100
x in km
0 50 100 150 200 250 300 350 400 450 500
600
800
Logarithmic strain rate (s^-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

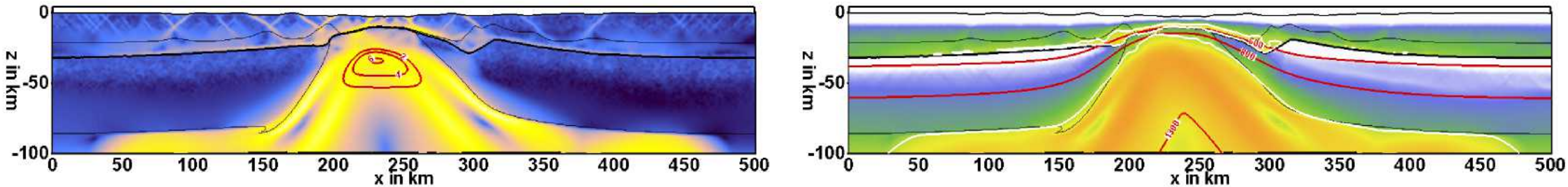

Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 12 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 12 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 12 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
600
800
1300
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity $10^{20.5}$ Pa s


Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 14 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 14 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 14 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
Logarithmic strain rate (s-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (°C)
Isoviscosity 10^20.5 Pa s

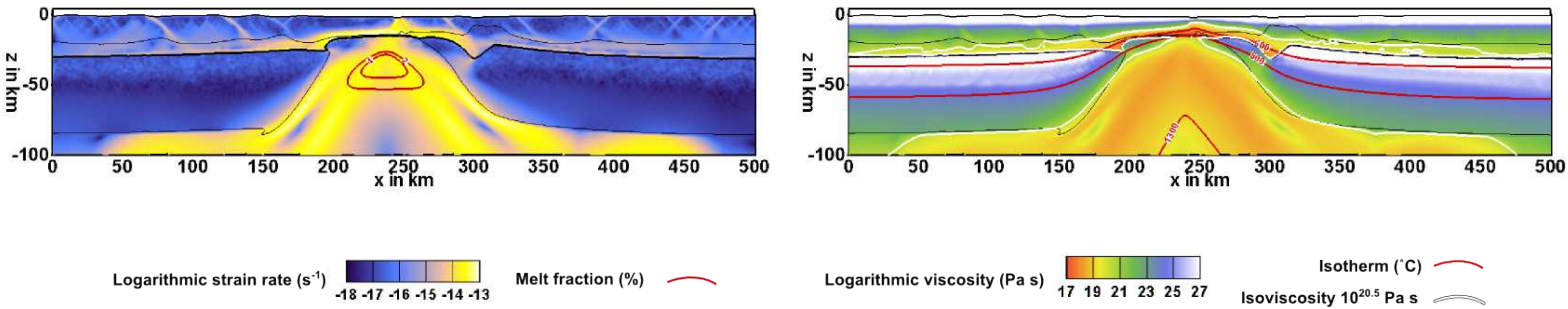
Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 16 My (every 2 My)

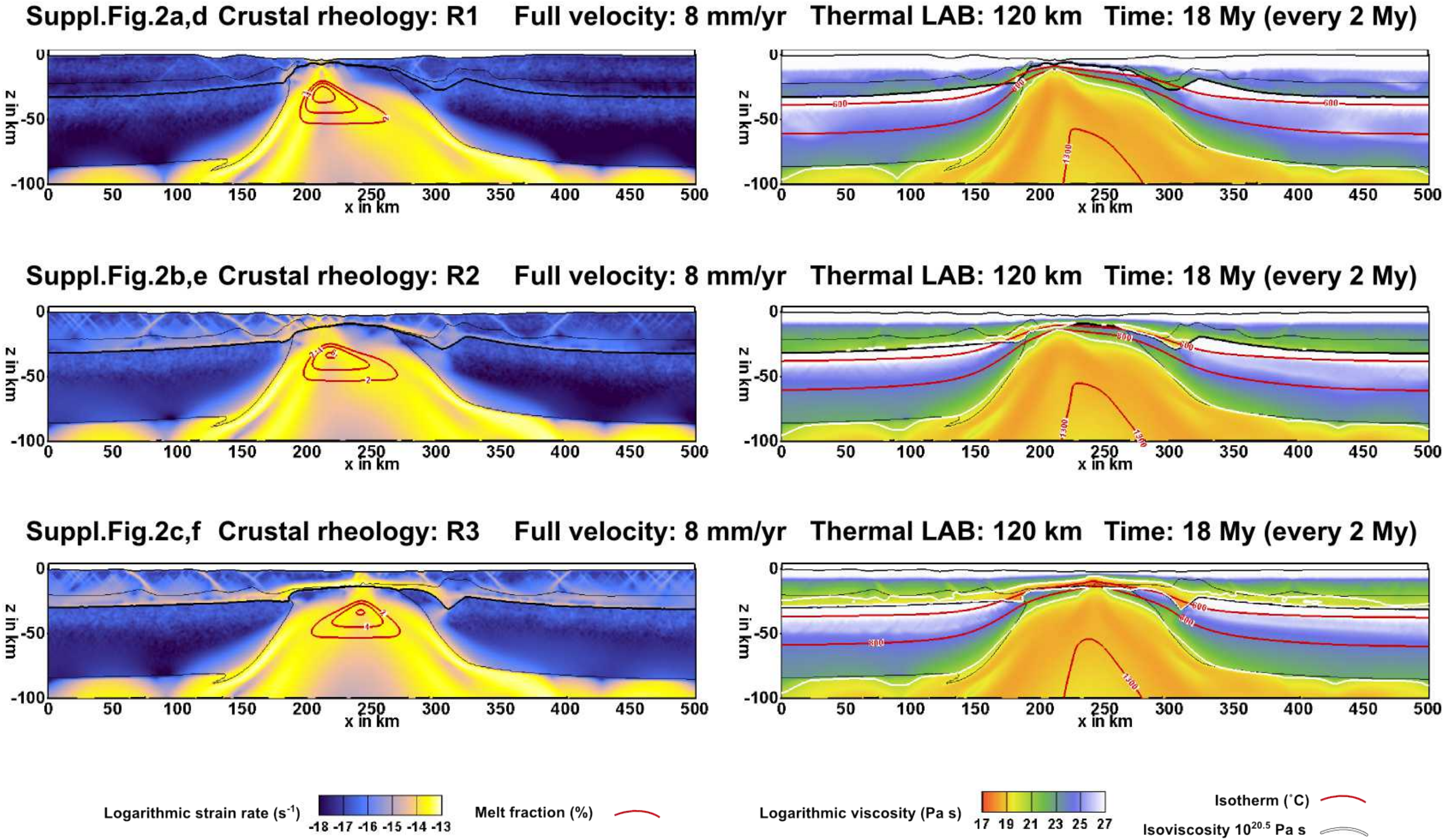


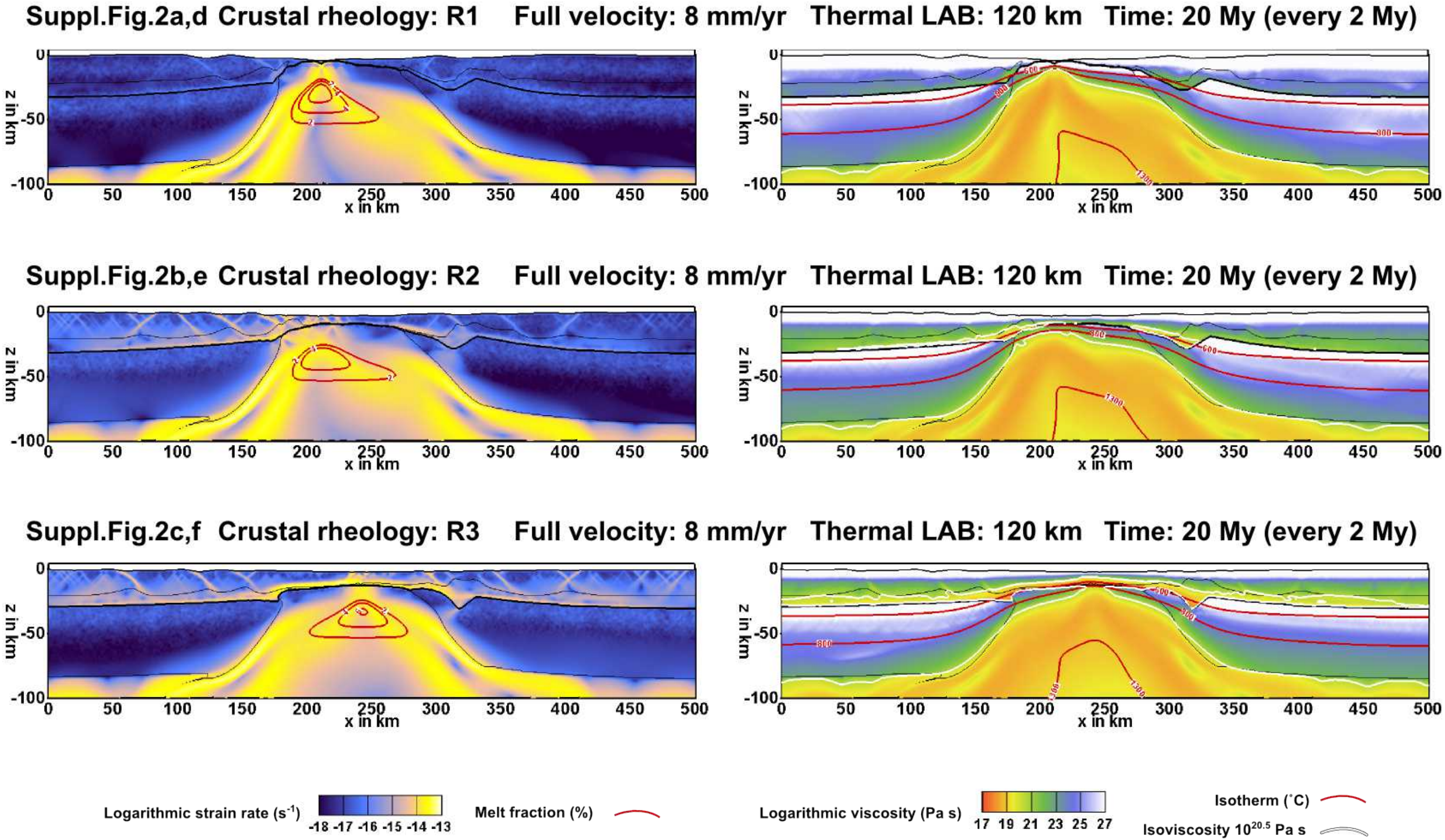
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 16 My (every 2 My)



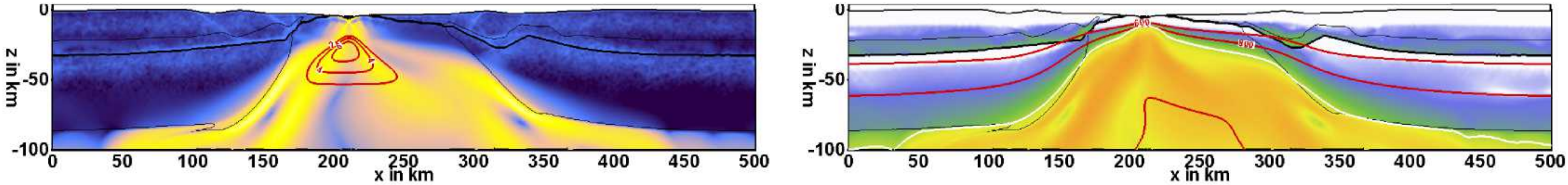
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 16 My (every 2 My)



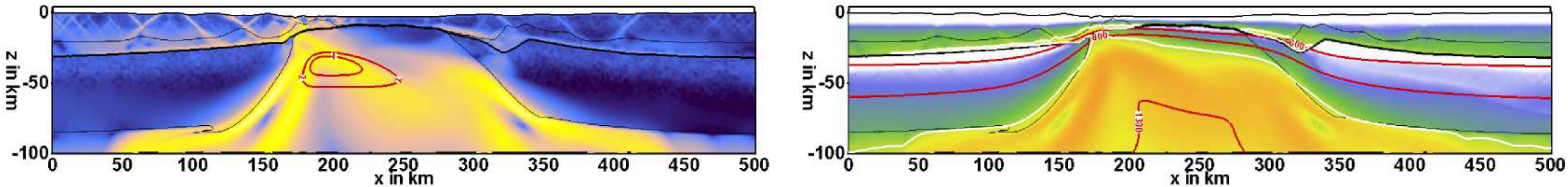

Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 18 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 18 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 18 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
600
800
1300
Logarithmic strain rate (s-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s


Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 20 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 20 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 20 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (°C)
Isoviscosity $10^{20.5}$ Pa s

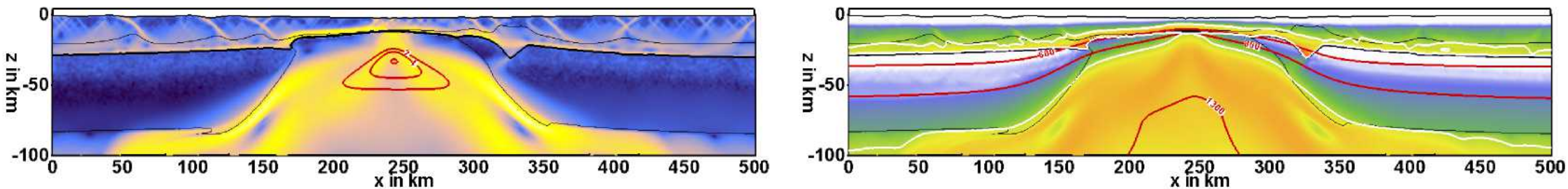
Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 22 My (every 2 My)



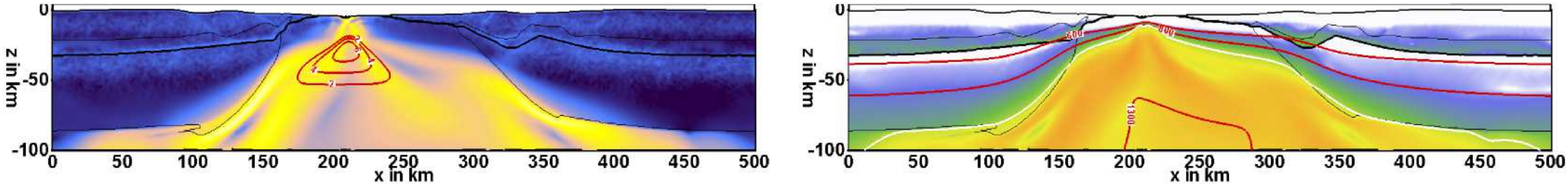
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 22 My (every 2 My)



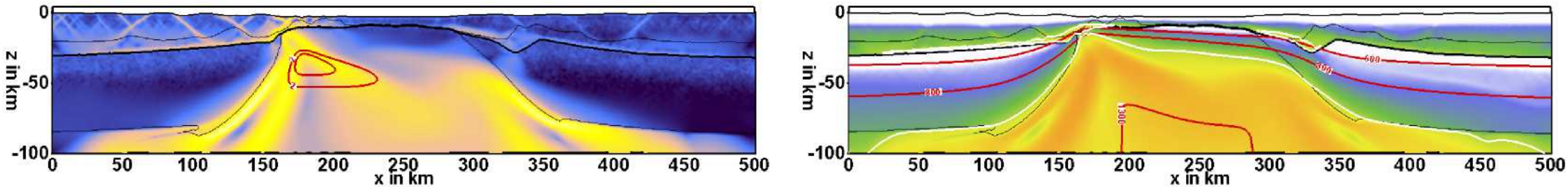
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 22 My (every 2 My)



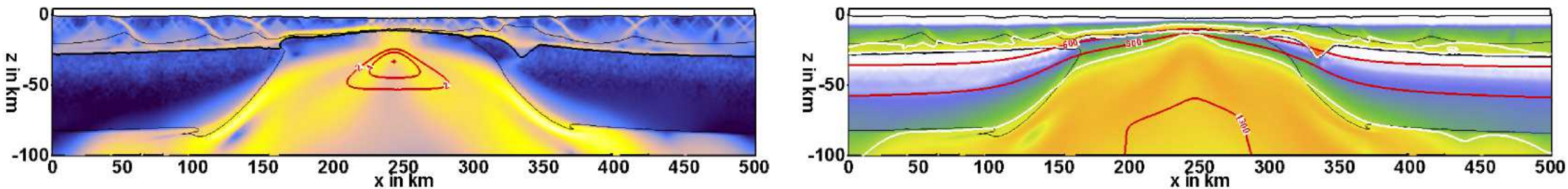
Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 24 My (every 2 My)



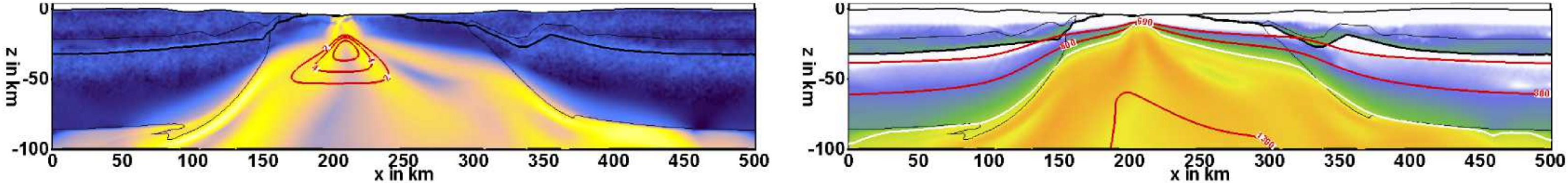
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 24 My (every 2 My)



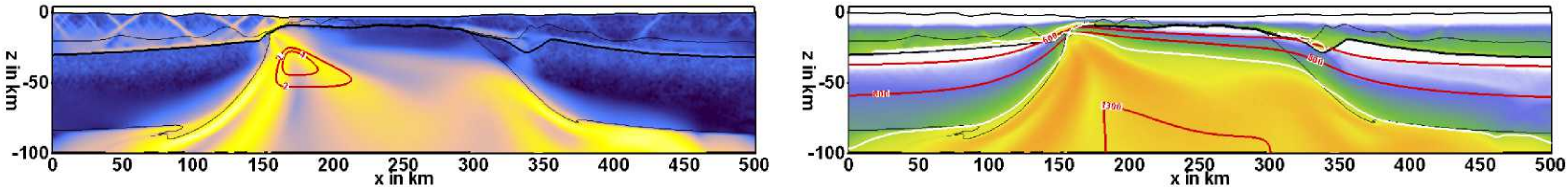
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 24 My (every 2 My)



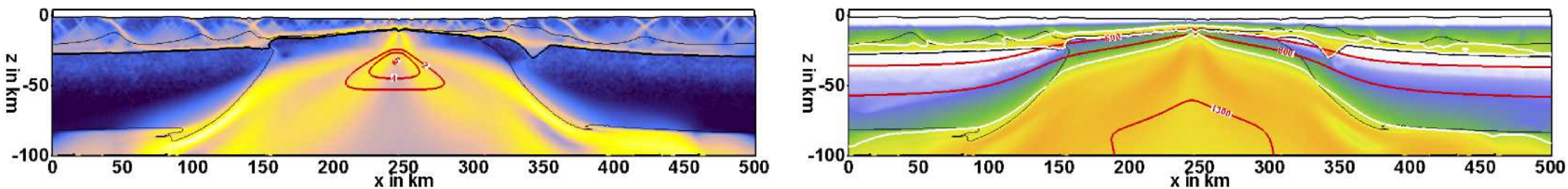
Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 26 My (every 2 My)

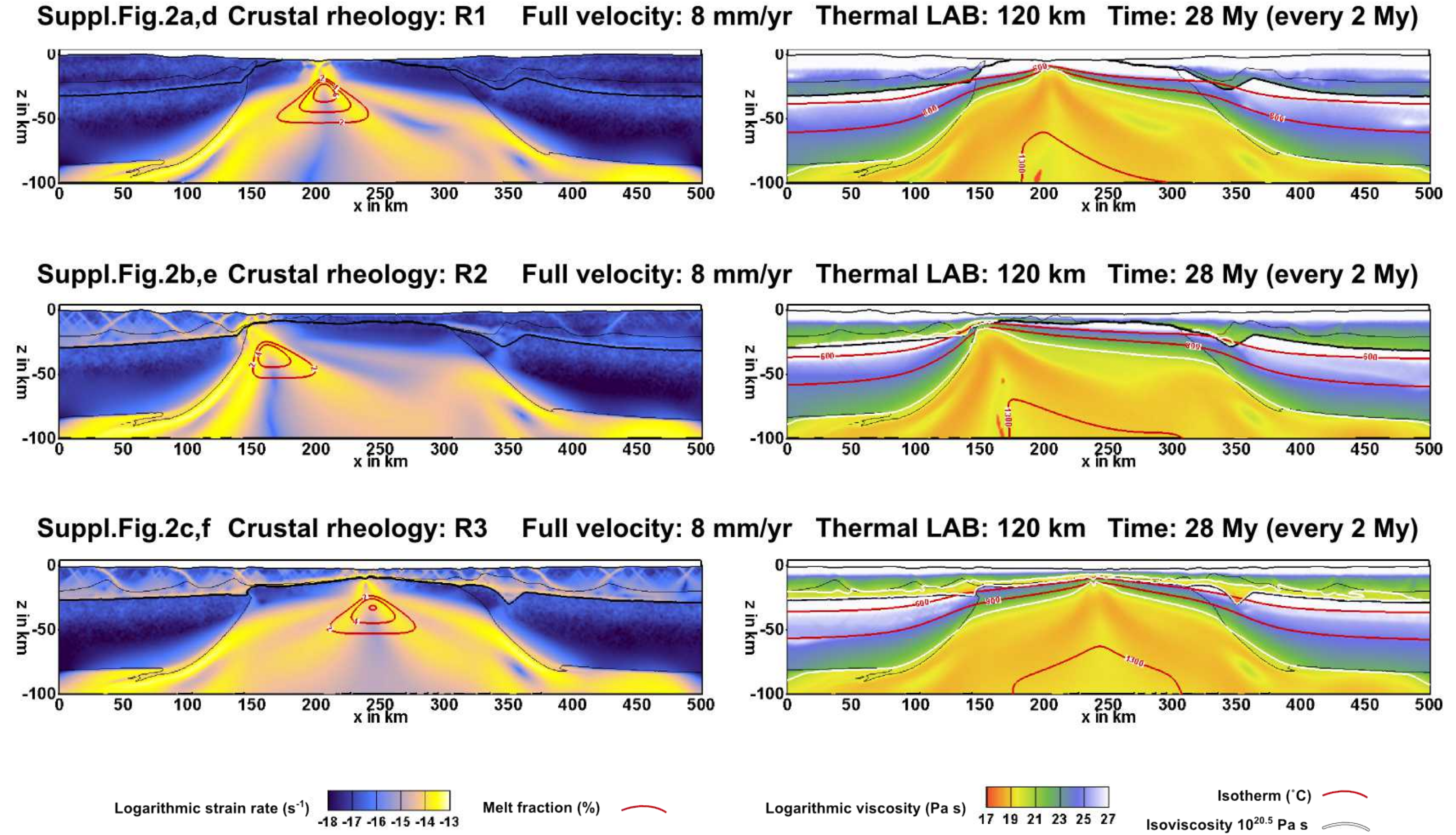


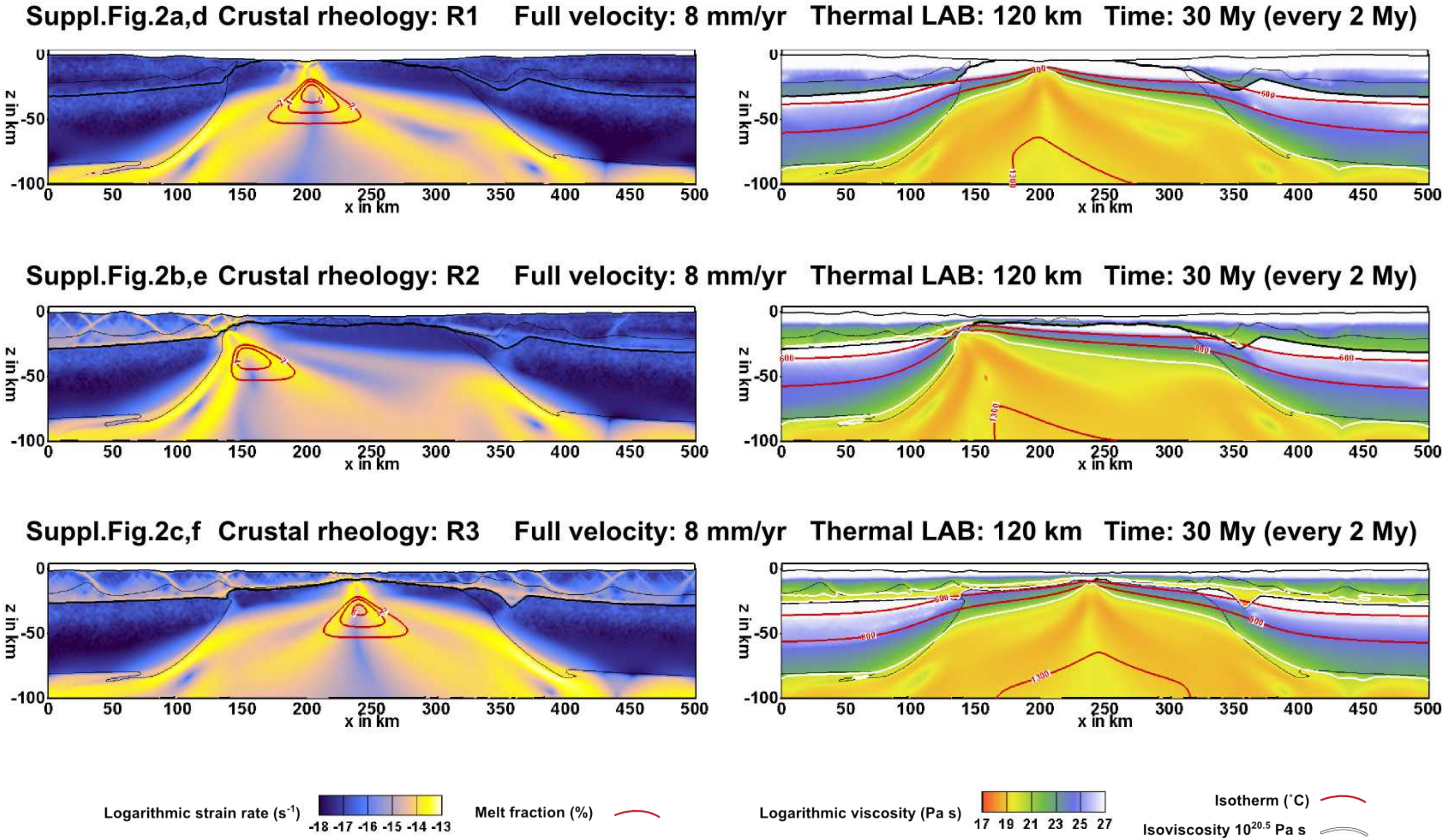
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 26 My (every 2 My)



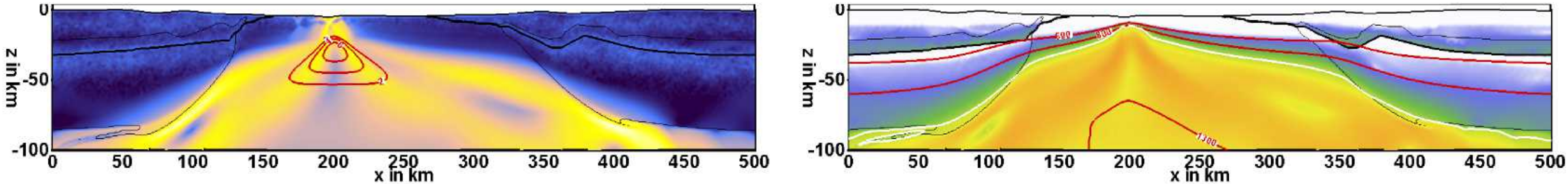
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 26 My (every 2 My)



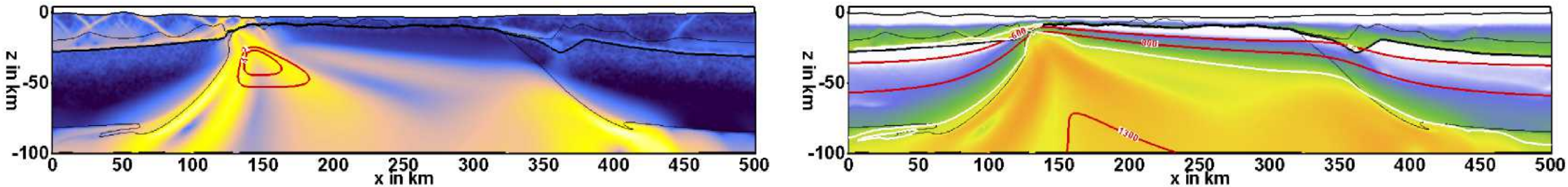

Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 28 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 28 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 28 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
600
900
1300
Logarithmic strain rate (s^{-1})
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10$^{20.5}$ Pa s


Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 30 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 30 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 30 My (every 2 My)
z in km
x in km
Logarithmic strain rate (s-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

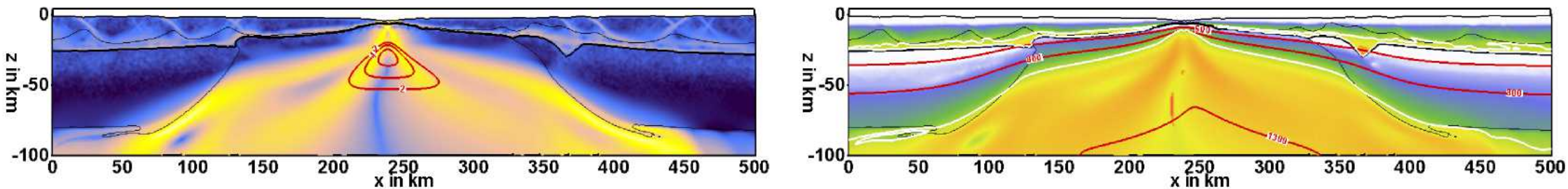
Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 32 My (every 2 My)



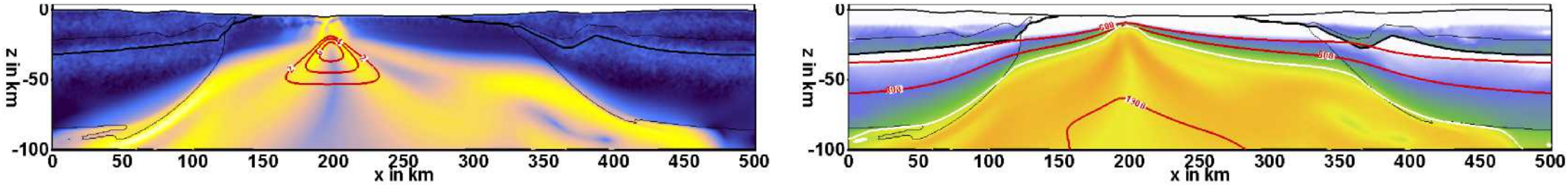
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 32 My (every 2 My)



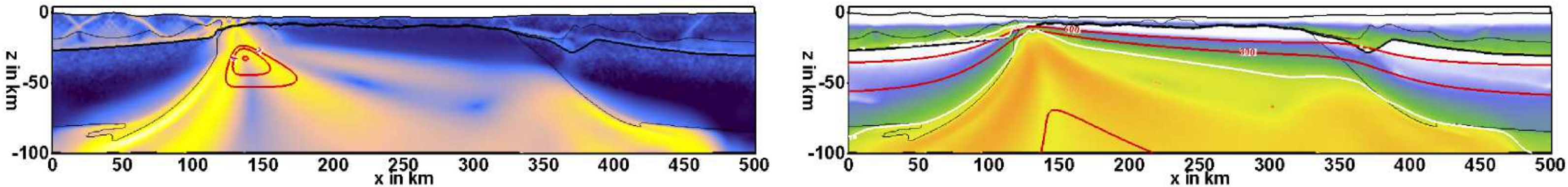
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 32 My (every 2 My)



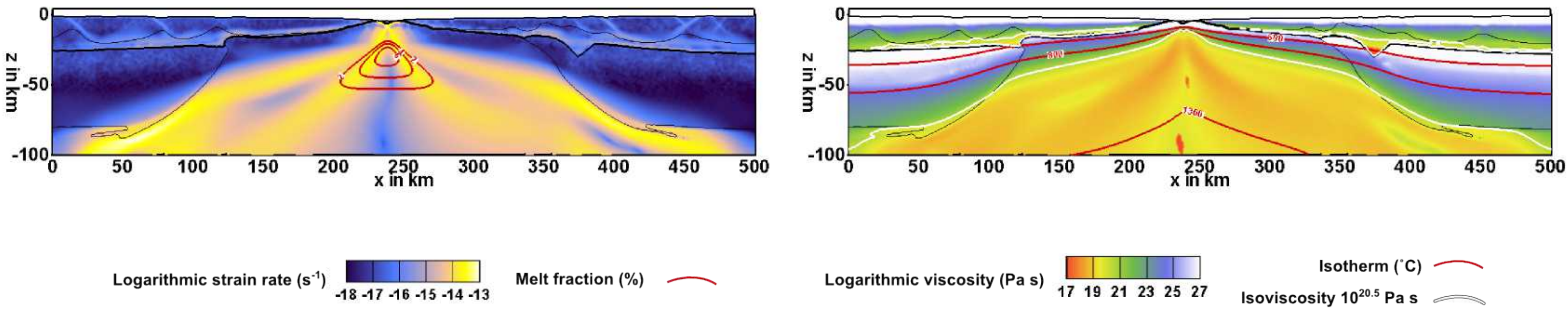
Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 34 My (every 2 My)

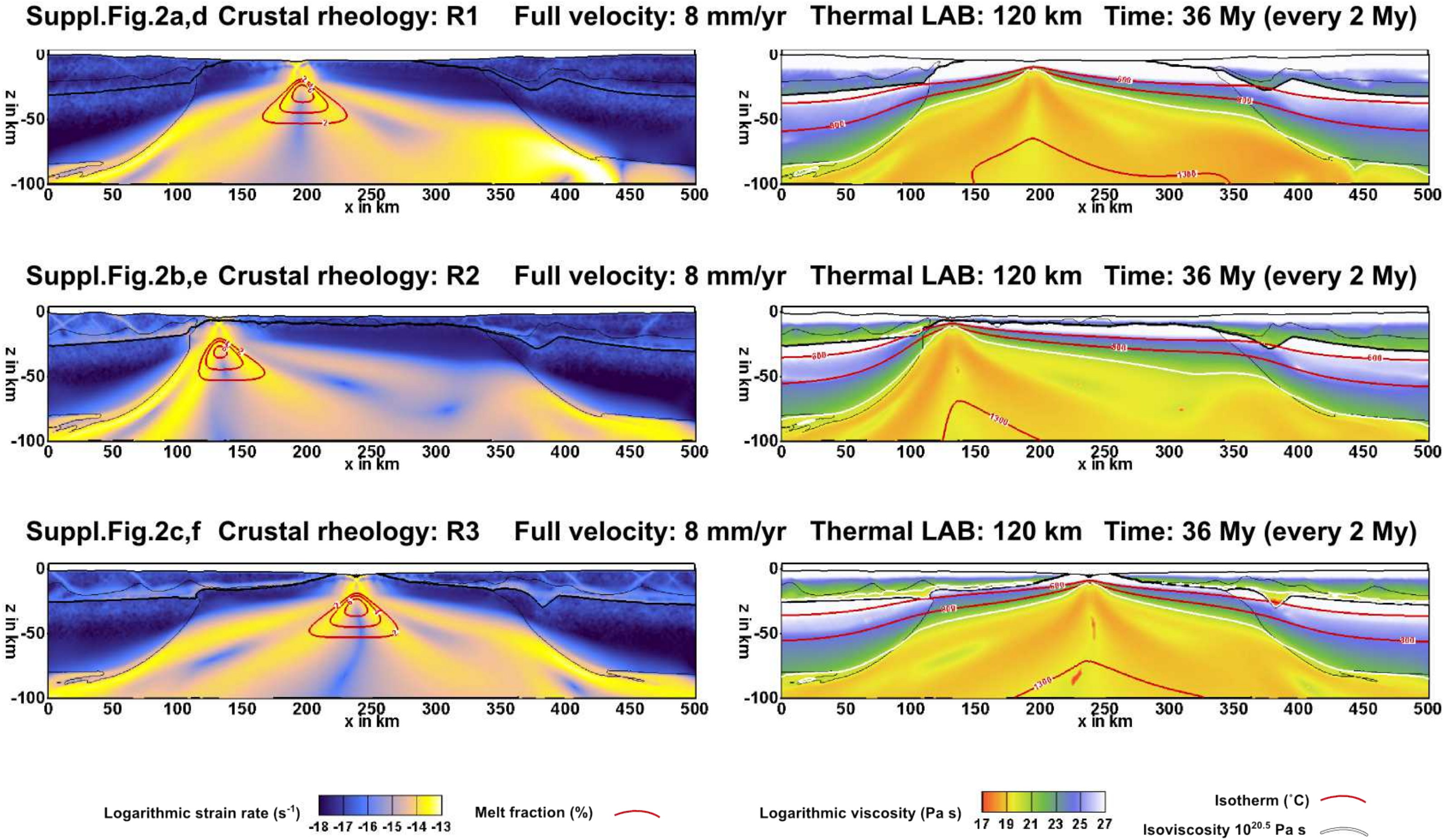


Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 34 My (every 2 My)

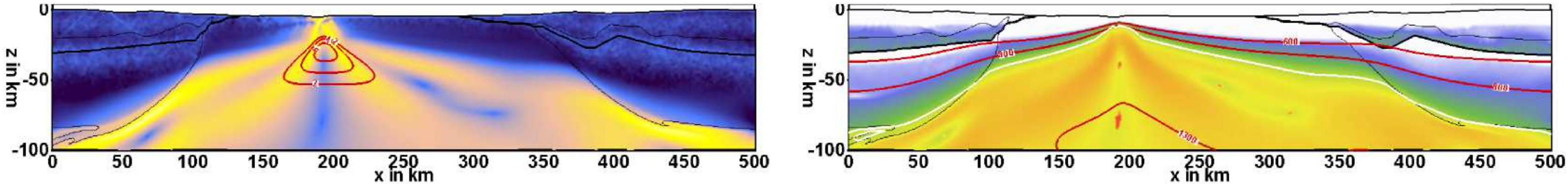


Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 34 My (every 2 My)

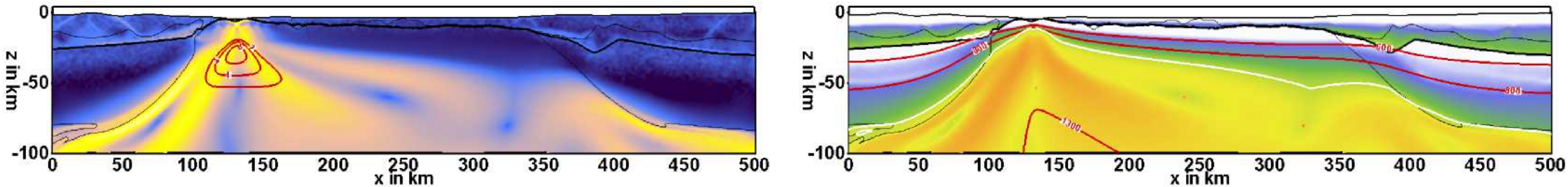



Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 36 My (every 2 My)
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 36 My (every 2 My)
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 36 My (every 2 My)
z in km
x in km
0
-50
-100
0 50 100 150 200 250 300 350 400 450 500
600
900
1300
Logarithmic strain rate (s^-1)
-18 -17 -16 -15 -14 -13
Melt fraction (%)
Logarithmic viscosity (Pa s)
17 19 21 23 25 27
Isotherm (˚C)
Isoviscosity 10^20.5 Pa s

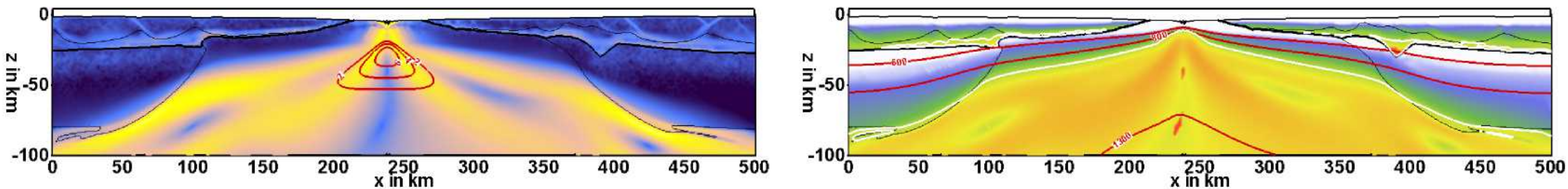
Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 38 My (every 2 My)



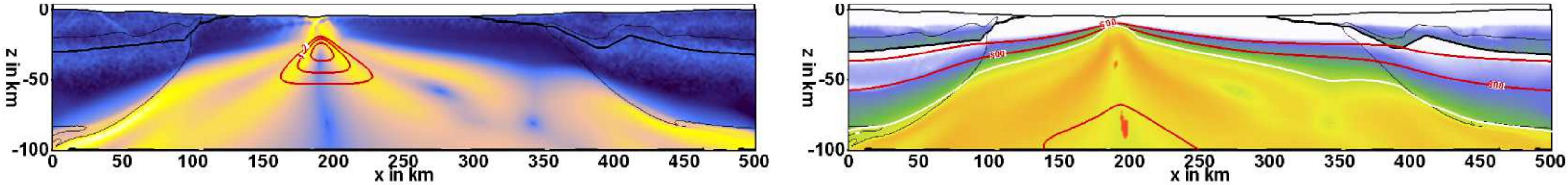
Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 38 My (every 2 My)



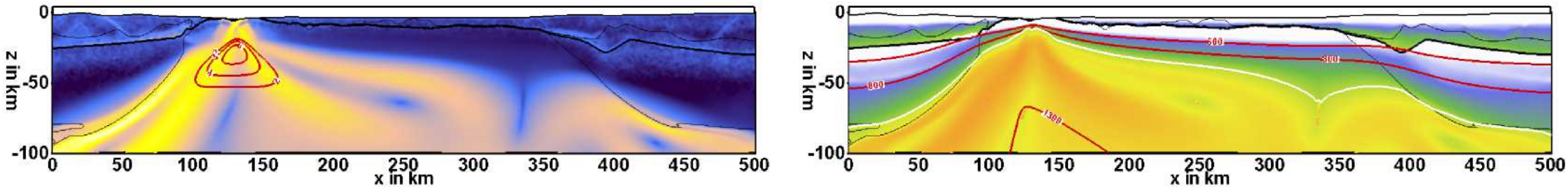
Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 38 My (every 2 My)



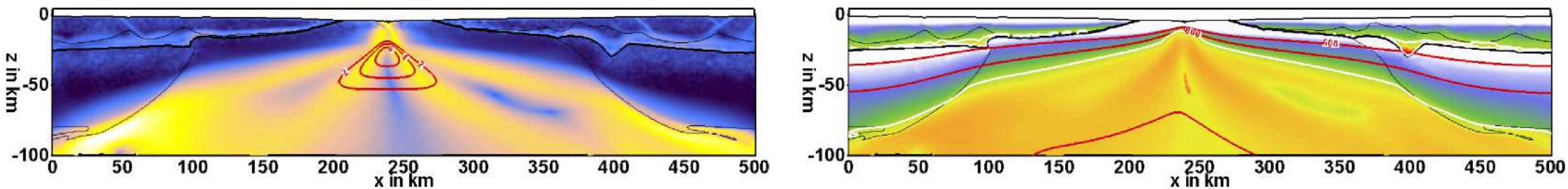
Suppl.Fig.2a,d Crustal rheology: R1 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 40 My (every 2 My)



Suppl.Fig.2b,e Crustal rheology: R2 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 40 My (every 2 My)



Suppl.Fig.2c,f Crustal rheology: R3 Full velocity: 8 mm/yr Thermal LAB: 120 km Time: 40 My (every 2 My)



Supplementary Figure 4

Detailed evolution of models shown in Supplementary Figure 2. *The left panel shows logarithmic strain rate, melt fraction (red contours), and material boundaries (black lines). The right panel depicts logarithmic viscosity, 600 °C and 800 °C isotherms (red lines), the isoviscosity contour of* $10^{20.5}$ *Pas (white line), and material boundaries (black lines).* Grey regions where viscosity is maximal deform via brittle behaviour.

Parameter	Upper Crust	Lower Crust	Strong Mantle	Weak Mantle
Density, ρ (kg m^{-3})	2700	2850	3280	3300
Thermal expansivity, α_T (10^{-5} K^{-1})	2.7	2.7	3.0	3.0
Bulk modulus, K (GPa)	55	63	122	122
Shear modulus, G (GPa)	36	40	74	74
Heat capacity, C_p (J kg^{-1} K^{-1})	1200	1200	1200	1200
Heat conductivity, λ (W K^{-1} m^{-1})	2.5	2.5	3.3	3.3
Radiogenic heat production, A (μW m^{-3})	1.5	0.2	0.0	0.0
Initial friction coefficient, μ (-)	0.5	0.5	0.5	0.5
Cohesion, c (MPa)	5.0	5.0	5.0	5.0
Pre-exponential constant for diffusion creep, log(B_{Diff}) (Pa^{-1} s^{-1})	-	-	-8.65	-8.66
Activation energy for diffusion creep, E_{Diff} (kJ / mol)	-	-	375	335
Activation volume for diffusion creep, V_{Diff} (cm^{-3} / mol)	-	-	6	4
Pre-exponential constant for dislocation creep, log(B_{Disloc}) (Pa^{-n}s^{-1})	-28.00	-15.40	-15.56	-15.05
Power law exponent for dislocation creep, n	4.0	3.0	3.5	3.5
Activation energy for dislocation creep, E_{Disloc} (kJ / mol)	223	356	530	480
Activation volume for dislocation creep, V_{Disloc} (cm^{-3}/mol)	0	0	13	10

Supplementary Table 1

Thermo-mechanical parameters. *During frictional and viscous strain softening, the respective factor for* μ *and* B_{Disloc} *vary linearly for brittle and viscous strain between 0 and 1. For strains larger than 1, they remain constant. We mimic the heterogeneous distribution of faults by randomizing the initial friction coefficient at each element between values of 0.4 and 0.5.*

Parameter	R1	R2	R3
Pre-exponential constant for dislocation creep, $\log(B_{\mathrm{Disloc}})$ (Pa^{-n} s^{-1})	-28.0	-19.6	-17.4
Power law exponent for dislocation creep, n	4.0	2.4	2.3
Activation energy for dislocation creep, E_{Disloc} (kJ / mol)	223	156	154

Supplementary Table 2

Flow law parameters for quartzite. *These parameters are used in Supplementary Figure 2, and Supplementary Discussion. Both R2 and R3 derive from the same publication[16], whereas R2 represents dry and R3 wet quartzite.*

Supplementary Discussion

Simplified setup with purely felsic crustal rheology

Many previous numerical rift models involve a crust that consists of a single material layer with felsic composition[1–5]. Keeping in mind that seismic indicators[6–11] and geological observations[12–14] attest a mafic lower crustal composition, we evaluate the robustness of our results by conducting simplified alternative models with different purely felsic crustal rheologies (Supplementary Figure 2). Therefore, we apply three different laboratory-derived quartzite flow laws to the whole crust: R1[15], R2[16], R3[16] in order to test their effect on rift evolution and margin asymmetry (Supplementary Table 2). Note that the crustal strength decreases successively from R1 to R2 to R3. All other parameters of the model setup including the extension velocity remain identical to those in Fig. 1. All models are animated in Supplementary Figure 4.

Model R1 starts with a moderately decoupled crust-mantle deformation pattern. Multiple normal faults develop that level into the completely viscous lower crust. This initial phase of deformation where simultaneously active faulting occurs involves a relatively wide area (200 km). After 14 My, a somewhat asymmetric, thin exhumation channel is generated within the lower crust and induces a short rift migration phase that generates 50 km of stretched crust. This sequentially faulting phase evolves similar to both the models with 4 mm/yr extension rate (Fig. 3a,d) and the one with a thermal lithosphere of initially 105 km thickness (Fig. 5c,d, 6b). Note that the final margin configuration compares well to the Newfoundland-Iberia geosection (Fig. 6c), illustrating the aforementioned trade-off between crustal rheology and thermal structure.

Applying a weaker crustal rheology (R2) enhances decoupling between crust and mantle. This prolongates the phase of simultaneously active faulting until the crust is even thinned to less than 10 km thickness. This first phase evolves nearly symmetric until 18 My, when the rift center commences to migrate leftward. The weak crustal rheology sustains the low-viscosity pocket leading to 180 km of sequentially formed hyper-extended crust.

Model R3 with an extremely weak crust decouples crust and mantle deformation even more than Model R2. In agreement with previous numerical models[5], the crust is stretched almost independently of the mantle lithosphere. Breakup of the compositionally strong mantle lithosphere occurs after 10 My, but the low viscosity of the crust impedes crustal breakup until 34 My. The resulting margin architecture exhibits symmetric wide margins with shallow faults (<3 km vertical extent). Throughout rifting, crustal deformation occurs over the entire model domain in a pure shear style. This means that any sediment that is deposited during this time experiences significant basal strain causing severely faulted stratigraphy. Note that this contradicts the observation of undisturbed pre-salt layers in the South Atlantic.

In summary, crustal rheology has a complex influence on the final margin architecture. During the initial rift phase, a weak crust enhances distributed faulting in a symmetric manner over a wide area (R1: 200 km, R2: 290 km, R3: >450 km). In case that rift migration is initiated, however, a low crustal viscosity prolongates the sequential faulting phase by maintaining the low-viscosity exhumation channel. We find that several model setups with different rheological parameters, extension rates, and thermal configuration may lead to a qualitatively similar model evolution. Note that rift migration is featured by several different setups corroborating the robustness of the proposed rift evolution scheme.

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