



Supplement of

Geothermal implications of the lithosphere's thermal structure in northern Pakistan

Muhammad Anees et al.

Correspondence to: Muhammad Anees (muhammad.anees@liag-institut.de)

The copyright of individual parts of the supplement might differ from the article licence.

Section S1 1D Steady-State Models

Table S1 Parameters used for the steady-state conductive thermal model of Nanga Parbat Massif. Ind-1 and Ind-2, respectively, refer to high and low heat-producing crustal layers. BG refers to basement gneiss, which is present in the core of NPM and has high surface RHP.

	Crustal depth range (km)	Radiogenic heat production ($\mu\text{W m}^{-3}$)	Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
<i>Model 1</i>			
Upper crust (Ind-1)	0 - 20	4.0	2.3
Mid crust (Ind-2)	20 - 30	2.0	2.5
Lower crust	30 - 60	0.4	2.6
<i>Model 2</i>			
Upper crust (Ind-1)	0 - 15	4.0	2.3
Mid crust (Ind-2)	15 - 30	2.0	2.5
Lower crust	30 - 60	0.4	2.6
<i>Model 3</i>			
Upper crust (Ind-1)	0 - 10	4.0	2.3
Mid crust (Ind-2)	10 - 30	2.0	2.5
Lower crust	30 - 60	0.4	2.6
<i>Model 4</i>			
Upper crust (Ind-1)	0 - 5	4.0	2.3
Mid crust (Ind-2)	5 - 30	2.0	2.5
Lower crust	30 - 60	0.4	2.6
<i>Model 5</i>			
Upper crust (BG)	0 - 5	5.33	2.3
Mid crust (Ind-2)	5 - 30	2.0	2.5
Lower crust	30 - 60	0.4	2.6
<i>Model 6</i>			
Upper crust (BG)	0 - 10	5.33	2.3
Mid crust (Ind-2)	10 - 30	2.0	2.5
Lower crust	30 - 60	0.4	2.6
<i>Model 7</i>			
Upper crust (BG)	0 - 10	5.33	2.3
Mid crust (Ind-2)	10 - 30	1.0	2.5
Lower crust	30 - 60	0.4	2.6

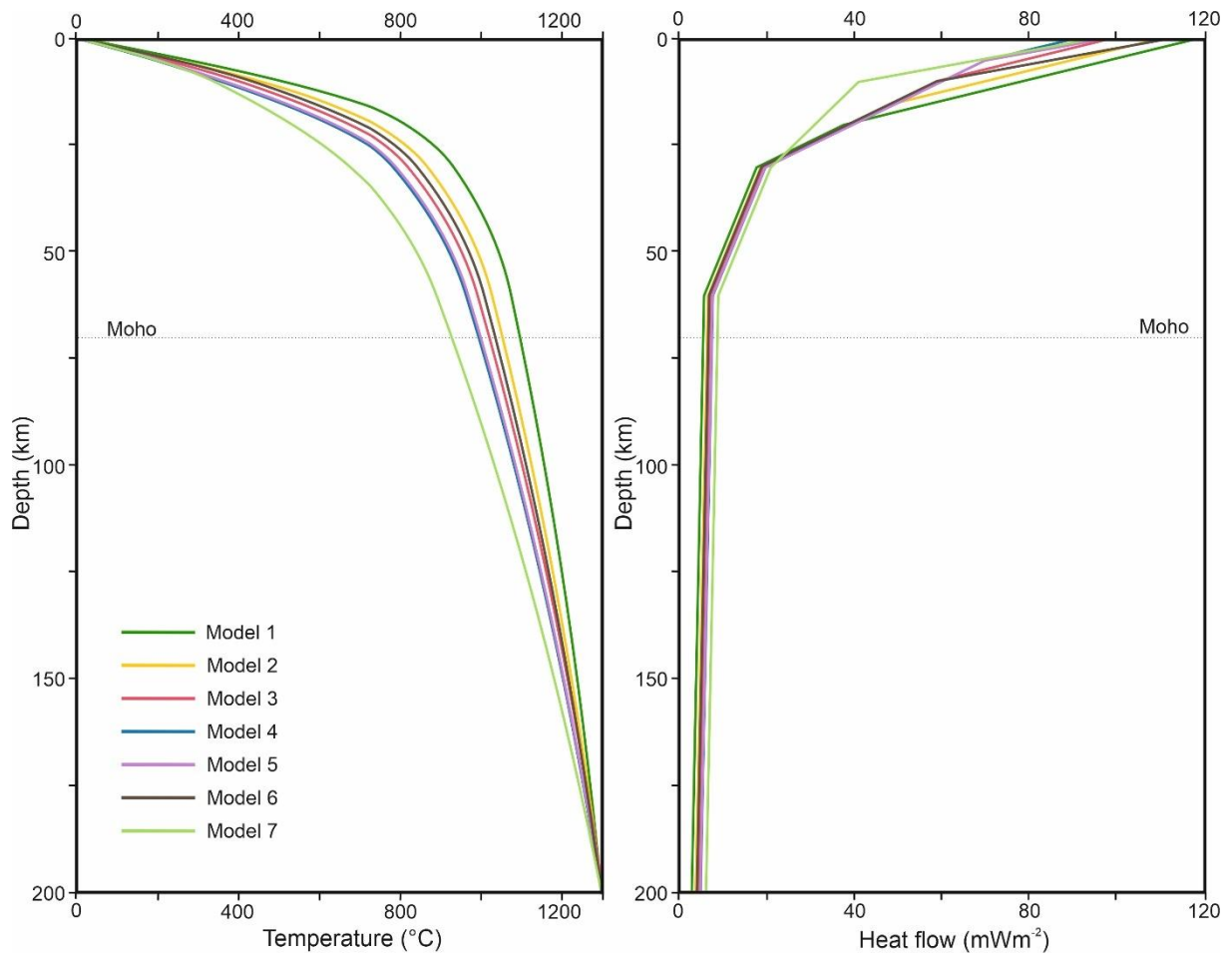


Figure S1 1D steady-state conductive geotherms and heat flow plots for different modelling scenarios with varying parameters in the Nanga Parbat Massif. In Models 1 to 4, the thickness of the heat-producing upper crust with $4 \mu\text{W m}^{-3}$ is reduced from 20 km to 5 km, while the crust with $2 \mu\text{W m}^{-3}$ increases from 10 to 25 km. Models 5 and 6 assume a highly enriched upper crust ($5.33 \mu\text{W m}^{-3}$) with thicknesses of 5 and 10 km, respectively. Model 7 assumes a 10 km thick enriched upper crust ($5.33 \mu\text{W m}^{-3}$) but a 20 km thick slightly depleted mid-crust.

Table S2 Parameters used for the steady-state conductive thermal model of Kohistan arc. Koh-F and Koh-M, respectively, refer to the upper felsic and lower mafic Kohistan crust overlying the Indian crust.

	Crustal depth range (km)	Radiogenic heat production ($\mu\text{W m}^{-3}$)	Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
<i>Model 1</i>			
Upper crust:			
Koh-F	0 - 10	1.0	2.3
Koh-M	10 - 20	0.08	3.0
Mid crust:			
Ind-1	20 - 30	4.0	2.3
Ind-2	30 - 40	2.0	2.5
Lower crust	40 - 70	0.4	2.6
<i>Model 2</i>			
Upper crust:			
Koh-F	0 - 10	1.0	2.3
Koh-M	10 - 20	0.08	3.0
Mid crust:			
Ind-1	20 - 25	4.0	2.3
Ind-2	25 - 40	2.0	2.5
Lower crust	40 - 70	0.4	2.6
<i>Model 3</i>			
Upper crust:			
Koh-F	0 - 10	1.0	2.3
Koh-M	10 - 20	0.08	3.0
Mid crust:			
Ind-2	25 - 40	2.0	2.5
Lower crust	40 - 70	0.4	2.6
<i>Model 4</i>			
Upper crust:			
Koh-F	0 - 10	1.0	2.3
Koh-M	10 - 20	0.08	3.0
Mid crust:			
Ind-1	20 - 30	2.0	2.3
Ind-2	30 - 40	1.0	2.5
Lower crust	40 - 70	0.4	2.6
<i>Model 5</i>			
Upper crust:			
Koh-F	0 - 10	1.0	2.3
Koh-M	10 - 20	0.08	3.0
Mid crust:			
Ind-1	20 - 30	1.0	2.3
Ind-2	30 - 40	0.5	2.5
Lower crust	40 - 70	0.4	2.6
<i>Model 6</i>			
Upper crust:			
Koh-F	0 - 15	1.0	2.3
Koh-M	15 - 20	0.08	3.0
Mid crust:			
Ind-1	20 - 30	1.0	2.3
Ind-2	30 - 40	0.5	2.5
Lower crust	40 - 70	0.4	2.6
<i>Model 7</i>			
Upper crust:			
Koh-F	0 - 15	1.0	2.3
Koh-M	15 - 20	0.08	3.0
Mid crust:			
Ind-1	20 - 30	2.0	2.3
Ind-2	30 - 40	1.0	2.5
Lower crust	40 - 70	0.4	2.6

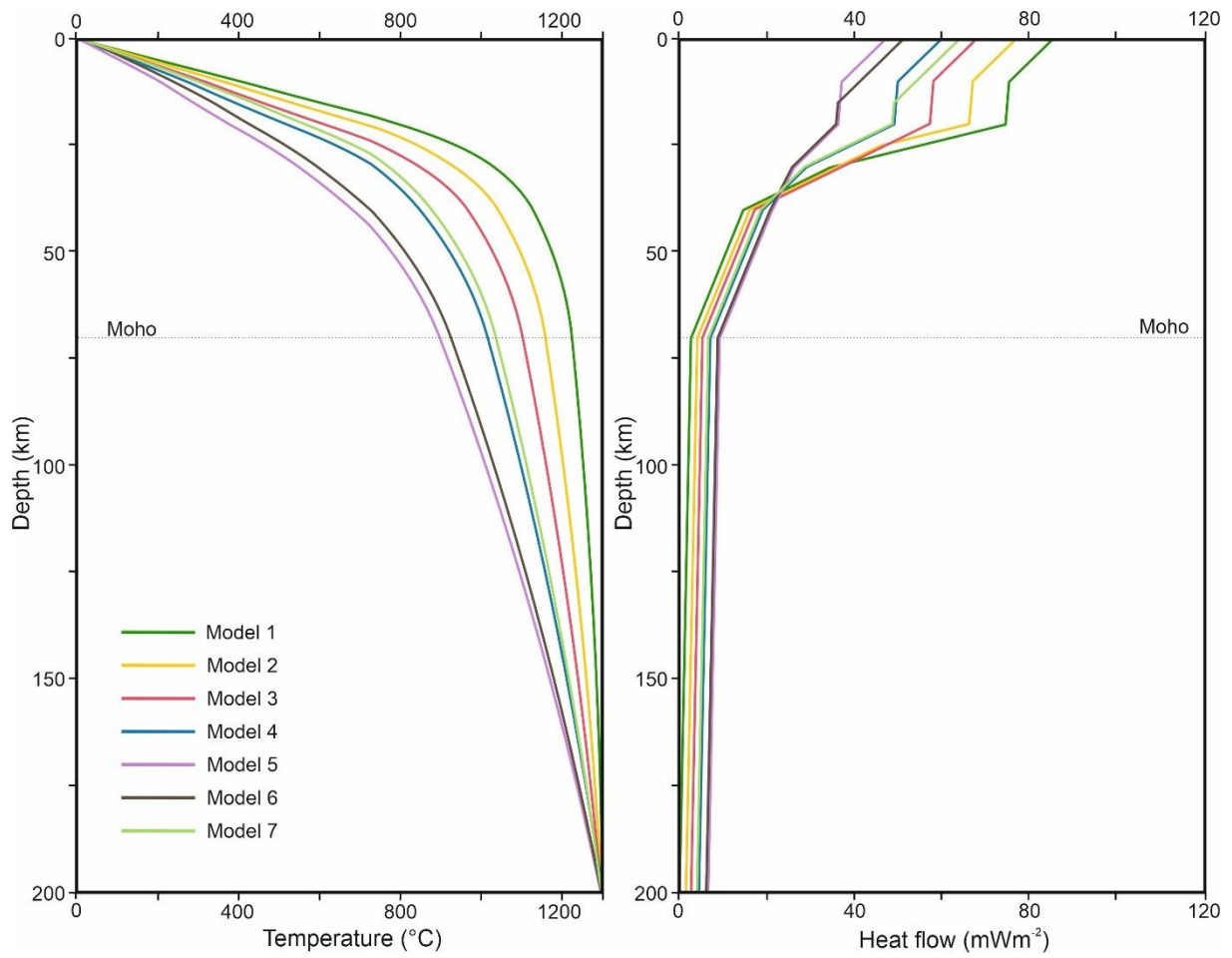


Figure S2 1D steady-state conductive geotherms and heat-flow plots for Kohistan arc. In Models 1 to 5, the upper crust is assumed to comprise felsic (Kohistan batholith) and mafic (amphibolite-granulite) components, each with 10 km thickness. The weighted average radiogenic heat production of Kohistan batholith is $1 \mu\text{W m}^{-3}$, and $0.08 \mu\text{W m}^{-3}$ for the mafic layer (Mukai et al., 1999). The lower crust for all models is assumed to be similar to the case of NPM, i.e., 30 km thick with $0.4 \mu\text{W m}^{-3}$. For the mid-crustal region, two basements of Indian origin (Ind-1 & Ind-2) with different radiogenic heat production are assumed. For model 1, Ind-1 and Ind-2 are assumed to be 10 km each with RHP of 4 and $2 \mu\text{W m}^{-3}$, respectively. For model 2, Ind-1 is reduced to 5 km, while Ind-2 is increased to 15 km. Model 3 assumes only Ind-2 (20 km thick) at mid-crustal level.

Table S3 Parameters used for the steady-state conductive thermal model of Karakoram. KB-Karakoram batholith, KMC-Karakoram metamorphic complex, DG-Dassu gneiss, HG-Hushe gneiss.

	Crustal depth range (km)	Radiogenic heat production ($\mu\text{W m}^{-3}$)	Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
<i>Model 1</i>			
Upper crust (KB)	0 - 15	2.5	2.3
Mid crust (KMC)	15 - 25	1.0	2.5
Lower crust	25 - 70	0.2	2.6
<i>Model 2</i>			
Upper crust			
KB	0 - 15	2.5	2.3
KMC	15 - 30	1.0	2.5
Mid crust			
Ind-1	30 - 40	2.0	2.3
Ind-2	40 - 50	1.0	2.5
Lower crust	50 - 70	0.4	2.6
<i>Model 3</i>			
Upper crust			
KB	0 - 15	2.5	2.3
KMC	15 - 30	1.0	2.5
Mid crust			
Ind-1	30 - 40	1.0	2.3
Ind-2	40 - 50	0.5	2.5
Lower crust	50 - 70	0.2	2.6
<i>Model 4</i>			
Upper crust (KB)	0 - 10	2.5	2.3
Mid crust (DG)	10 - 30	3.15	2.5
Lower crust	30 - 70	0.2	2.6
<i>Model 5</i>			
Upper crust (KB)	0 - 10	2.0	2.3
Mid crust (DG)	10 - 30	2.5	2.5
Lower crust	30 - 70	0.2	2.6
<i>Model 6 (KB-Kande pluton)</i>			
Upper crust	0 - 10	5.0	2.0
Mid crust (HG)	10 - 30	2.0	2.3
Lower crust	30 - 70	0.2	2.6
<i>Model 7</i>			
Upper crust (KB)	0 - 10	2.5	2.3
Mid crust (HG)	10 - 30	2.0	2.5

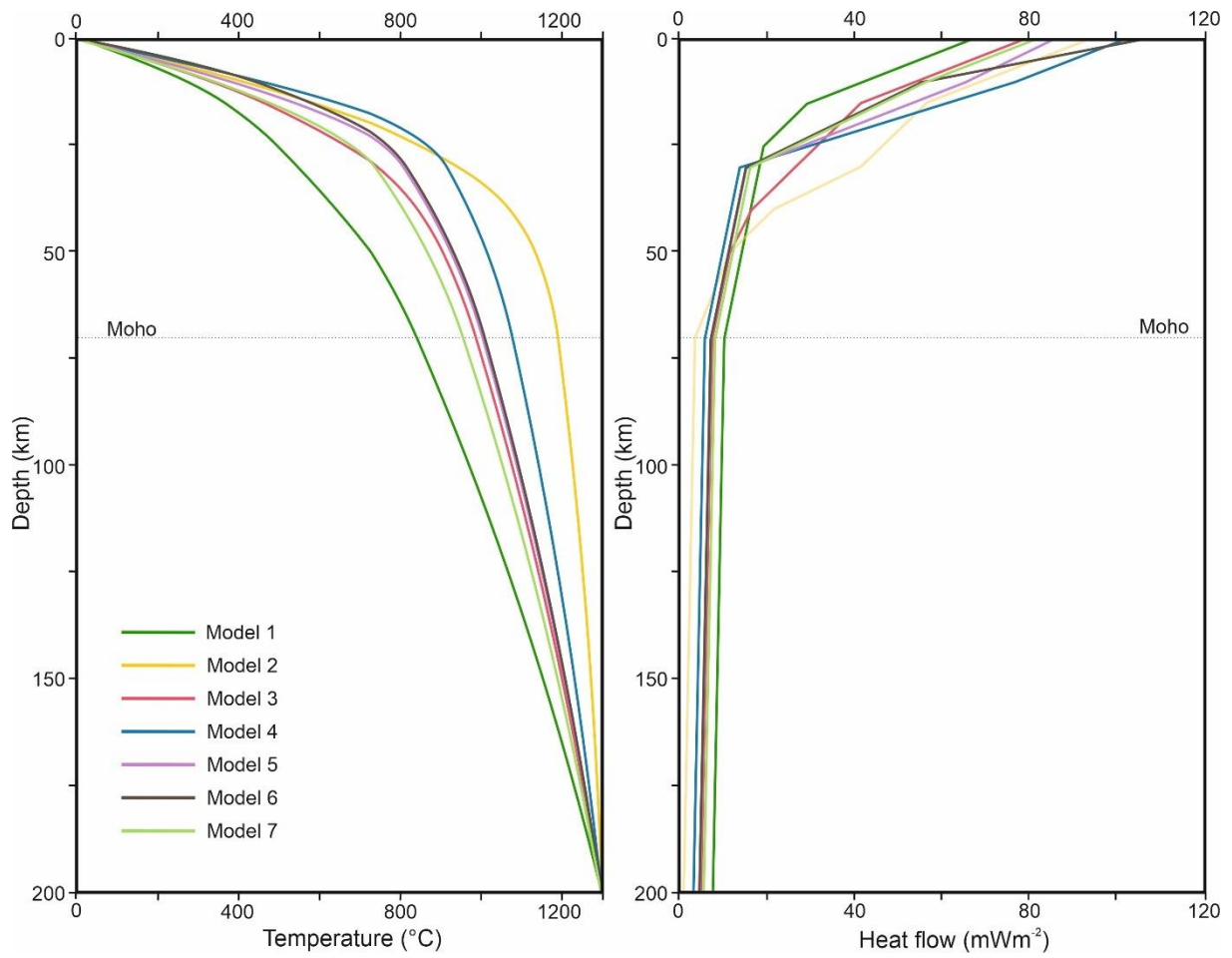


Figure S3 1D steady-state conductive geotherms and heat-flow plots for different modelling scenarios with varying parameters in the Karakoram. For model 1, the 15 km thick upper crust comprises Karakoram batholith (KB), while the 10 km mid-crust comprises Karakoram metamorphic complex (KMC) with RHP values of 2.5 and 1 $\mu\text{W m}^{-3}$, respectively. Model 2 assumes a 30 km upper crust with KB and KMC, each 15 km thick, and a 20 km mid-crust comprising Ind-1 and Ind-2 with RHP of 2 and 1 $\mu\text{W m}^{-3}$, respectively. The lower crust for this model is 20 km thick with RHP of 0.4 $\mu\text{W m}^{-3}$. For model 3, the RHP of mid-crust is reduced by 50% (1 and 0.5 $\mu\text{W m}^{-3}$), while the rest of the parameters are the same as in model 2. For models 4 and 5, mid-crust (20 km) comprises Dassu gneiss (DG) with RHP of 3.15 (surface RHP) and 2.5 $\mu\text{W m}^{-3}$, respectively. The lower crust is assumed to be 40 km thick with RHP of 0.2 $\mu\text{W m}^{-3}$ (model 4 to 7). Model 6 assumes the upper crust (10 km) comprising of Kande pluton with the mean surface RHP 5 $\mu\text{W m}^{-3}$ and mid-crust (20 km) comprising of Hushe gneiss (HG) with RHP of 2 $\mu\text{W m}^{-3}$. For Model 7, RHP is assumed to be half (2.5 $\mu\text{W m}^{-3}$) of model 6, while other parameters are kept the same.

Section S2 2D Thermal Models

Table S4 Input basal temperatures (°C) for the 2D thermal models at 10 km below sea level. The upper part shows temperatures derived from the 1D steady-state conductive models at 10 km depth, whereas the lower part shows temperatures calculated using increment factors for different exhumation rates from the 1D transient advective–conductive models.

	Temperatures (°C) at 10 km from 1D steady-state conduction model		
	Model 1	Model 2	Model 3
	Low RHP	High RHP	Moderate RHP
NPM	343	506	405
Kohistan	211	413	299
Karakoram	274	461	385

	Temperatures (°C) at 10 km from 1D transient advective-conductive model		
	Model 1	Model 2	Model 3
	Fast exhumation, Low RHP	Slow exhumation, High RHP	Slow exhumation, Moderate RHP
NPM- core	623 (at 3 mm y ⁻¹)	657 (at 2 mm y ⁻¹)	564 (at 2 mm y ⁻¹)
NPM-sides	510 (at 2 mm y ⁻¹)	577 (at 1 mm y ⁻¹)	478 (at 1 mm y ⁻¹)
Kohistan	257 (at 1 mm y ⁻¹)	432 (at 0.5 mm y ⁻¹)	318 (at 0.5 mm y ⁻¹)
KMC	407 (at 2 mm y ⁻¹)	482 (at 0.5 mm y ⁻¹)	410 (at 0.5 mm y ⁻¹)
KB	497 (at 3 mm y ⁻¹)	525 (at 1 mm y ⁻¹)	454 (at 1 mm y ⁻¹)

Table S5 Petrophysical parameters based on previous studies (Anees et al., 2023, 2024) used for the 2D thermal models.

	Radiogenic heat production (μW m ⁻³)	Thermal conductivity (W m ⁻¹ K ⁻¹)	Specific heat capacity (J kg ⁻¹ K ⁻¹)	Density (kg m ⁻³)
<i>Nanga Parbat Massif</i>				
Core gneiss	5.33	2.26	750.7	2650
Cover metasediments	2.06	2.15	753.8	2700
Pegmatite	4.79	3.37	754.5	2610
Granite	6.8	1.86	749.3	2590
<i>Kohistan</i>				
KLB	1.08	2.4	755.4	2700
Metavolcanics	0.5	2.13	760.4	2800
<i>Karakoram</i>				
KMC	2.01	2.2	750.9	2670
KB	2.36	1.68	766.6	2700