B1T: A public domain model for 1D temperature and rheology construction in basement-sedimentary geothermal exploration

J. Limberger[1], D. Bonté[1], G. de Vicente[2], F. Beekman[1], S. Cloetingh[1] and J.-D. van Wees[1,3]

[1]Universiteit Utrecht, Princetonlaan 6, Utrecht, The Netherlands
[2]G.I. Tectonofísica Aplicada, Universidad Complutense de Madrid, C/ Jose Antonio Novais n2,
28040 Madrid, Spain
[3]TNO-Energy, Postbus 80015, 3508 TA Utrecht, The Netherlands

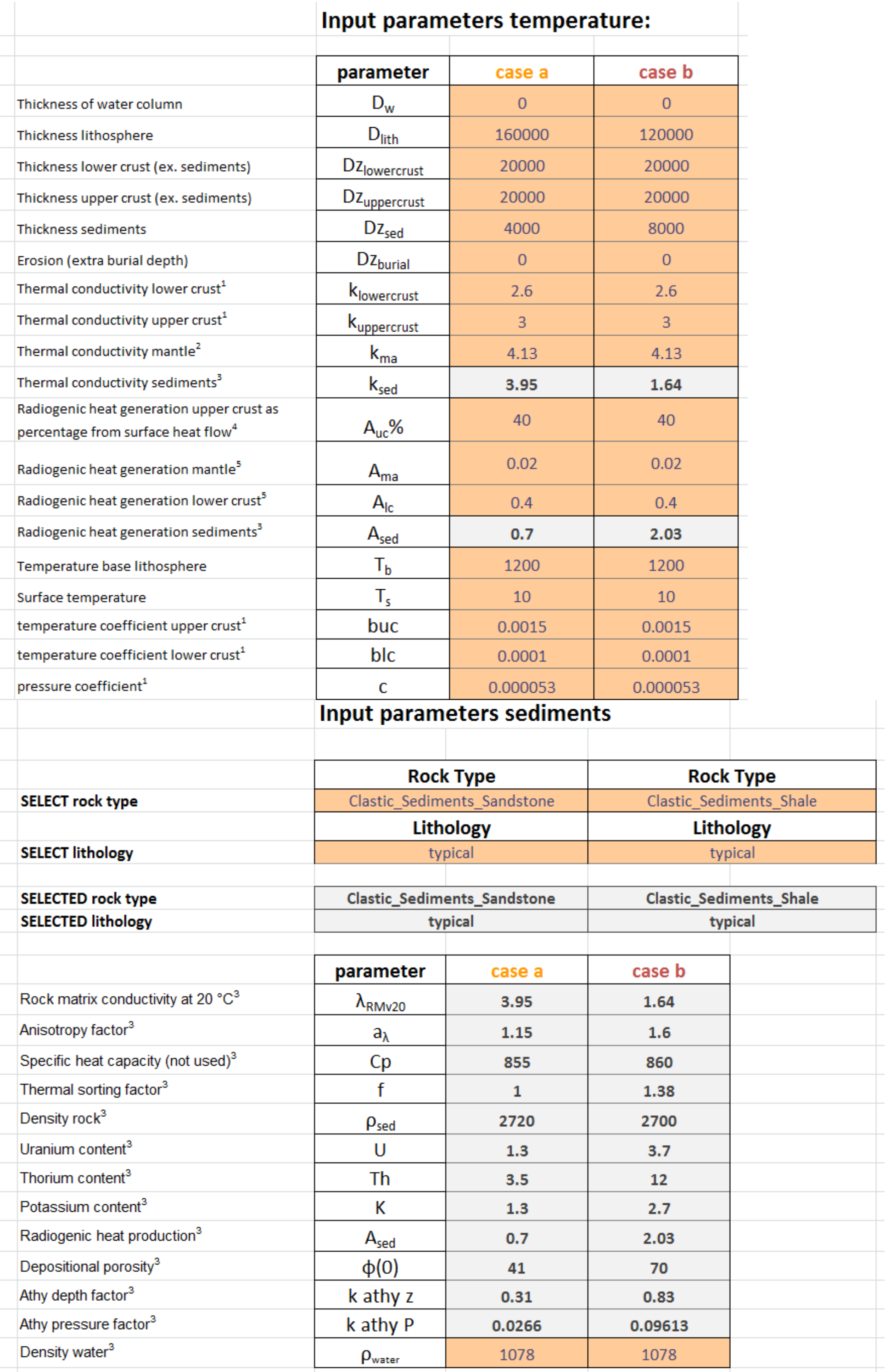
Gathering data for green field geothermal regions, often lacking data on rock thermal-mechanical properties, can be time-consuming and expensive. If there is need for a quick, first-order assessment, or when the model area is very large and there are gaps in data availability, it can be sufficient to use generic properties. For this purpose we have developed a generic property database that can be used to gain insight in the thermal properties and mechanical strength that one could expect for different basin settings, crustal geometries, and thermal-tectonic ages (Limberger et al., 2017). To this end, we have combined the thermal property tables from Hantschel & Kauerauf (2009) and rheological properties (Tesauro et al., 2009) and coupled them with a simple 1D thermal-mechanical model into a tool that can be used for the above described purposes.

The tool can be used to compare two different scenarios for crustal and sediment configuration. As input the user can give estimates for the thickness of the layers including sediments, upper and lower crust and the total lithosphere (Fig. 1). With a drop-down menu, different lithologies can be selected for the sediments, automatically returning the corresponding thermal-mechanical properties (Fig. 1). Thermal conductivity is temperature and pressure dependent throughout the whole crust (Fig. 3) and is updated iteratively and automatically with a 1D steady-state thermal solution (cf. Eq. 1).

$$T(z) = T_{z_0} + \frac{Q}{k}\,(z - z_0) - \frac{A}{2k}(z - z_0)^2 \quad \text{(Eq. 1)}$$

For the sediment layer compaction curves are calculated and used to determine porosities and the subsequent bulk thermal conductivity by mixing the pore fluid with the matrix thermal conductivity (see paper and Fig. 3). Burial anomalies can be included to take into account the effects of anomalous compaction, affecting thermal properties.

The temperature output is used together with the rheology to calculate strength profiles and give an estimate of the integrated strength for compression and extension (cf. Table 3.1). Different rheological properties can be chosen for upper and lower crust and lithosphere mantle by selecting different rheologies from the drop-down menu (Fig. 2).



Input parameters temperature:

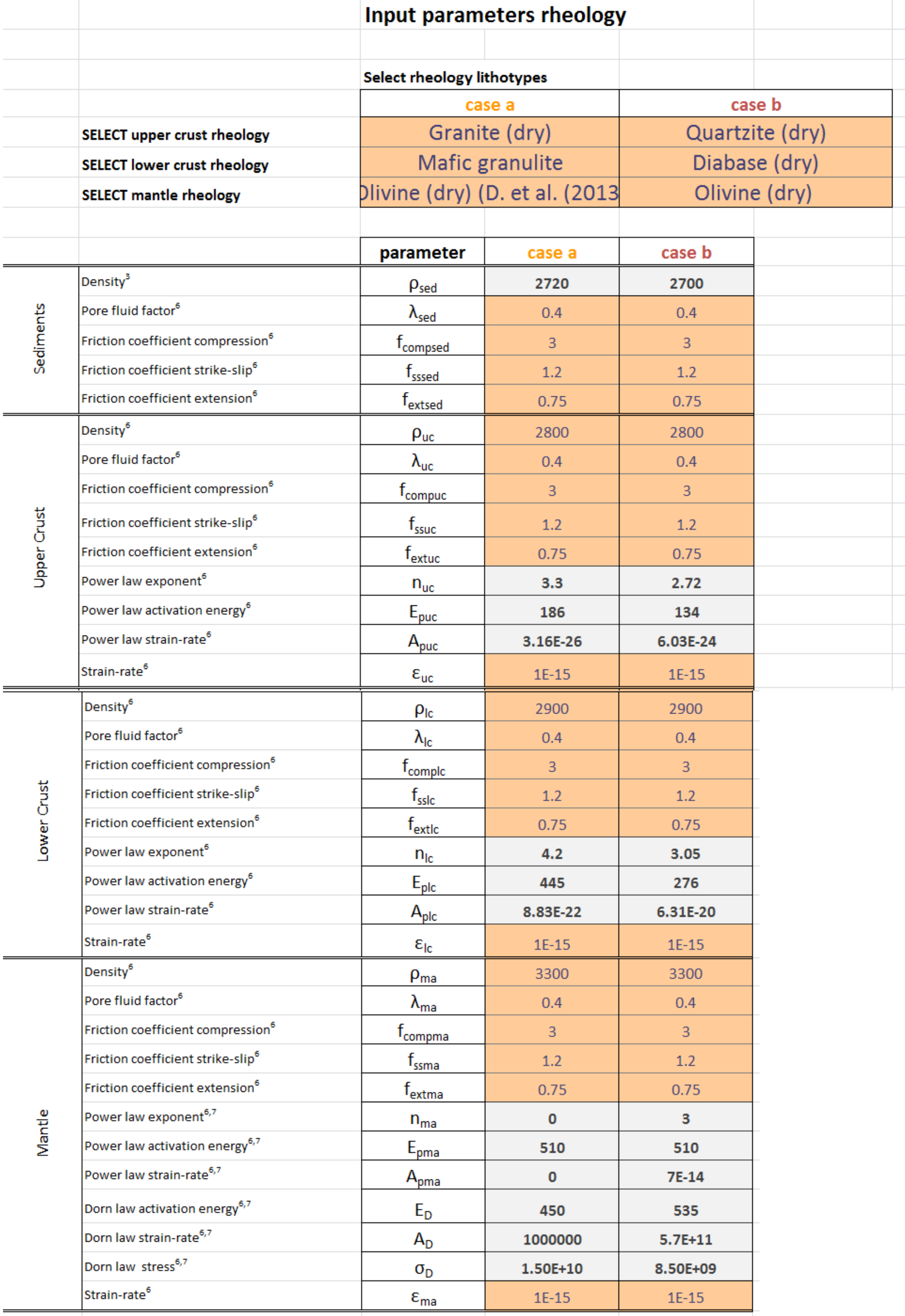
	parameter	case a	case b
Thickness of water column	D_w	0	0
Thickness lithosphere	D_{lith}	160000	120000
Thickness lower crust (ex. sediments)	$Dz_{lowercrust}$	20000	20000
Thickness upper crust (ex. sediments)	$Dz_{uppercrust}$	20000	20000
Thickness sediments	Dz_{sed}	4000	8000
Erosion (extra burial depth)	Dz_{burial}	0	0
Thermal conductivity lower crust[1]	$k_{lowercrust}$	2.6	2.6
Thermal conductivity upper crust[1]	$k_{uppercrust}$	3	3
Thermal conductivity mantle[2]	k_{ma}	4.13	4.13
Thermal conductivity sediments[3]	k_{sed}	**3.95**	**1.64**
Radiogenic heat generation upper crust as percentage from surface heat flow[4]	$A_{uc}\%$	40	40
Radiogenic heat generation mantle[5]	A_{ma}	0.02	0.02
Radiogenic heat generation lower crust[5]	A_{lc}	0.4	0.4
Radiogenic heat generation sediments[3]	A_{sed}	**0.7**	**2.03**
Temperature base lithosphere	T_b	1200	1200
Surface temperature	T_s	10	10
temperature coefficient upper crust[1]	buc	0.0015	0.0015
temperature coefficient lower crust[1]	blc	0.0001	0.0001
pressure coefficient[1]	c	0.000053	0.000053

Input parameters sediments

	Rock Type	Rock Type
SELECT rock type	Clastic_Sediments_Sandstone	Clastic_Sediments_Shale
	Lithology	**Lithology**
SELECT lithology	typical	typical
SELECTED rock type	**Clastic_Sediments_Sandstone**	**Clastic_Sediments_Shale**
SELECTED lithology	**typical**	**typical**

	parameter	case a	case b
Rock matrix conductivity at 20 °C[3]	λ_{RMv20}	**3.95**	**1.64**
Anisotropy factor[3]	a_λ	**1.15**	**1.6**
Specific heat capacity (not used)[3]	Cp	**855**	**860**
Thermal sorting factor[3]	f	**1**	**1.38**
Density rock[3]	ρ_{sed}	**2720**	**2700**
Uranium content[3]	U	**1.3**	**3.7**
Thorium content[3]	Th	**3.5**	**12**
Potassium content[3]	K	**1.3**	**2.7**
Radiogenic heat production[3]	A_{sed}	**0.7**	**2.03**
Depositional porosity[3]	$\phi(0)$	**41**	**70**
Athy depth factor[3]	k athy z	**0.31**	**0.83**
Athy pressure factor[3]	k athy P	**0.0266**	**0.09613**
Density water[3]	ρ_{water}	1078	1078

Fig. 1: Screenshot from the input and selection fields of the thermal part of the generic property tool. Fields in orange can be changed or selections can be made from a drop-down menu.



Input parameters rheology

Select rheology lithotypes

	case a	case b
SELECT upper crust rheology	Granite (dry)	Quartzite (dry)
SELECT lower crust rheology	Mafic granulite	Diabase (dry)
SELECT mantle rheology	Dlivine (dry) (D. et al. (2013	Olivine (dry)

		parameter	case a	case b
Sediments	Density[3]	ρ_{sed}	**2720**	**2700**
	Pore fluid factor[6]	λ_{sed}	0.4	0.4
	Friction coefficient compression[6]	$f_{compsed}$	3	3
	Friction coefficient strike-slip[6]	f_{sssed}	1.2	1.2
	Friction coefficient extension[6]	f_{extsed}	0.75	0.75
Upper Crust	Density[6]	ρ_{uc}	2800	2800
	Pore fluid factor[6]	λ_{uc}	0.4	0.4
	Friction coefficient compression[6]	f_{compuc}	3	3
	Friction coefficient strike-slip[6]	f_{ssuc}	1.2	1.2
	Friction coefficient extension[6]	f_{extuc}	0.75	0.75
	Power law exponent[6]	n_{uc}	**3.3**	**2.72**
	Power law activation energy[6]	E_{puc}	**186**	**134**
	Power law strain-rate[6]	A_{puc}	**3.16E-26**	**6.03E-24**
	Strain-rate[6]	ε_{uc}	1E-15	1E-15
Lower Crust	Density[6]	ρ_{lc}	2900	2900
	Pore fluid factor[6]	λ_{lc}	0.4	0.4
	Friction coefficient compression[6]	f_{complc}	3	3
	Friction coefficient strike-slip[6]	f_{sslc}	1.2	1.2
	Friction coefficient extension[6]	f_{extlc}	0.75	0.75
	Power law exponent[6]	n_{lc}	**4.2**	**3.05**
	Power law activation energy[6]	E_{plc}	**445**	**276**
	Power law strain-rate[6]	A_{plc}	**8.83E-22**	**6.31E-20**
	Strain-rate[6]	ε_{lc}	1E-15	1E-15
Mantle	Density[6]	ρ_{ma}	3300	3300
	Pore fluid factor[6]	λ_{ma}	0.4	0.4
	Friction coefficient compression[6]	f_{compma}	3	3
	Friction coefficient strike-slip[6]	f_{ssma}	1.2	1.2
	Friction coefficient extension[6]	f_{extma}	0.75	0.75
	Power law exponent[6,7]	n_{ma}	**0**	**3**
	Power law activation energy[6,7]	E_{pma}	**510**	**510**
	Power law strain-rate[6,7]	A_{pma}	**0**	**7E-14**
	Dorn law activation energy[6,7]	E_D	**450**	**535**
	Dorn law strain-rate[6,7]	A_D	**1000000**	**5.7E+11**
	Dorn law stress[6,7]	σ_D	**1.50E+10**	**8.50E+09**
	Strain-rate[6]	ε_{ma}	1E-15	1E-15

Fig. 2: Screenshot from the input and selection fields for the rheology part of the generic property tool. Fields in orange can be changed or selections can be made from a drop-down menu.

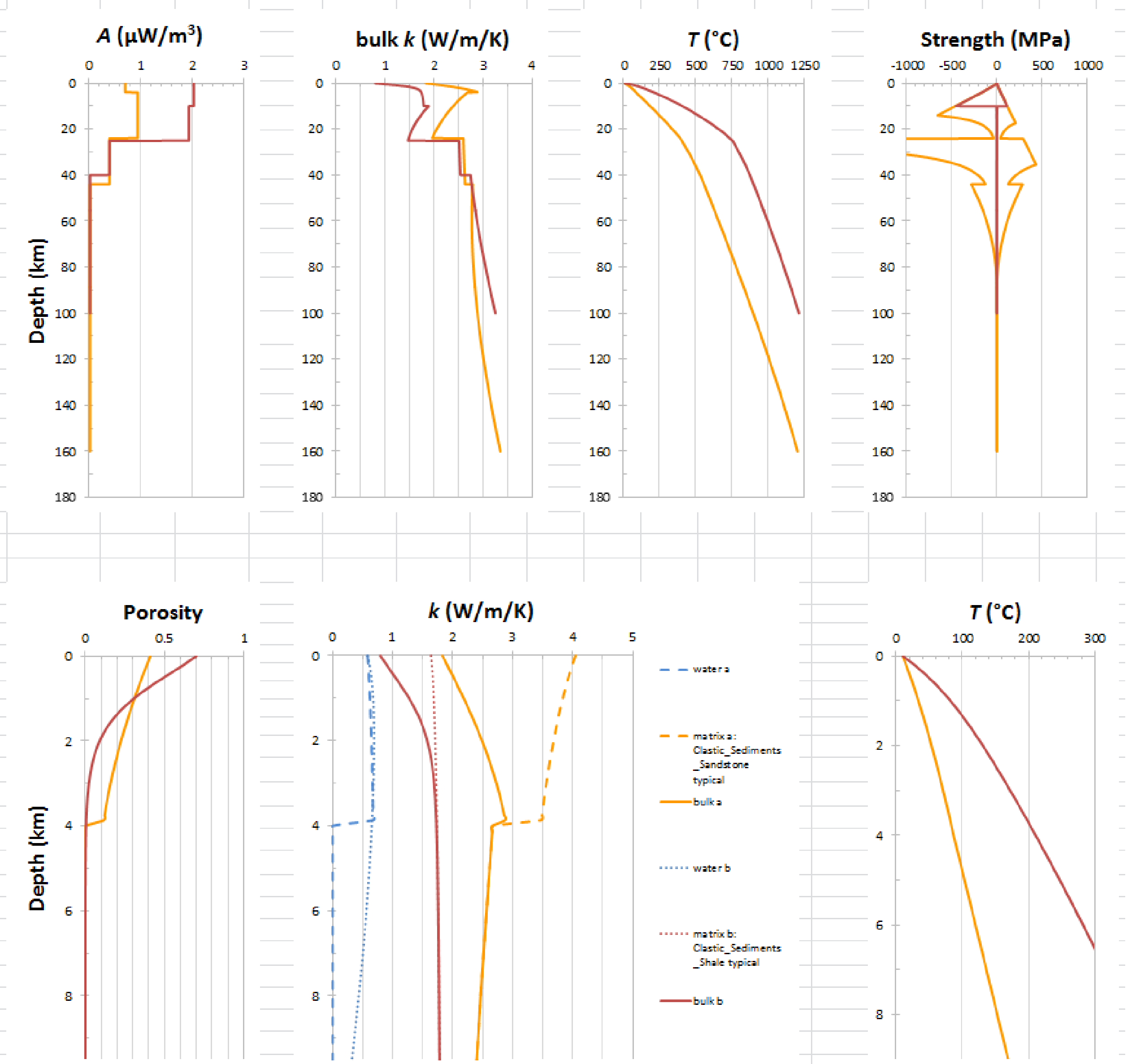
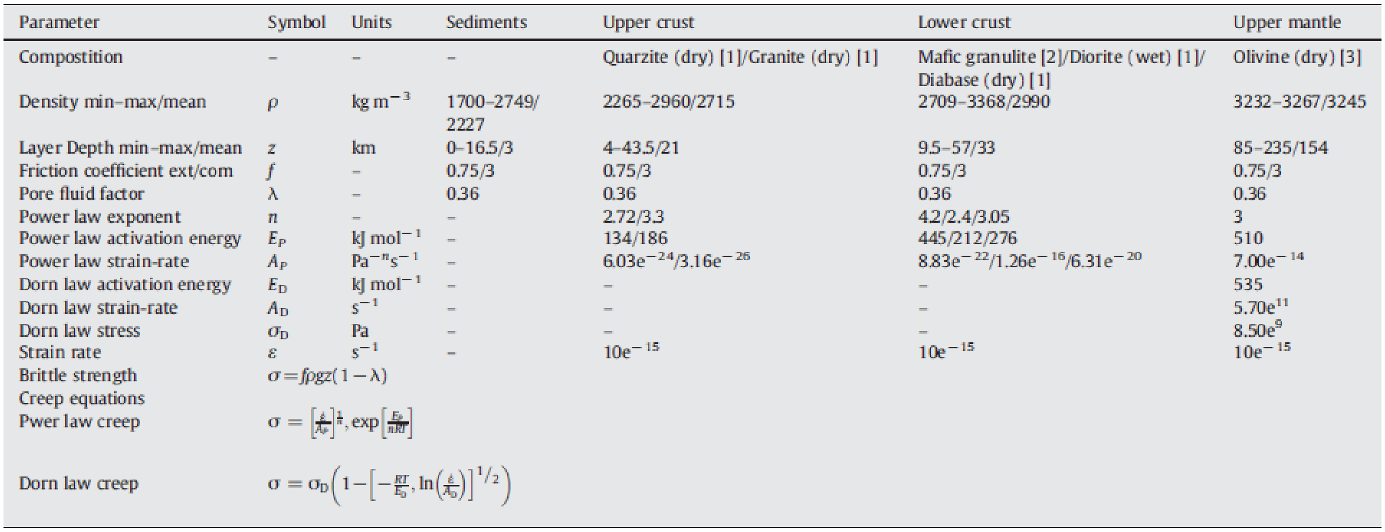


Fig. 3: Screenshot from the output graphs of the generic property tool. Two scenarios with a different lithology and thermal regime can be compared (orange and red). Upper panels show full depth range. Lower panels show the upper 10 km in more detail, including the thermal conductivity of the matrix (dashed orange and red) and pore fluid (blue) compared to the bulk thermal conductivity (solid orange and red).



Parameter	Symbol	Units	Sediments	Upper crust	Lower crust	Upper mantle
Compostition	–	–	–	Quarzite (dry) [1]/Granite (dry) [1]	Mafic granulite [2]/Diorite (wet) [1]/ Diabase (dry) [1]	Olivine (dry) [3]
Density min–max/mean	ρ	kg m^{-3}	1700–2749/ 2227	2265–2960/2715	2709–3368/2990	3232–3267/3245
Layer Depth min–max/mean	z	km	0–16.5/3	4–43.5/21	9.5–57/33	85–235/154
Friction coefficient ext/com	f	–	0.75/3	0.75/3	0.75/3	0.75/3
Pore fluid factor	λ	–	0.36	0.36	0.36	0.36
Power law exponent	n	–	–	2.72/3.3	4.2/2.4/3.05	3
Power law activation energy	E_P	kJ mol^{-1}	–	134/186	445/212/276	510
Power law strain-rate	A_P	$Pa^{-n}s^{-1}$	–	$6.03e^{-24}/3.16e^{-26}$	$8.83e^{-22}/1.26e^{-16}/6.31e^{-20}$	$7.00e^{-14}$
Dorn law activation energy	E_D	kJ mol^{-1}	–	–	–	535
Dorn law strain-rate	A_D	s^{-1}	–	–	–	$5.70e^{11}$
Dorn law stress	σ_D	Pa	–	–	–	$8.50e^{9}$
Strain rate	ε	s^{-1}	–	$10e^{-15}$	$10e^{-15}$	$10e^{-15}$
Brittle strength	$\sigma = f\rho gz(1-\lambda)$					
Creep equations						
Pwer law creep	$\sigma = \left[\frac{\dot{\varepsilon}}{A_P}\right]^{\frac{1}{n}}, \exp\left[\frac{E_P}{nRT}\right]$					
Dorn law creep	$\sigma = \sigma_D\left(1-\left[-\frac{RT}{E_D}, \ln\left(\frac{\dot{\varepsilon}}{A_D}\right)\right]^{1/2}\right)$					

Table 3.1: Power law and Dorn law creep parameters for sediments, crust and mantle (from Tesauro et al., 2009). Numbers in brackets denote different sources of the data.

References

Hantschel, T. and Kauerauf, A. I. (2009): Fundamentals of Basin and Petroleum Systems Modeling. Springer Berlin Heidelberg, Germany, ISBN 978-3540723172.

Limberger, J., Bonté, D., de Vicente, G., Beekman, F., Cloetingh, S., van Wees, J.-D. (2017): A public domain model for 1D temperature and rheology construction in basement-sedimentary geothermal exploration: An application to the Spanish Central System and adjacent basins, Acta Geodaetica et Geophysica, DOI: 10.1007/s40328-017-0197-5.

Tesauro, M., Kaban, M.K., Cloetingh, S.A.P.L. (2009): A new thermal and rheological model of the European lithosphere. Tectonophysics, 476 (3-4), pp. 478-495.